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Monitoring Forsmark – evaluation and recommendations for programme update

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Preface

This document gives a presentation and evaluation of the geoscientific and ecological monitoring performed by the Swedish Nuclear Fuel and Waste Management Company (SKB) at Forsmark, Sweden. The evaluation results in a set of discipline-specific and general recommendations for the continued development of the Forsmark monitoring programme that are summarised in Chapters 8 and 9 of the report.

SKB has submitted applications concerning construction of new nuclear waste facilities at Forsmark within two of its repository programmes, i.e. the programme for high-level nuclear waste, which aims to build a new repository for spent nuclear fuel, and that for low- and intermediate-level waste, where the submitted application concerns an extension of the existing SFR repository. This report is focused on the current pre-construction stages of these programmes, especially on recommendations regarding monitoring and related developments that need to be undertaken during the period before construction activities commence.

This report has been produced by a group of experts organised by the undersigned within the framework of the Forsmark site management unit at SKB. The group consists of experts on the subject areas included in the monitoring programme, i.e. geology, hydrology, hydrochemistry and ecology, as well as representatives for the users of monitoring data. Specifically, the following persons have contributed to the discipline-specific sections of the report:

Geology: Susanna Andrén (SKB), Raymond Munier (SKB), Lennart Ekman (LE Geokonsult AB) and Hans Thunehed (GeoVista AB).

Hydrology: Kent Werner (EmpTec), Sven Follin (Golder Associates AB) and Sten Berglund (HydroResearch AB).

Hydrochemistry: MatsTröjbom (MTK AB), Ann-Chatrin Nilsson (Geosigma AB) and Cecilia Berg (SKB).

Ecology and nature values: Anders Löfgren (Ecoanalytica), Tobias Lindborg (SKB) and Mikael Gontier (SKB).

The general parts of the report, i.e. the introductory, background, methodology and concluding sections, were written by Sten Berglund and Tobias Lindborg, who also served as editors of the report. The report was written and reviewed in 2014–15. During 2016–17, the report has been updated based on review comments and supplemented with some recent monitoring reports. The status of unpublished Forsmark monitoring reports was reviewed, resulting in reclassification of many recent reports to make them available for referencing.

The factual review of the report has been performed by Karl-Erik Almén (SKB), Ari Ikonen (EnviroCase Oy, Finland), Mike Thorne (Mike Thorne and Associates Ltd, UK). Their contributions, and those from a large number of persons within SKB who provided comments on various versions the report, are gratefully acknowledged.

Tobias Lindborg

Geoscientific coordinator, Forsmark site management unit, SKB

Abstract

The Swedish Nuclear Fuel and Waste Management Company (SKB) is performing geoscientific and ecological monitoring at the Forsmark site in Sweden for existing and planned nuclear waste disposal facilities. Specifically, monitoring is carried out to follow the operation of the existing SFR repository for low- and intermediate-level nuclear waste, and as a part of the preparations for extending the SFR repository and for constructing a new repository for high-level waste in the form of spent nuclear fuel.

The SFR extension and the spent fuel repository are both subjects of on-going licensing processes, where SKB has submitted applications to the authorities and presently are performing monitoring to further develop site understanding and provide input to various preparations and activities related to the licensing processes. Important aspects of this monitoring are to extend time series and establish a baseline that provides a proper description of site conditions prior to the launching of construction activities related to the planned waste disposal facilities, including relevant "natural" variations.

This report is focused on the present baseline period of the monitoring at Forsmark, and aims at providing recommendations concerning both discipline-specific measurements and general development needs associated with the monitoring programme. The report has been produced by a group of experts organised within the framework of the Forsmark site management unit at SKB. The group consists of experts on the subject areas included in the monitoring programme, i.e. geology, hydrology, hydrochemistry and ecology, as well as representatives for the users of monitoring data.

Monitoring is a common and important task for all nuclear waste management organisations, and has therefore been the subject of several recent projects organised by international organisations in this field. A brief account of some of these international projects and of monitoring within some national programmes is given in the report, along with a summary of nomenclature, definitions and legislation.

The monitoring at Forsmark is performed for a variety of purposes associated with different activities and end-users. Users and uses of monitoring data include (1) development of site understanding and site descriptive models, (2) assessment of long-term radiological safety, (3) assessment of the environmental impact of repository construction and operation, and (4) repository design. Following a general description of conceptual models for the "natural" and "disturbed" systems to be monitored, an overview of these user needs is given as a starting point for the detailed analyses.

The main part of the report is devoted to discipline-specific descriptions and evaluations of the present monitoring programme. Specifically, the subject areas and the parameters or parameter groups monitored within them are summarised as follows.

- Geological monitoring: measurements of rock deformation, earth electrical currents and the global magnetic field.
- Meteorological and hydrological monitoring: measurements of meteorological parameters, groundwater levels and fluxes in bedrock, groundwater levels in regolith, surface water levels and surface-water discharges.
- Hydrochemical monitoring: chemical sampling and analyses of various surface waters, near-surface groundwater and bedrock groundwater.
- Monitoring of ecology and nature values: this monitoring includes general monitoring of mammals and birds, and monitoring of threatened species and specific objects of particular interest for the assessment of environmental impacts.

Detailed descriptions of the on-going monitoring and how the subject experts think it should be developed during the rest of the pre-construction phase are provided in separate chapters for each discipline. The resulting recommendations are compiled in a separate chapter (Chapter 8), which constitutes a somewhat lengthy "executive summary" of the recommendations proposed by the expert group. A more condensed presentation is provided in the final chapter of the report (Chapter 9), where also a set of recommendations on further investigations are presented.

In addition to the specific development needs specified for each monitoring discipline, the expert group recommends that SKB initiates investigations directed towards the following issues (see Chapter 9 for descriptions detailing each issue).

- Establishment of baseline and reference measurements.
- Monitoring of objects with high nature values.
- Monitoring of environmental parameters potentially affected by construction and operation activities.
- Monitoring of atmospheric parameters.
- Data handling and organisation of environmental monitoring.
- Establishment of a sample archive.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) utför geovetenskaplig och ekologisk monitering i Forsmark i norra Uppland för befintliga och planerade anläggningar slutförvarsanläggningar för radioaktivt avfall. Monitering genomförs för att följa driften av det befintliga slutförvaret SFR för kortlivat låg- och medelaktivt avfall och även som ett led i förberedelserna för en utbyggnad av SFR och för byggandet av ett slutförvar för högaktivt avfall i form av utbränt bränsle från kärnkraftverken.

Utbyggnaden av SFR och byggandet av kärnbränsleförvaret är båda föremål för pågående tillståndsprocesser där SKB har lämnat in ansökningar till myndigheterna. Pågående monitering utförs i syfte att ytterligare utveckla kunskapen om Forsmark och för att stödja tillståndsprocesser och andra aktiviteter kopplade till förvarsanläggningarna. Viktiga målsättningar för moniteringen är att förlänga existerande tidsserier mätdata och att etablera tillräckligt detaljerade beskrivningar av förhållandena på platsen för att dessa ska kunna användas som referens vid utvärderingar av effekter och konsekvenser av planerade verksamheter. Det senare kallas ofta ”baseline”.

Denna rapport är fokuserad på moniteringen under resten av perioden innan byggstart och innehåller rekommendationer avseende både enskilda ämnesområden och generella utvecklingsbehov relaterade till moniteringsprogrammet. Rapporten har producerats av en expertgrupp organiserad inom ramen för SKB:s platsförvaltning i Forsmark. Gruppen har innehållit experter inom alla ämnesområden som ingår i det nuvarande moniteringsprogrammet, det vill säga geologi, hydrologi, hydrokemi och ekologi, samt representanter för moniteringsorganisationen i Forsmark och användare av moniteringsdata.

Monitering är en viktig och gemensam arbetsuppgift för alla organisationer som bygger och driver anläggningar för radioaktivt avfall och har därför varit föremål för flera projekt som genomförts av internationella organisationer inom detta område. Rapporten innehåller en kortfattad genomgång av några sådana projekt och vissa nationella program, samt en sammanfattning av relevant nomenklatur, definitioner och lagstiftning.

Moniteringen i Forsmark genomförs för att tillgodose ett antal olika behov kopplade till olika aktiviteter och användare av data. Användare och användningsområden inkluderar (1) utveckling av platsförståelse och platsbeskrivande modeller, (2) utvärdering av radiologisk säkerhet efter förslutning, som kan omfatta mycket långa tider, (3) utvärdering av miljöpåverkan och konsekvenser av byggande och drift av förvarsanläggningarna, (4) projektering av yt- och undermarksanläggningar. Rapporten ger en övergripande beskrivning av konceptuella modeller för de ”naturliga/ostörda” och ”störda” system som ska moniteras och, som en inledning till de detaljerade ämnesvisa analyserna, även av användningen av moniteringsdata.

Rapportens huvuddel behandlar disciplinspecifika beskrivningar och utvärderingar av det nuvarande moniteringsprogrammet. Programmets olika delar och dessas huvudsakliga innehåll kan sammanfattas som följer.

- Geologisk monitering: mätningar av bergets rörelser, jordströmmar och det globala magnetfältet.
- Meteorologisk och hydrologisk monitering: mätningar av meteorologiska parametrar, grundvattennivåer och -flöden i berg, grundvattennivåer i jordlager, och av nivåer och flöden i ytvatten.
- Hydrokemisk monitering: kemisk provtagning och analys av olika former av ytvatten (hav, sjöar och vattendrag), och av grundvatten i jordlager och berg.
- Monitering av ekologi och naturvärden: denna monitering innefattar allmän monitering av däggdjur och fåglar, samt monitering av särskilt skyddsvärda arter och objekt såsom våtmarksmiljöer med höga naturvärden.

Detaljerade beskrivningar av pågående monitering och hur de olika ämnesexperterna anser att den bör vidareutvecklas under resten av perioden fram till byggstart ges i separata kapitel för varje ämnesområde enligt ovan. De resulterande rekommendationerna har samlats i ett gemensamt kapitel (kapitel 8), vilket också kan tjäna som en lite mer omfattande sammanfattning av vad som föreslås.

En mer kondenserad sammanfattning ges i rapportens slutkapitel (kapitel 9), där också föreslagen monitering presenteras i tabellform.

Förutom utvecklings- och moniteringsbehov kopplade till enskilda ämnesområden, har expertgruppen identifierat att SKB snarast behöver initiera utredningar och utveckling med sikte på följande frågeställningar, behov och funktioner i ett framtida moniteringssystem i Forsmark (beskrivningar kopplade till varje rubrik finns i kapitel 9).

- Etablering av ”baseline” och erforderliga referensmätningar.
- Monitering av objekt med höga naturvärden.
- Monitering av miljöparametrar som kan komma att påverkas av byggande och drift.
- Monitering av atmosfärsparametrar.
- Utveckling av system för datahantering och moniteringsorganisation.
- Etablering av provarkiv.

Contents

1 Introduction

1.1 Background

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Company (SKB). The Swedish programme for handling of radioactive waste, which also includes waste from other sources (e.g. health care), involves systems and facilities for transport and storage of different types of waste. In this context, different types of waste, as distinguished by the level and longevity of their radioactivity, are handled in different ways, especially when it comes to the interim storage and final disposal of the waste.

The Forsmark area in central Sweden is very important for SKB's waste management programme, as a location for both operating and planned disposal facilities. Specifically, Forsmark hosts the SFR repository for low- and intermediate-level waste, which is planned to be extended relatively soon, and is also the intended site for the planned repository for the spent fuel from the Swedish nuclear power plants (see Section 1.4). Therefore, extensive site investigations have been carried out at Forsmark, and monitoring of a variety of geoscientific and ecological processes and parameters is currently performed for purposes related to existing and planned facilities.

This report describes and evaluates the Forsmark monitoring programme and how it needs to be developed to meet data needs during forthcoming stages of the repository projects. Specifically, the report is focused on data and development needs during the remainder of the present period of preparations for construction and operation of nuclear waste repositories at Forsmark.

1.2 Nuclear waste handling in Sweden

As described in some detail in, for instance, SKB's most recent research and development programmes (SKB 2013a, 2016a), the Swedish system for nuclear waste management includes transport and storage functions for different types of waste, where some parts of the system are in operation and others in different stages of planning and development. Concerning waste disposal facilities, there are also ongoing licensing processes, in which SKB applications for constructing and operating waste repositories are being determined in accordance with environmental legislation and nuclear safety legislation.

For the spent nuclear fuel, also referred to as high-level nuclear waste, an interim storage facility, Clab, in Simpevarp (Figure 1-1) and a transportation system are presently (2015) in operation. Several decades of research and development have led SKB to put forward the KBS-3 method (SKB 2013a) for the final stage of spent nuclear fuel management. In this method, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at a depth of approximately 500 metres in groundwater-saturated, crystalline rock. Essentially, this concept implies that at the end of the operational period the repository is sealed and then left to be saturated by inflowing groundwater.

Around 12 000 tonnes of spent nuclear fuel are forecasted to arise from the currently approved Swedish nuclear power programme (where the last of the ten reactors presently in operation will be decommissioned in 2045), corresponding to roughly 6 000 canisters in the KBS-3 repository concept. Two principal remaining tasks in the spent fuel programme are to build and operate (i) an encapsulation plant, in which the spent fuel will be emplaced in the above-mentioned copper canisters, and (ii) the final repository for the spent nuclear fuel. An application for realising a system according to the KBS-3 method, including construction and operation of these two facilities, was submitted to the Swedish authorities in 2011. According to this application, the encapsulation plant is to be placed in association with the Clab interim storage facility at Simpevarp, whereas the spent fuel repository will be built in Forsmark (Figure 1-1).

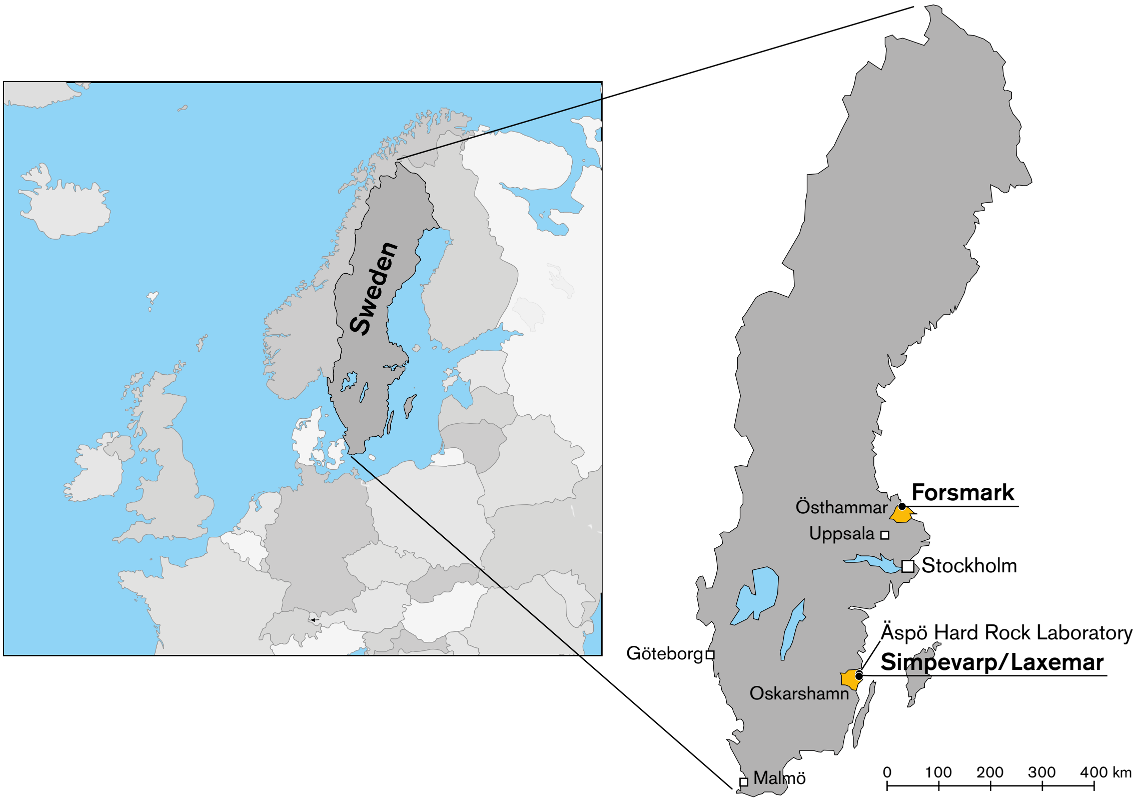

Figure 1-1. *Locations of SKB's underground research laboratory (Äspö), investigation areas for the spent fuel repository (investigations were performed at Forsmark, Simpevarp and Laxemar), and nuclear waste management facilities. In the KBS-3 permit application, Simpevarp is the location intended for the encapsulation plant, whereas Forsmark is proposed as the spent fuel repository site.*

Short-lived low- and intermediate-level nuclear waste is stored in the SFR facility in Forsmark (Figure 1-1), which has been in operation since 1988, and in near-surface repositories at the nuclear power plants. The near-surface repositories, where only wastes with very low levels of activity are deposited, are operated by the waste producers (the power plants), whereas SFR is operated by SKB. Most of the short-lived waste comes from the nuclear power plants. Other waste comes from Clab and from facilities belonging to Studsvik Nuclear AB and AB SVAFO. There are also other waste sources outside the nuclear industry, e.g. health care and research. In the future, SFR will also receive waste from the combined Clab and encapsulation plant facility (referred to as Clink) and from decommissioned nuclear power plants. This implies a need for increased storage capacity in SFR, and an application for extending SFR and operating the extended facility was submitted to the authorities in December 2014.

Regarding low- and intermediate-level waste, it should also be mentioned that SKB is planning a separate repository for the long-lived waste components. This repository, which according to present SKB nomenclature is called SFL, is in a relatively early planning stage; no site has been selected for this repository. The status of the SFL repository project is described in SKB (2013a).

1.3 The Forsmark site

The Forsmark site is located in the northern part of the County of Uppsala (and the Uppland province) in central Sweden, within the municipality of Östhammar and about 120 km north of Stockholm (Figure 1-1). Extensive site investigations were performed at Forsmark during the period 2002–2007 to collect data for the site-descriptive model (SDM, for short) that was developed and used as a basis for the licence application to start construction of a spent fuel repository; this model, referred to as SDM-Site, is reported in SKB (2008). Unless otherwise stated, the information in the remainder of this section comes from this “SDM-Site report” (SKB 2008). Later, additional site investigations were performed for the SFR extension project. The results of these investigations are reported in SKB (2013b). Figure 1-2 provides an overview of the Forsmark site, illustrating its coastal location, current lakes, wetlands and streams, and existing nuclear facilities (SFR and the nuclear power plant). A map covering a larger area and more objects of interest is presented in Appendix 1.

The Forsmark area is characterised by a crystalline bedrock that belongs to the Fennoscandian Shield formed 1.85 to 1.89 billion years ago. The area represents a typical coastal site on the shoreline of the Baltic Sea in northern Uppland. Post-glacial land uplift, in combination with the flat topography, implies fast shoreline displacement that has resulted in a very young terrestrial system that contains a number of newly formed shallow lakes and wetlands (Figure 1-3). The lakes themselves are also of a specific type that is found only in northern Uppland. Shallow and with sediments rich in calcium, the lakes are unique in Sweden. As discussed in more detail below and in the environmental impact assessment of the spent fuel repository (SKB 2011a), one consequence of this is that there exist some rare/threatened plant and animal species in the smallest Forsmark lakes (hereinafter often called ponds) and wetlands.

The regolith (a general term for all unconsolidated deposits on top of the bedrock) consists mostly of Quaternary deposits and is relatively thin, with an average thickness of approximately four metres in the land parts of the Forsmark site investigation area. The surface distribution of regolith is dominated by till, which in lake and wetland areas is overlain by various mostly low-permeable materials, such as glacial and postglacial clays. The flat topography is reflected in a pattern of relatively small recharge and discharge areas of groundwater in the regolith. The average values of the main water balance components, where the average refers to a time scale of a few decades, have been estimated to 560, 400 and 160 mm/year for precipitation, actual evapotranspiration and runoff, respectively (Johansson 2008).

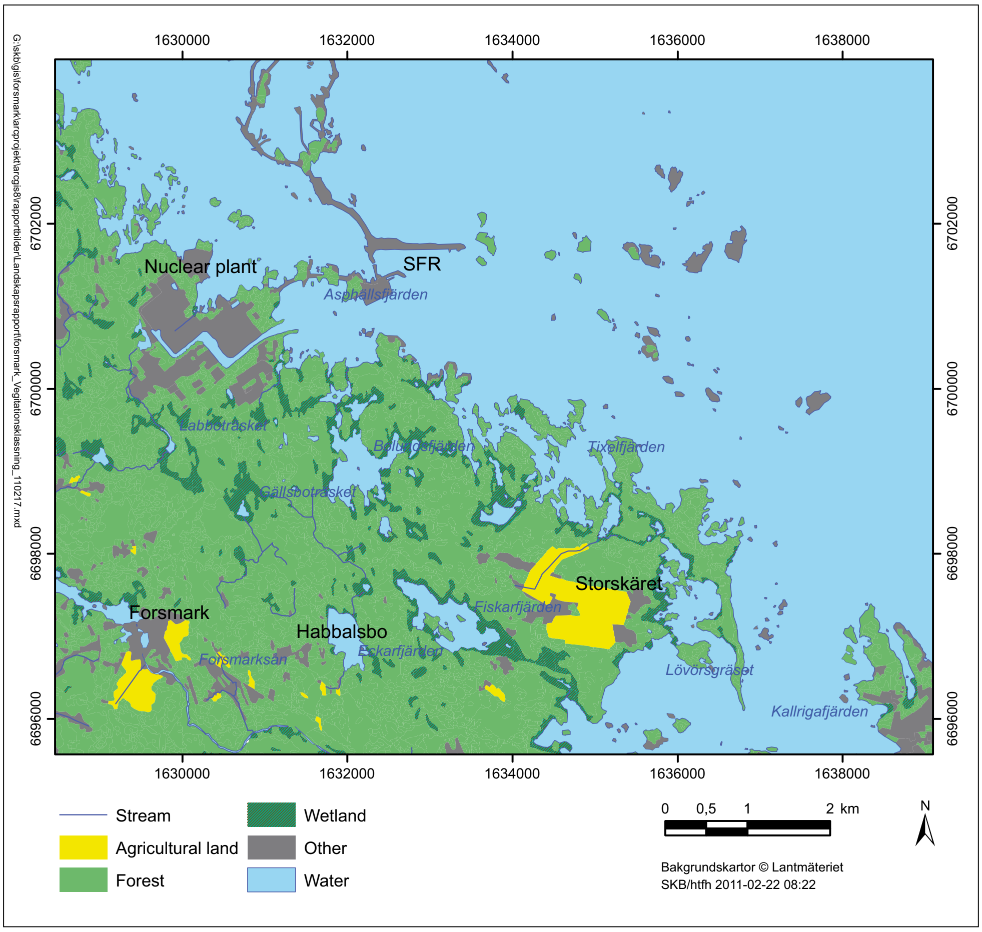

Figure 1-2. Overview of Forsmark showing the present coastline and various objects discussed in the present report, including existing nuclear facilities (the nuclear power plant and the underground SFR facility).

Figure 1-3. Coastline and lake surrounded by mire at the Forsmark site. Shoreline displacement effects on the landscape are considerable and newly formed lakes are seen just inside the shoreline.

In the bedrock, tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed in between ductile high-strain belts. The so-called candidate area (Figure 1-4) is located in the northwestern-most part of one such tectonic lens; this is the area where most of the site investigations for the spent fuel repository were performed, and also where SKB intends to build the repository for spent nuclear fuel. As shown in Figure 1-4, the tectonic lens in Forsmark extends from northwest of the nuclear power plant southeastwards to the area around Öregrund. The figure also shows that the SFR repository is located just outside the lens, separated from the lens by a major deformation zone called the Singö zone.

Three major sets of deformation zones with distinctive orientations have been recognised in the geological modelling of the bedrock. In addition to vertical and steeply dipping zones, there are also zones gently dipping southeast and south. These gently dipping zones are more frequent in the south-eastern part of the candidate area (volume) for the spent fuel repository and have higher hydraulic transmissivity than vertical and steeply dipping deformation zones at the site. The frequency of fractures classified as "open" and "partly open" (see SKB 2008) is very low below approximately 300 m depth compared to what is observed in the upper part of the bedrock in the northwestern part of the candidate area, which is the "target area" where the spent fuel repository is planned to be located. In addition, the rock stresses are relatively high compared to typical conditions in the Swedish bedrock.

The geological characteristics of the site imply that the area differs from the regional pattern also when it comes to the hydrogeological properties. Highly permeable structures are associated with the complex network of gently dipping and sub-horizontal, open and partly open fractures in the upper part of the bedrock. This means that the upper 100 to 150 m of the bedrock overlying the volume intended for the spent fuel repository contain many highly transmissive (water-conducting) fractures extending in the horizontal plane, which results in hydraulic connections over relatively large distances. Conversely, the deeper bedrock has very low permeability and few transmissive fractures. At the proposed repository depth (c. 470 m), the average distance between transmissive fractures is more than 100 m according to the results of the surface-based site investigations.

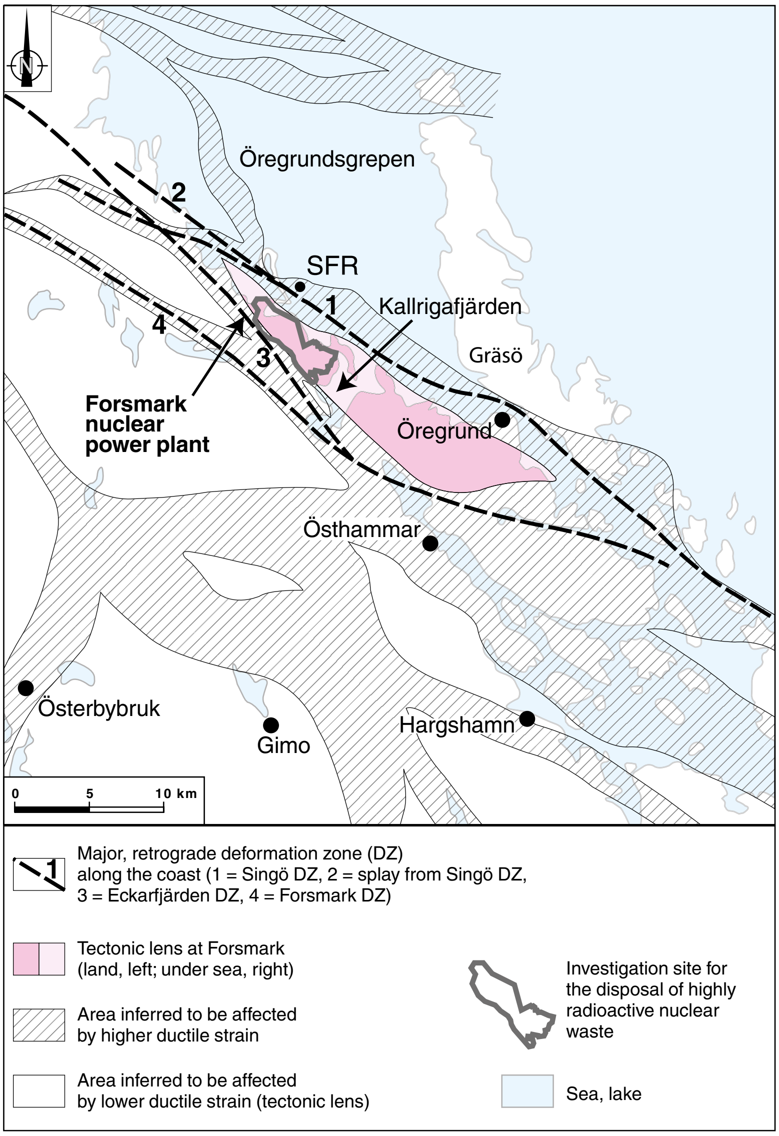

***Figure 1-4.** The tectonic lens with the major deformation zones (DZ) at Forsmark and the candidate area of the site investigation for the spent fuel repository; nearby areas affected by strong ductile deformation are also shown (figure from SKB 2008).*

The hydrogeochemical site investigations show that groundwater in the uppermost 100 to 200 m of the bedrock displays a wide range of chemical variability, with chloride concentrations in the range 200 to 5 000 mg/L suggesting influence of both brackish marine water and meteoric (from recent precipitation) waters. At depths between 200 and 800 m, the salinity remains fairly constant (5 000–6 000 mg/L) and the water composition indicates remnants of water from the Littorina Sea that covered Forsmark between 9 500 and 5 000 years ago. At depths between 800 and 1 000 m, the salinity increases to even higher values.

1.4 Existing and planned repositories at Forsmark

The existing and planned nuclear waste repositories at Forsmark are the reasons for SKB's monitoring activities in the area, and descriptions of the SFR and spent fuel repositories are therefore given here as a background to the remainder of the report. Only brief descriptions are provided; more details can be found in the technical descriptions associated with permit applications (SKB 2011b, 2014b), and also in related environmental impact statements (SKB 2011a, 2014c) and safety assessment reports (SKB 2011c, 2014d).

As stated in Section 1.1, there already exists an underground repository for short-lived, low- and intermediate-level operational waste at the Forsmark site, the SFR facility. Construction started in 1983 and the facility became operational in 1988. The waste is stored in rock caverns situated in the bedrock at c. 60 m depth below the seabed in the bay Öregrundsgrepen off Forsmark. The vaults are accessed via tunnels that descend from an island called "Stora Asphällan", where also the SKB and SFR office buildings and the Forsmark harbour are located (Figure 1-5)

SKB plans to extend the SFR repository. Specifically, the plan is to create an entirely new section (SFR 3) directly adjoining the existing SFR (SFR 1), see Figure 1-5. The extension will primarily be used for decommissioning waste from Sweden's nuclear facilities, consisting of reactor components, scrap metal, concrete and other building materials. The new section for decommissioning waste will be built at larger depth than the vaults of the present SFR 1, at roughly 120 m below the seabed, where studies have shown that suitable bedrock for the purpose exists. The construction works are planned to commence within a few years, depending on the legalisation process initiated by SKB's application submitted in December 2014.

A second, considerably larger repository for long-lived, high-level nuclear waste, i.e. spent nuclear fuel, is intended to be constructed southwest of the SFR facility. Figure 1-6 shows a cross-sectional view of the underground parts of the spent fuel repository, which consist of accesses (ramp tunnel and shafts) from the surface and a network of tunnels along which the waste-containing canisters are to be placed. As a background to the forthcoming discussions of site investigations and consequences of construction and operation, Figure 1-7 shows an outline of areas planned to be utilised for the surface facility of the repository (marked "operations area") and other activities with implications for man and the environment (such as the storage of waste rock in the "rock heap" area). Once fully developed, the operations area will contain a number of buildings for a wide range of purposes, including information/visitor services, geoscientific investigations and documentation, and handling of the nuclear waste canisters.

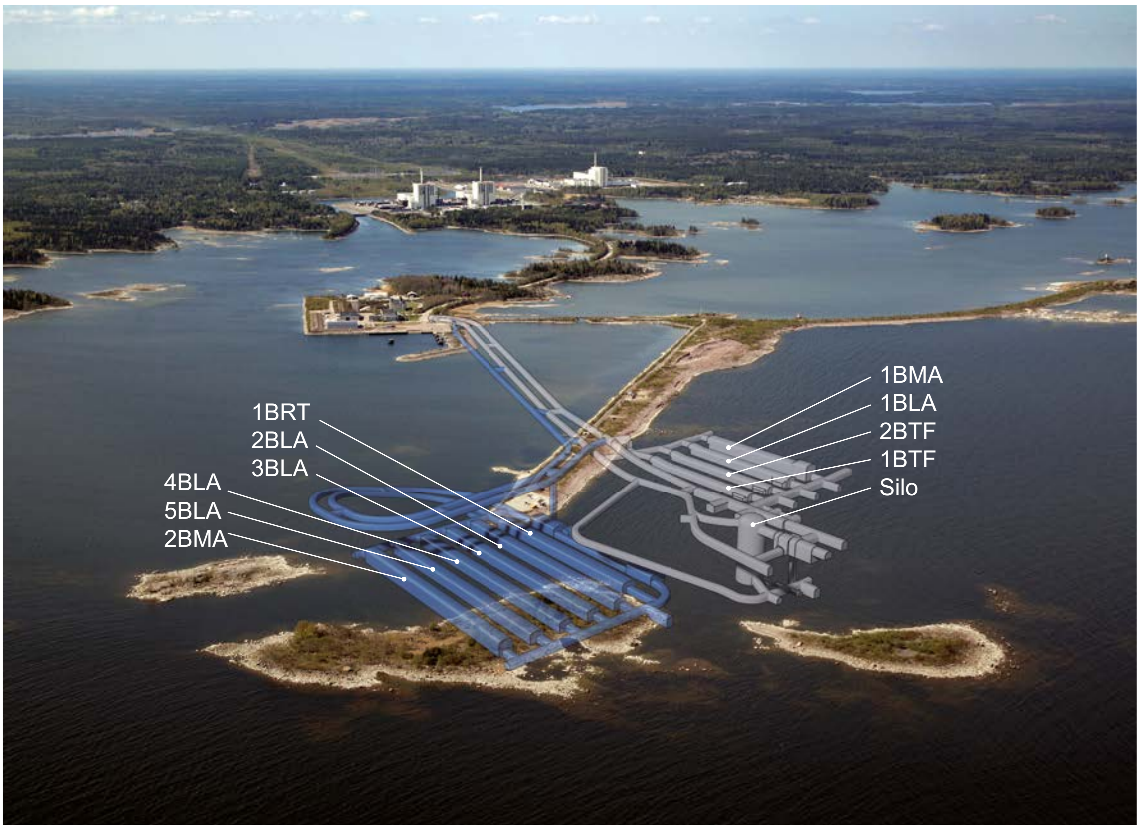

Figure 1-5. *Perspective view of the Forsmark-SFR area from the southeast with the existing SFR 1 facility indicated to the right (grey) and the planned expansion, SFR 3, to the left (blue, design according to 2014 licence application). The SFR pier, the access tunnels from the SFR surface facility in the Forsmark harbour, and the nuclear-power reactor buildings are also shown.*

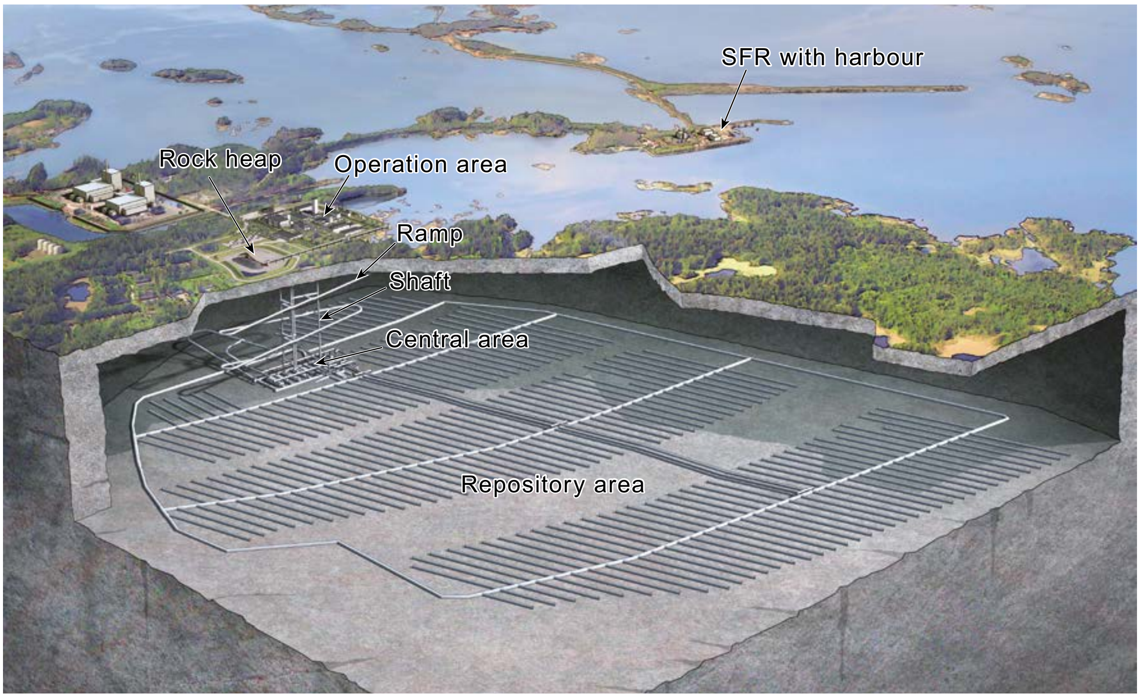

Figure 1-6. *Schematic view of the planned repository for spent nuclear fuel from the southwest, with the nuclear-power reactor buildings to the left, and the planned surface facility above the access tunnel loop. The Forsmark-SFR area (Figure 1-5) is shown in the background with the SFR pier extending from left to right behind the "Stora Asphällan" island with the Forsmark harbour.*

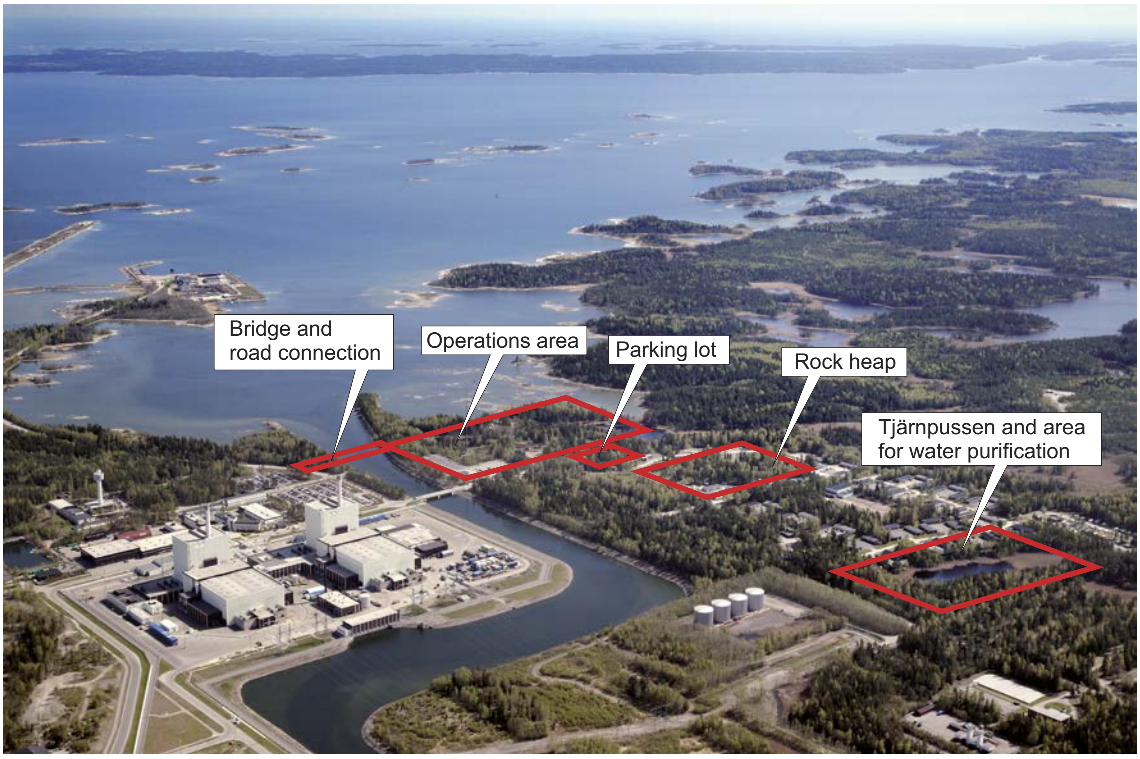

Figure 1-7. *Aerial photo from the northwest showing areas on the surface planned to be utilised for the spent fuel repository and associated constructions and activities, as presented in the 2011 licence application (SKB 2011a). The area marked "operations area" is where the tunnel entrance and the buildings constituting the surface facility of the repository will be located.*

The construction of the spent fuel repository is also estimated to start within a few years, see SKB (2016a) for details on current plans, depending on when the legal process that started in 2011 is completed. This means that the construction periods for the spent fuel repository and the extension of SFR may partly overlap each other. However, production of the tunnel system for the spent fuel repository will continue for decades after completion of the SFR construction works (e.g. SKB 2013a, 2016a). The two repositories will be situated geographically relatively close to each other, and construction activities at one of the repositories causing tremors, e.g. blasting, will possibly be detectable also at the other repository. This implies that if construction periods overlap such interferences must be considered in the planning of construction-related monitoring.

1.5 Site understanding and monitoring

Nuclear waste repository programmes that have reached the stages where they consider specific sites (e.g. the site selection or licensing stages) by necessity include site-specific assessments of, for instance, future radiological consequences to man and non-human biota. This implies that site data and site-specific conditions must be stored in databases, understood and expressed in terms of models such that they can be used in the assessments to be performed. Thus, site understanding is central to the development of site descriptions, and also for the identification of realistic projections concerning long-term conditions at the investigated site. Essentially, site understanding has four main components: site data, development of site-specific conceptual and numerical models, development and reporting of site descriptive models, and the increase in general scientific knowledge that emerges when working with a site for a long time.

Past and present surface and near-surface conditions at Forsmark are considered well known and are described in a number of SKB reports; this knowledge is summarised and synthesised in Lindborg (2008) and SKB (2010a, 2014a), as well as in scientific papers (e.g. Lindborg et al. 2013, Sohlenius et al. 2013). The understanding of bedrock conditions at Forsmark, primarily the bedrock geology, hydrogeology and hydrogeochemistry, is summarised in the site descriptive model report for SDM-Site (SKB 2008), and the corresponding report from the SFR extension project (SKB 2013b).

In the overall assessment methodology employed by SKB, information from the site descriptions is used (together with generic data) as a basis for building discipline-specific conceptual and numerical models describing properties and process understanding that are used to develop descriptions of possible future conditions at the Forsmark site. This conceptualisation and descriptive modelling of the present Forsmark situation was an important preparatory task for the long-term radiological safety and environmental impact assessments, and the subsequent development of repository layouts for the SFR extension and the spent fuel repository.

Site understanding requires site data, i.e. data obtained from measurements or other observations at the considered site. With respect to temporal variations, site data can be subdivided into two types, i.e. parameters that are expected to be constant and hence (in principle) can be measured on a single occasion, and parameters that vary significantly during the observation period and hence cannot be sufficiently well characterised by a single measurement. In the latter case, time series are required, and time series are obtained from monitoring. Data obtained from monitoring constitute an important basis for site understanding. The need for time series data to support process understanding and for quantification of natural ranges of variability is one of the main motivations for establishing a monitoring network. In any assessment of consequences where changes are to be related to an "undisturbed" present state, this present state must be established. This reference state is commonly referred to as the "baseline" (cf. Section 2.1).

As described in more detail in Section 2.1, several organisations and international projects have presented definitions of the term "monitoring" in the context of geological repositories for nuclear waste. In particular, IAEA (2014, p 7) defines monitoring as

"… continuous or periodic observations and measurements to help evaluate the behaviour of the components of a waste disposal system and the impact of the waste disposal system on the public and the environment."

However, a definition that might be considered even more relevant in the current stage of the Swedish programme, especially for the spent nuclear fuel, is given in the SKB report by Bäckblom and Almén (2004, p 5), as follows:

"Continuous or repeated observations or measurements of parameters to increase the scientific understanding of the site and the repository, to show compliance with requirements or for adaptation of plans in light of the monitoring results."

While largely similar to the IAEA definition above, the definition presented in the SKB report emphasises site understanding, which is consistent also with present SKB reasoning related to site data collection and modelling (cf. above). A monitoring definition formulated specifically for the present work is not considered necessary. However, in agreement with existing definitions, it is understood that monitoring includes both measurements and other observations, that they can be continuous or repeated, and that they could be made for purposes of site understanding, assessment of impacts on the public and the environment, and to provide support for decision-making in a step-wise repository programme. In addition, monitoring could encompass "engineering, environmental, radiological or other parameters and indicators/characteristics" (Modern 2014a, p 2).

1.6 Objectives, scope and intended use of the report

This report is written to describe and evaluate the present programme for geoscientific and environmental monitoring at Forsmark (Section 3.3.3 and Chapters 4 through 7), and to provide recommendations regarding modifications of the programme and further investigations needed to develop the programme. Based on the experiences and results of more than a decade of monitoring at the site, the report presents and discusses the present status of the programme, and provides input to its further development. The general objective of this work is to support further development of the Forsmark monitoring programme by evaluating present measurements and providing recommendations regarding strategy, methods and specific measurements and parameters. The report has the following specific objectives:

- Summarise and present information on earlier and ongoing monitoring at Forsmark, including descriptions of monitoring installations, measurements and data handling.
- Evaluate the monitoring programme with respect to all known requirements and needs, including known future needs.
- Identify needs for modifications of the monitoring programme and describe the new or changed monitoring activities to be included in an updated programme. These modifications could concern both specific measurements and more general features of the monitoring programme and its supporting activities.
- Describe needs for additional studies in cases when monitoring needs are identified but the associated activities cannot be precisely described based on presently available information and the analyses performed today.
- Communicate and thereby raise awareness of present state, available data and development needs associated with the monitoring programme, thereby providing a basis for decisions on resource allocation and initiation of necessary activities.

Concerning the scope of the work and the contents of the report, the following should also be noted:

- The report contains general discussions and overviews of all stages in repository projects, but the actual recommendations regarding the Forsmark programme are focused on the period before underground construction works for the planned waste disposal facilities commence. However, since the pre-construction period to large extent is about preparations for forthcoming stages, also these later stages are to some extent considered in the present study.
- The evaluation and recommendations presented herein do not include the monitoring performed as a part of the operation of repositories or associated facilities such as transport tunnels or shafts (existing or planned). This means that the monitoring in the existing SFR facility is described, but not evaluated in terms of possible improvements of installations or other aspects of the monitoring programme. Monitoring to be performed in planned disposal facilities is handled by each repository project (cf. below).

- The programme updates and recommendations do not consider potential monitoring of the engineered barriers after their installation. This will be presented in other documents. In this respect, it should also be noted that the issue whether the engineered barriers are manufactured and installed in conformity with requirements primarily is the task of the Quality Control programme, rather than a monitoring issue.
- The construction-related monitoring performed to guide and otherwise support repository design and forthcoming excavations of tunnels and shafts and subsequent construction works within and around them is not described here. Since there are obvious connections between different monitoring activities (e.g. they collect data from the same rock volume), clear distinctions between them may not be that simple to make. However, for the purposes of the present report it is sufficient to say that no recommendations are made regarding equipment or methods for monitoring in planned underground constructions.
- The programme is evaluated based on present site conditions, including existing surface and underground facilities and known effects of their operation. These include the effects of the present SFR (SFR 1), the nuclear power plant and the handling of electricity in the area.
- Current plans (as of autumn 2016) regarding the designs of the spent fuel repository and the SFR extension are taken into account in the present work. However, most illustrations of planned constructions in this report are taken from publications submitted with the licence applications, and do not reflect more recent developments.
- The monitoring activities run by the authorities and the nuclear power plant operator are not evaluated. However, some of the recommendations given herein could be viewed as, and possibly also organised as, additions to the ongoing environmental monitoring.

This work is part of the preparations for forthcoming repository construction works and related activities that SKB are conducting in parallel with ongoing licensing processes, with the aim of being as well prepared as possible when/if the necessary permits to commence construction activities are received. As indicated above, these preparations include other monitoring-related activities. In particular, a programme for detailed site investigations during the construction and operation phases of the spent fuel repository project has recently been published (SKB 2016b). This is a general programme that will be detailed in terms of operative investigation programmes for the different stages of repository construction and combined construction and operation.

The work presented herein is carried out in order to provide a basis for improving the existing programme with respect to end-user needs, ability to answer site-specific questions and general adaptation to forthcoming phases of repository construction in Forsmark. The report is written to be used as a platform for strategic decisions to be taken before coming phases of the nuclear waste programme, to present and motivate modifications of the monitoring programme, and to provide input to the formulation of measurement specifications and guidelines to be used by the staff performing the monitoring. The report is also intended to provide a description of the monitoring programme at Forsmark that can be used to inform the authorities and others outside SKB. Thus, the intended users include parties outside SKB, as well as internal decision makers and those planning and performing the actual monitoring at SKB.

As further explained in Chapters 2 and 3, this report handles monitoring during the baseline (pre-construction) phase, which involves preparations for forthcoming construction and operational phases. However, no specific limit is set for how long these programme updates are supposed to be valid, and whether and when they will be complemented. It seems reasonable that the monitoring programme will be modified successively as new data needs and external requirements emerge, but a complete revision could also be needed at some point if the conditions upon which the programme is based change significantly.

Development of site understanding is an overarching objective of monitoring and other types of collection of site data (Section 1.5). In SKB's basic strategy for analysing sites and developing repositories for nuclear waste disposal (e.g. SKB 2008), site-descriptive models are produced for and applied by three main end users: environmental impact assessment, EIA, with main focus on the construction and operational stages until repository closure, assessment of long-term radiological safety, which primarily considers radiological consequences after repository closure, and repository design, where the various surface and subsurface parts of the facility are designed and described.

A strategy for the continued development of site understanding and site descriptive models is currently being deployed within the modelling group of the Forsmark site management unit at SKB. This strategy involves partial and complete SDM updates, as required by future safety assessments to be performed within the repository projects and by the fact that monitoring data accumulate continuously and need to be checked against existing models. One early step in the modelling strategy that that relates to the present monitoring evaluation is to compile, present and evaluate all data representing baseline conditions, i.e. to produce a descriptions of site conditions prior to construction works.

1.7 Present monitoring programme and structure of report

This report describes end-user needs and recommendations for programme updates needed to produce the relevant monitoring data in the present baseline/pre-construction stage. The monitoring programme is here divided into the following four disciplines or sub-programmes:

- Geology: monitoring of rock deformations, earth electrical currents, and the global magnetic field.
- Meteorology and hydrology: meteorological measurements in local automatic weather stations, snow and ice observations, surface water discharges and levels, and groundwater levels in bedrock and regolith.
- Hydrochemistry: hydrochemical monitoring of different types of surface water (seawater and freshwater) and groundwater (in bedrock and regolith).
- Ecology and nature values: general monitoring of mammals and birds, monitoring of certain rare species and objects of high nature value.

The present report has been produced by a group of experts on the subject areas included in the monitoring programme. The expert group has been organised within the modelling function of the Forsmark site management unit at SKB, and includes also representatives for the monitoring organisation at Forsmark and for users of monitoring data. This group is also responsible for the management of the Forsmark SDM, including associated data evaluation and modelling activities. The different disciplines within the monitoring programme produce data of somewhat different characteristics. For instance, the hydrological monitoring produces large amounts of data (due to high temporal resolution and many observation points) on a small number of parameters, whereas the data from the hydrochemical monitoring are characterised by lower temporal and spatial resolutions and a very large number of parameters. The organisation of the discipline-specific parts of the report (cf. below) reflects these differences among the disciplines and the fact that different parts were written by different authors, who were given some freedom to organise their respective chapters in line with their preferences and the needs of each specific discipline.

The report is organised as follows. Chapter 1 gives a background to the SKB programme at Forsmark, and a brief introduction to the Forsmark site and the existing and planned nuclear waste repositories there. This chapter also contains a description of the aims of the report and introduces some central definitions. Chapter 2 contains additional, more detailed background material in the form of international context and recommendations, definitions, repository programme stages and methodology. In addition, Swedish regulations and the monitoring performed within two other nuclear waste programmes providing vital input to the present work (i.e. those in Finland and France) are summarised.

Chapter 3 focuses on SKB and Forsmark, providing overviews of monitoring needs, programmes and experience within SKB and especially at Forsmark. It describes conceptual models and associated monitoring during different stages in repository development. This chapter also describes data users, key issues to be addressed using monitoring data and the methodology employed in the present update of the Forsmark programme. Chapters 4 through 7 contain discipline-specific presentations and evaluations. Each of these chapters covers the monitoring within one of the four scientific disciplines outlined above and describes installations, measurements, data handling, resulting time-series data, and an evaluation of the present monitoring programme.

Chapter 8 provides recommendations for continued monitoring where complementary investigations are described by scientific discipline, and Chapter 9 is a summarising chapter presenting the main monitoring programme updates and prioritised further investigations. This means that those interested in one specific discipline could focus on (parts of) Chapters 1–3, one of the discipline-specific chapters and the associated section of Chapter 8, and the summary in Chapter 9.

2 Requirements and international experience

This chapter provides further background descriptions of guidelines, recommendations, rules and regulations, and also summarises some relevant monitoring terminology and practises. The emphasis is on recommendations and other inputs from international organisations. However, overviews of relevant Swedish regulations and of the monitoring performed within two other national programmes (the Finnish and the French) are also provided.

2.1 International guidelines and recommendations

2.1.1 Recent international projects and reports

In recent years, several international studies and projects partly or entirely focused on monitoring of nuclear waste disposal facilities have been reported. Below, a brief summary of these works is given, emphasising aspects of importance for the present study, i.e. primarily those related to general methodology, objectives and definitions.

The International Atomic Energy Agency (IAEA) recently published the report *"Monitoring and surveillance of radioactive waste disposal facilities"* (IAEA 2014). This is a report in the IAEA series of "specific safety guides" and the objective of the report is "to provide guidance for the monitoring and surveillance of radioactive waste disposal facilities throughout their entire lifetime" (IAEA 2014, p 4). The report considers both near-surface facilities and geological disposal facilities, and addresses the different periods of the lifetime of a disposal facility, from work on a candidate site to the period after closure of the facility. For the present report, it primarily provides definitions of terminology and time periods, and discussions of monitoring strategies and objectives.

Also in 2014, the OECD Nuclear Energy Agency (NEA) presented the report *"Monitoring of geological disposal facilities: Technical and societal aspects"* (NEA 2014). This report is based on two NEA studies, of which one provides an overview of what is referred to as "technical aspects of monitoring". In practise, this means that the report gives a useful summary of monitoring objectives and questions that need to be answered, a conveniently brief (one page) literature review covering similar international overviews (and also some national reports), a summary of national projects, and an outline of monitoring programme development and the challenges involved.

A third recently completed international effort is the project *"Monitoring developments for safe repository operation and staged closure"* (referred to as "Modern" or "MoDeRn"), which presented a synthesis report and its final report in 2014 (Modern 2014a and Modern 2014b, respectively). This concluded a four-year collaborative project funded under the 7th framework programme for nuclear research and training (Euratom). The main goal of the project was to establish a "roadmap" for developing and implementing various monitoring activities for deep geological repositories. As a core part of its activities, Modern provided a description of monitoring objectives and strategies, taking into account a variety of physical and societal contexts, available monitoring technology, and feedback from both expert and non-expert interactions. The main output from the work is the "Modern monitoring workflow", which is further described below (Section 2.1.5); the descriptions of the activities in this workflow and the underlying objectives are the main inputs to the present study.

Another category of projects providing useful input to the present work is the site-specific monitoring programme development undertaken by SKB and other waste management organisations. In particular, the report describing the development of the monitoring programme for the Olkiluoto site in Finland (Posiva 2012) has given valuable contributions to the present work (as indicated in this and the following chapters). In addition, monitoring performed within the French nuclear waste programme (Andra n d) has provided useful insights, especially regarding parameters and types of monitoring currently not included in the Forsmark programme (see Section 2.3). Finally, earlier SKB reports of both generic (e.g. SKB 2001a) and site-specific character (e.g. SKB 2007) have been used in the present work.

2.1.2 Definitions and terminology

As mentioned already in Section 1.5, several organisations and projects have proposed definitions of the term “monitoring” in the nuclear waste management context, and also other monitoring-related terminology has been discussed and defined in various publications. In most cases, the definitions of monitoring terminology that can be found in the nuclear waste literature are similar to or slightly modified versions of definitions proposed by IAEA. For example, the IAEA report “Monitoring of geological repositories for high level radioactive waste” (IAEA 2001, p 1) defines monitoring as *“…continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment”*. This definition addresses what to monitor, i.e. which types of parameters, as well as how and why the monitoring is performed.

Later, IAEA has presented a somewhat modified definition that conveys more or less the same message, but in two parts (IAEA 2014, p 7): *“In the context of this Safety Guide, the term “monitoring” refers to continuous or periodic observations and measurements to help evaluate the behaviour of the components of a waste disposal system and the impact of the waste disposal system on the public and the environment. Most specifically, it covers the measurement of radiological, environmental and engineering parameters”*. This definition separates “the public” from “the environment”, and indicates that both should be protected. It should be noted that IAEA has published the “IAEA Safety Glossary” (IAEA 2007), which is a report dedicated to the specification of terminology within nuclear safety and radiation protection.

The following definition was formulated as a part of a generic study (Bäckblom and Almén 2004) at a relatively early stage of the Swedish programme, i.e. during the initial site investigations for the spent fuel repository but before Forsmark was selected to host the repository: *“Continuous or repeated observations or measurements of parameters to increase the scientific understanding of the site and the repository, to show compliance with requirements or for adaptation of plans in light of the monitoring results”* (Bäckblom and Almén 2004, p 5). This definition specifies site understanding as a monitoring objective, which is consistent with the SKB view on site data and modelling that emphasises the role of site understanding based on site data in the process of developing models describing the present and future conditions at the site. It can also be noted that the SKB definition refers to “repeated” rather than “periodic” measurements, as an alternative or complement to the continuous ones, which perhaps can be viewed as indicating a greater flexibility concerning the regularity of measurements defined as monitoring.

Also other projects and organisations have formulated definitions of monitoring, which in most cases are similar to, but not identical with, that given by IAEA. For instance, the definitions in the monitoring programme for the Finnish Olkiluoto site (Posiva 2012) and in the synthesis report of the Modern project (Modern 2014a) emphasise that monitoring should support decision making during the process of implementing the disposal concept. However, as already explained in Section 1.5, a monitoring definition formulated specifically for the present report is not considered necessary.

Monitoring programme is a general term denoting a programme for monitoring activities, irrespective of the purpose and use of the programme and the data produced. This means that monitoring programmes could be developed to meet internal or external demands, for general or more specific data collection, research activities, or to provide data used to check compliance with conditions formulated in a permit to an operator of a potentially environmentally hazardous activity.

Surveillance is a related term frequently used in IAEA (2014), where it is usual to refer to “monitoring and surveillance” and “monitoring and surveillance programme”, rather than just “monitoring”. In the same IAEA report, the following definition is given: *“In the context of this Safety Guide, the term “surveillance” refers to the physical inspection of a waste disposal facility in order to verify the integrity of the safety barriers”* (IAEA 2014, p 8). This clarifies that surveillance is restricted to physical inspections of the facility, which means that it is outside the scope of the present report (Section 1.6). However, as noted in IAEA (2014) not all waste disposal programmes make a distinction between the concepts of monitoring and of surveillance. It should also be noted that surveillance of monitoring equipment is an important part of any monitoring programme, especially a programme for long-term monitoring such as that discussed in the present report.

For the purposes of the present report, additional concepts and terminology related to monitoring are defined as follows:

Characterisation of a site or unit, i.e. a specific investigation area or volume, implies a description of properties and conditions there with respect to the present state and ongoing processes. This is achieved by performing investigations, which may include both monitoring and investigations performed "once and for all". In this context, monitoring is performed to characterise parameters or processes expected to change significantly in the time frame that can be studied, and where the temporal variations are so large that they need to be described as a part of the characterisation.

Baseline is a central concept associated with monitoring programmes, which has been discussed and defined in most of the reports referred to above (e.g. Bäckblom and Almén 2004, IAEA 2014, NEA 2014). A broad definition of baseline cited in Bäckblom and Almén (2004) is "a set of critical observations or data used for comparison or a control", which essentially states that the baseline is the reference when making comparisons. Specifically, in the present nuclear waste context Bäckblom and Almén (2004, p 21) propose a definition of what they call "primary baseline", as "site-specific conditions prior to start of construction of the repository (before going underground)", which defines the baseline as the conditions prevailing before the disturbance caused by the initiation of repository construction.

The above-mentioned NEA report (NEA 2014) provides additional input for clarifying the concept of a baseline and how baseline conditions are established. In particular, the NEA report states that the general principle *"...is to create a set of reference data against which changes brought about by repository development and operation can be evaluated and distinguished from natural and other man-made temporal and spatial variations in the repository environment"* (NEA 2014, p 24). In the same report, it is also explained that baseline conditions *"...are understood to consist of "undisturbed data" from the site of interest, both surface and subsurface"*, which implies that *"...the relevant monitoring project should commence prior to the start of repository construction (before underground invasion), ideally as one element of surface and underground investigation"* (NEA 2014, p 24).

Concerning the reference to "undisturbed conditions" made above (and also in many other definitions of baseline conditions), it should be noted that this refers to undisturbed as in undisturbed by the construction (and operation) of the particular facility to be studied in the monitoring programme under development. At most prospective repository sites other disturbances exist, which could make it difficult (or irrelevant) to establish a baseline of "natural undisturbed conditions", and which also need to be monitored in order to distinguish the effects of the planned facility. The SFR 1 repository in Forsmark is an obvious example of an existing facility that affects the baseline conditions for the planned spent fuel repository and which needs to be monitored to distinguish the effects of the planned repository.

Another important aspect to note regarding baseline monitoring is that it must start sufficiently long in advance of any construction works to be able to establish baseline conditions with respect to all relevant parameters. How long in advance monitoring must commence is likely (to some extent) to be both parameter- and site-specific. Among other factors, the required time for a given parameter depends on the variations of that parameter and whether they are correlated to other parameters.

Impact, effect and consequence are central terms in environmental impact assessments. As explained in SKB 2011a), an environmental impact is a change in the environment, which can lead to an environmental effect, which, in turn, can have environmental consequences for certain interests. In SKB (2011a), these concepts are exemplified for a hypothetical groundwater diversion from an underground facility, where the impact is the lowering of the groundwater table caused by the groundwater diversion required to keep the facility dry during construction/operation. The effect of this lowered groundwater table is the drying-up of wetlands, which changes the living conditions for the animals and plants in those wetlands, and the consequence is quantified or classified based on an evaluation of the effect in terms of what it means for different interests. In this example, an affected wetland is evaluated based on whether it is a rare habitat, whether it harbours species particularly worthy of protection, and its importance for the natural environment and biodiversity in the area where it is located.

2.1.3 Stages and time frames

Different kinds of monitoring activities are necessary in each period of the lifetime of a radioactive waste disposal facility. The IAEA Safety Guide (IAEA 2014) discusses monitoring and surveillance based on a subdivision of this lifetime into pre-operational, operational, closure and post-closure periods. In addition, the report addresses monitoring for emergency response. Excluding the monitoring performed specifically for emergency situations, a slightly modified outline of monitoring periods over the lifetime of a waste disposal facility can be outlined as follows:

- Monitoring of undisturbed conditions during the pre-operational period (establishment of baseline conditions before construction and operation).
- Monitoring during the pre-operational construction period (construction work before operation).
- Monitoring during the operational period, which in many cases involves simultaneous construction and operation (i.e. construction and operation in different parts of the facility).
- Monitoring for closure (which may be performed partly in parallel with construction and operational activities).
- Post-closure monitoring.

Note that a subdivision into distinct construction, operation and closure periods may not be possible, especially not for a large repository where all these activities may be going on simultaneously in different parts of the facility. Therefore, the Forsmark monitoring programme is discussed in terms of three distinct periods – the pre-construction, construction and operation, and post-closure periods (see Section 3.1) – of which the focus of this report is on monitoring during the first period. In such cases, different types of monitoring activities are distinguished by their objectives, and not based on when in a sequence of activities they occur. Monitoring objectives are discussed in detail in the next section.

Based on the IAEA Safety Guide (IAEA 2014), brief descriptions of the monitoring activities in the pre-operational and operational stages are presented as follows.

Monitoring during the pre-operational period. This period includes both pre-construction and construction stages. Prior to construction, the monitoring programme should be focused on establishing a baseline for the site. During construction (but prior to operation), monitoring should be used to assess the ongoing impact of construction activities on the public and environment, to document the “as built” conditions, and to help ensure that the performance of the facility will meet regulatory requirements and comply with safety requirements.

Monitoring during the operational period. During this period, deposition of radioactive waste takes place and construction work will also proceed. The monitoring programme should contribute to operational safety, should measure potential impacts on the public and environment, and should inform assessments of the performance of the disposal system. Monitoring should continue to encompass evaluation of the features, events and processes important to the assessment of post-closure radiological safety, as part of a programme for confirming the performance of the facility. This will enhance understanding of the behaviour of the disposal system and provide input to refined operational and post-closure safety cases.

The baseline monitoring aims at describing the undisturbed system and to capture parameter variations caused by relatively short-term variability such as daily or seasonal cycles. This stage is also used to collect time series for the development and validation of models. Baseline monitoring is the basis and datum for all other monitoring and is regarded as a reference in time for the site (Section 2.1.2). The time frame for the baseline phase is parameter specific and has to be assessed carefully in order to achieve the right level of precision and process and parameter understanding.

During the construction phase, the data delivered from the monitoring programme are used to assess the impacts of the construction on the system, as specified in the environmental impact assessment (EIA) and the associated monitoring programme(s). During this phase, the site should have established a functional monitoring system that can respond quickly and deliver data, describe and assess impacts and/or effects (e.g. by comparison with the established baseline and thresholds) and, if necessary, send out warnings. When the repository is in operation, which for some repositories coincides with parallel ongoing construction, essentially the same types of monitoring as during the construction period are applied. However, operation-specific monitoring, for detection of, for instance, accidental radioactive releases during operation, is also needed.

2.1.4 Monitoring objectives

Similarly to definitions and terminology (Section 2.1.2), monitoring objectives have been presented in several studies by various international agencies and projects and by national waste management organisations. The formulation of monitoring objectives is an important step in the development of a monitoring programme, because a structured approach requires that proposed monitoring activities can be associated with clearly stated objectives. In particular, this coupling is central for the motivation and design of monitoring installations and measurement activities. A thorough analysis of monitoring objectives is also required to make sure that monitoring needs are not overlooked.

The IAEA Safety Guide (IAEA 2014) concludes that the monitoring and surveillance of disposal facilities for radioactive waste has five broad objectives.

- To demonstrate compliance with regulatory requirements and with the licence conditions.
- To verify that the disposal system is performing as expected, as set out in the safety case. This means that the components of the disposal system are carrying out their functions as identified in the safety assessment.
- To verify that the key assumptions made and models used to assess safety are consistent with actual conditions.
- To establish a database of information on the disposal facility, the site and its surroundings. This database is used to support future decisions when proceeding from siting to construction, operation, closure and the period after closure. The database is also used to support decisions relating to updating concepts and procedures for monitoring.
- To provide information for the public.

These objectives put some emphasis on the compliance with and verification of various regulations, expectations and assumptions, in addition to decision support and information to the public. Similar lists of objectives are presented in earlier IAEA reports (e.g. IAEA 2001) and in NEA (2014), whereas a more condensed outline of four "fundamental main objectives" is given in the final report of the Modern project (Modern 2014b, p 7):

- To support the basis for repository performance evaluations.
- To support operational safety.
- To support environmental protection.
- To support nuclear safeguards.

The waste management organisations have provided monitoring objectives that may be regarded as slightly more operational (and, obviously, conditioned on their programme-specific conditions, approaches and needs). The SKB report describing generic monitoring programme development (Bäckblom and Almén 2004), i.e. generic with respect to site but specific with respect to waste type (spent nuclear fuel), lists a set of "specific rationales for monitoring", namely to (Bäckblom and Almén 2004, p 21):

- Obtain knowledge of undisturbed conditions in nature and their seasonal variations (baseline) in order to identify and evaluate the impact of activities related to the deep repository during different phases.
- Obtain a better understanding of the function of the deep repository system to support the safety account and to test models and assumptions.
- Monitor the environmental impact of the deep repository.
- Provide evidence that the working environment is safe with regard to radiological and non-radiological effects.
- Show that requirements on radioactive waste verification (safeguards) are fulfilled.

The Finnish programme for spent nuclear fuel is of particular interest, since the first part of the repository has been built. Specifically, the access tunnel, shafts and tunnels for technical facilities at the intended deposition depth have been completed, which means that the current monitoring programme for the site already collects data in a disturbed system. In the report describing the development of this monitoring programme, the following six main objectives are defined (Posiva 2012, p 27).

1. Long term safety (site). Demonstrating that the conditions in the surroundings of the repository remain favourable for long-term safety despite repository construction and operation.
2. Feedback to site characterisation and modelling. Acquiring data that can be used to define and test various models of the surroundings of the repository, which increases the understanding of the site and its evolution.
3. Monitoring the environmental impact.
4. Providing feedback for construction and design on the impact of construction on the geosphere and surface environment.
5. EBS (engineered barrier system) performance. Monitoring the performance of the engineered barrier system to confirm the basis for expected/predicted behaviour.
6. Compulsory radiological monitoring. Conducting the mandatory monitoring of radiation and of releases of radioactive substances in the environment of the repository.

Except for objective 5, which reflects the fact that Posiva already has a repository of a specific design, the monitoring objectives listed in the report appear useful also in the context of the present report (which is focused on the pre-construction period, not addressing monitoring within planned repositories). The Finnish programme considers monitoring needs associated with site characterisation/understanding, long-term safety, environmental impact, repository construction and design, and radiological monitoring. In addition, for programmes/sites that have not reached the construction and/or operational phases, the establishment of baseline conditions is a major monitoring objective.

2.1.5 Strategies for monitoring programme development

Recommendations and methodology development for the formulation of monitoring programmes are also presented by several organisations and projects. One starting point for a programme could be to answer a set of questions, such as those proposed in the NEA monitoring report (NEA 2014, p 10):

- Why monitor (purpose and process identification)?
- What to monitor (parameters and/or human activities)?
- How to monitor (measurement and observational procedures and corresponding equipment)?
- When to monitor (timing, frequency and duration)?
- How to use/interpret the results (modelling, synthesis of the inputs, records)?

In the same report, it is also remarked that the monitoring of disposal facilities typically focuses on the collection of technical and environmental information, whereas non-technical stakeholders or decision-makers may also require information on societal and economic impacts of the disposal project during its progress.

As explained in Section 2.1.1, one of the recent international projects addressing monitoring, the Modern project (Modern 2014a, b), aimed at presenting a procedure for developing monitoring programmes. Specifically, as explained in more detail in the project synthesis report (Modern 2014a), the work on objectives and strategies included elaboration of a generic structured approach to the development and implementation of a monitoring programme, the Modern monitoring workflow (Figure 2-1). This workflow describes a step-by-step process for identifying what is required from monitoring and developing those requirements into a defined programme through analysis of the disposal system, in particular the safety functions of the engineered and geological barriers.

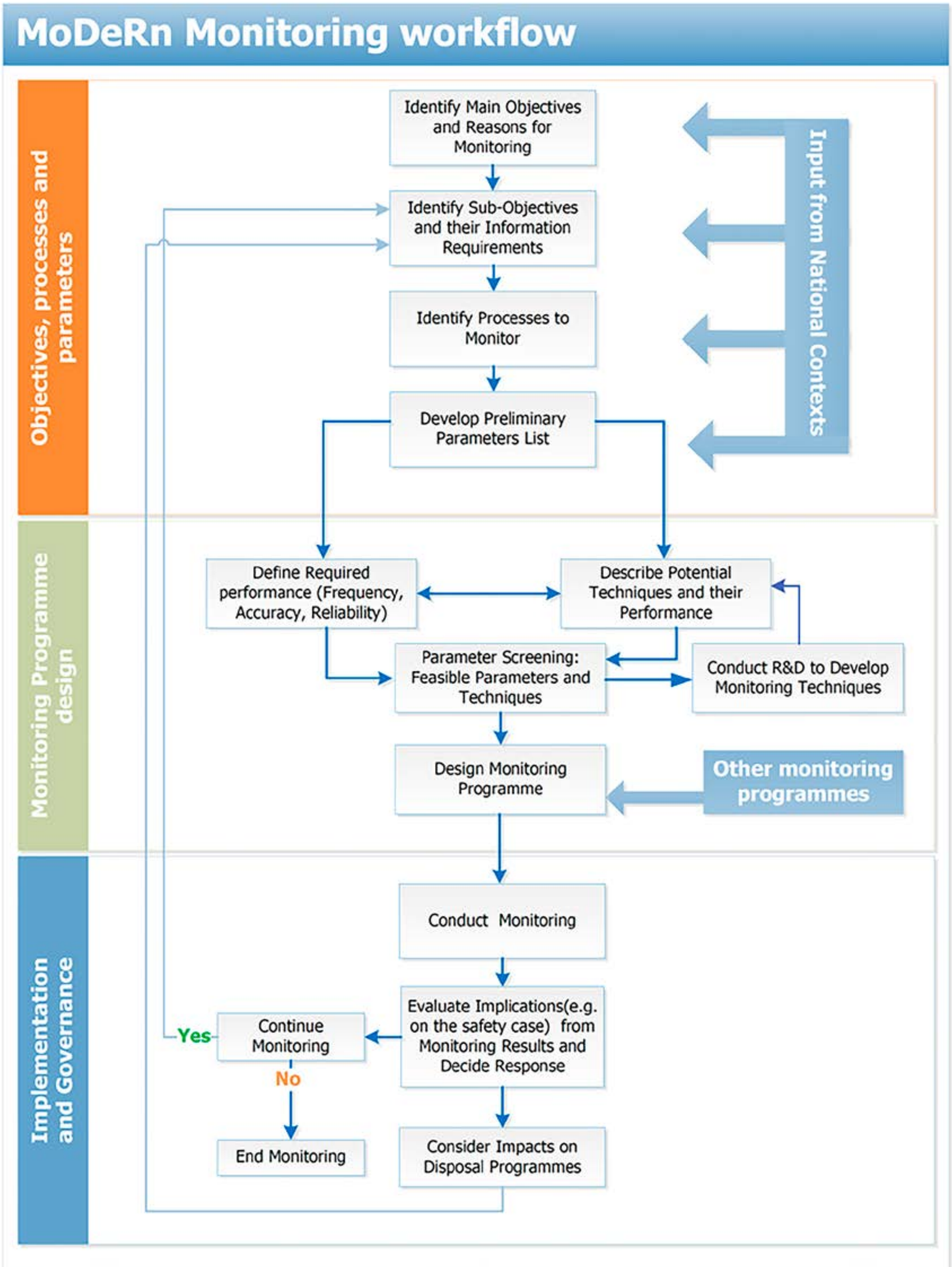

Figure 2-1. *The Modern workflow (Modern 2014a).*

The workflow identifies three key stages in the development and management of a monitoring programme, which in Modern (2014a) are described as follows (see also Figure 2-1).

1. Objectives and parameters: Identification of the objectives and sub-objectives of the monitoring programme, and relating these to processes and parameters to identify a preliminary parameter list. Processes and parameters may be identified through an analysis of the safety case, for example through consideration of safety functions and/or features, events and processes (FEPs) that may have an impact on the safety functions of specific disposal components, or may address key programme requirements, for example demonstrating an ability to retrieve waste.

2. Monitoring programme and design: An analysis of performance requirements, available monitoring technology and overlaps/redundancy to screen the preliminary parameter list and to facilitate design of the programme. The design will define how, where and when data will be collected, and will specify performance levels, trigger values and potential risk mitigation measures that could be implemented in response to certain monitoring results.

3. Implementation and governance: Conducting a monitoring programme and using the results to inform decision making. Whilst the programme is undertaken, there is a need to evaluate the results both on a continuous and a periodic basis. Continuous evaluation will focus on the assessment of individual monitoring results, whereas periodic evaluation will consider the overall influence of monitoring results on the safety case and on programme decisions.

As noted in the preceding section, the Finnish programme for handling of spent nuclear fuel is of particular interest; it is the most advanced of its kind, with the first stages of repository construction completed. Furthermore, a monitoring programme has been developed by following the generic approach proposed by the Modern project (i.e. a preliminary version of the Modern workflow, see Posiva 2012). The Posiva report gives the following summary of key stages in the procedure.

- Identification of monitoring objectives, and processes and parameters to monitor. This stage requires consideration of programme boundary conditions to identify a preliminary list of monitoring parameters (these are referred to as monitoring targets in the Posiva monitoring programme).
- Screening of the preliminary parameter list against requirements and feasibility to define final monitoring parameters linked to monitoring techniques.
- Design of the monitoring programme. This includes, for example, specification of the number of sensors that will be used, the locations where the sensors will be placed, and consideration of trigger values for responding to unexpected monitoring results.
- Conducting monitoring and responding to results. This stage includes evaluation of monitoring results and provision of information in support of the wider decision-making process for the repository programme.

Essentially, the workflow outlined above provides a structured approach connecting monitoring objectives to processes and parameters to monitor, and then describes how this is expressed in terms of a programme and then tested and applied at the site. The Finnish monitoring report (Posiva 2012) shows how this can be done in practise at a site with a repository under construction, which has given valuable contributions to the present work.

2.1.6 Additional considerations

This section summarises some additional considerations and recommendation related to good practise in connection with the development of monitoring programmes for nuclear waste facilities, as expressed in recent reports from international organisations (Section 2.1.1). In particular, the main input to this section is the IAEA Safety Guide (IAEA 2014), which provides recommendations on a wide range of issues related to monitoring of nuclear waste facilities.

In addition to technical and scientific aspects, the need to address public concerns and expectations should also be considered when defining the monitoring programme. Monitoring programmes also must be designed and implemented so as not to reduce the overall level of safety of the facility after closure. IAEA (2014) further states that the monitoring programme should be designed "in accordance with a graded approach", which means that "the extent of the monitoring programme should be commensurate with the level of risk associated with the disposal facility". This means that the monitoring effort should be related to the overall risk level, which sounds reasonable but perhaps could be difficult to implement in reality, given that the same risk criterion is used for different types of nuclear waste (i.e. low/intermediate- and high-level waste under Swedish regulations). There is also some minimum extent of the monitoring programme required to achieve an adequate understanding of the disposal system environment.

The Safety Guide also discusses the duration and frequency of monitoring measurements and states that they should be "in accordance with the timescale of natural variations in the processes and in the parameters being measured, as determined by regulatory requirements, and with changes in processes and parameters associated with construction and operation of the disposal facility". Thus, the design of the programme should take both nature and repository construction and operation into account when determining when and how often to measure.

The safety case is usually supported by data from a number of sources, including site-specific measurements, regional data and generic information. Generally, site-specific data are preferred. When site data are not available, relevant monitoring data may be obtained from other sources. In some cases, a combination of site data and data from elsewhere is used. A particular case that may be difficult to handle is when only very little (and hence uncertain) information is available from the site, whereas data from other sources are abundant. Although not dealing specifically with monitoring data, Tröjbom et al. (2013) give some insights and solutions that could useful in such situations.

Quoting IAEA (2011, p 44), the Safety Guide also states: *"A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. Information shall be obtained to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility. Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure."* This could be the starting point for a discussion on whether and how to monitor after closure. However, this issue is not considered further in the present report.

To interpret and understand the variations over time of different parameters is part of the effort to establish the "baseline data" of the site, i.e. the data representing "undisturbed" conditions prevailing at the site prior to construction of the studied repository. The monitoring activities already initiated are therefore an essential part of the site investigations. With early monitoring data as a reference, changes in conjunction with construction of the repository may be revealed, thereby enabling differentiation between natural changes and variations in time and space caused by human activities.

The identification and quantitative analyses of the effects of repository construction and operation are complicated by the fact that other things than the repository could affect future conditions in the surrounding environment. These include natural variations and trends in, for instance, meteorological conditions, and effects of human actions other than those related to the repository (e.g. other underground constructions and construction works, groundwater extraction, drilling and sampling activities). Common to all these disturbances is that they somehow must be "filtered out" from the monitoring data, in order to enable assessment of the repository-related effects. Proper baseline data are a necessary basis for this type of analysis, but reference data from monitoring at other locations than those affected by the repository are also needed. Such reference data could be obtained from within the area of the site investigations for the repository, or from other off-site areas of similar characteristics in terms of the processes of interest.

In addition to the establishment of a baseline, the aim of the monitoring is, by way of analysis of the pattern of variability with time, to increase the understanding of the processes governing the variations, which will benefit the site description and modelling. This will also contribute to an improved long-term safety assessment of the site. The monitoring should also provide a platform for the environmental impact assessment and statement for the site, and for the formulation of associated monitoring programmes.

2.2 The Swedish regulatory context

This section gives an overview of Swedish laws and regulation with implications for monitoring. The monitoring itself is not subject to specific laws or regulations, but constitutes an important tool for providing part of the input needed to motivate, formulate and check various aspects of legal permits and the associated requirements for underlying data and understanding. More information regarding the legislation associated with nuclear waste facilities can be obtained in the environmental impact statement for the spent fuel repository (SKB 2011a) and in recent SKB permit applications (SKB 2011b, 2014b). Besides Swedish legislation, Sweden has pledged to comply with certain international treaties and conventions.

There are two types of national legislation that need to be considered in connection with permits for nuclear waste deposition, namely legislation dealing specifically with facilities where radioactive materials are handled and general environmental legislation applicable to any potentially hazardous activity. In addition, other general laws and regulations, such as those for physical planning construction permits, are part of the legal process (not discussed further here). This means that by Swedish law SKB must apply for permits both according to the nuclear activities law and the environmental law, and that the legal processes associated with these two types of legislation are run in parallel once the applications have been submitted (for a description of the procedure, see Bjällås and Persson 2011).

As explained in SKB (2011a), the requirements on those who operate or apply for a licence to operate nuclear activities are laid down in laws, regulations and international conventions, which may be followed up and clarified via decisions and conditions in the licensing decisions, supervision and decrees of the authorities and the environmental courts. A brief overview of the most important laws and what they state is as follows (SKB 2011a).

- According to the requirements of the environmental code (SFS 1998:808), future generations shall be assured a healthy and sound environment. Reuse, recycling and other management of materials, energy and other resources shall be promoted.
- According to the requirements of the nuclear activities act (SFS 1984:3), the holder of a licence for nuclear activities shall make sure that any resulting spent nuclear fuel is disposed of in a safe manner. Post-closure safety shall be based on a system of passive barriers, and the final repository shall require neither monitoring nor maintenance.
- According to the requirements of the radiation protection act (SFS 1988:220), the effects of ionising radiation on man and the environment shall be calculated and shown to be acceptable both in connection with management of the spent nuclear fuel and in the future. Biological diversity and utilisation of biological resources shall be protected against the harmful effects of radiation.

Both environmental and radiation protection regulations are associated with monitoring. By environmental law, a monitoring programme is usually the key component in the activities carried out by the operator in order to show compliance with the conditions prescribed in the environmental legal process. However, the environmental laws also require each operator of a potentially environmentally harmful activity to perform self-monitoring, which implies that the programme directly motivated by showing compliance with conditions stipulated in a permit may only be a small part of the monitoring performed at the site.

In addition to the monitoring required by environmental law, measurements of radioactive releases are required during the operational phase. Specifically, this requirement concerns facilities that could release activity during normal operation, which according SKB's view is not applicable to the spent fuel repository (SKB 2011a). Whether and how this type of monitoring must be carried out for this repository will be determined in the ongoing legal process.

Legislation and related monitoring activities can be summarised as follows.

- Self-monitoring is to be performed in accordance with the environmental code (SFS 1998:808) and the ordinance on the activity operator's self-monitoring (SFS 1998:901). The environmental legislation requires the operator of any activity, i.e. also those who operate activities that do not require environmental permits, to be able to certify that the activity complies with environmental regulations, and to perform self-monitoring as needed. Thus, self-monitoring should always be performed, if the activity could affect the environment, and not just when explicitly required by the authorities. The activity operator is fully responsible for the activity and its compliance with a set of general rules given in the environmental code.

- Monitoring is to be performed in order to show compliance with conditions in permits. Conditions included in permits given by the environmental courts (which may have been proposed by others) may require monitoring of specific parameters, and could associate parameters with guideline or threshold values such as environmental quality standards. The conditions specify how reporting should be done, and could also stipulate specific measures to be undertaken if guideline values are exceeded.
- Monitoring is required of areas and/or species for which habitat and/or species protection are applicable. In particular, the environmental code (SFS 1998:808) and the associated ordinance on area protection (SFS 1998:1252) and the species protection ordinance (SFS 1997:845) may require the operator of an environmentally hazardous activity to perform monitoring of, for instance, specific protected species.
- The legislation on radiation protection requires measurements of radiation releases from nuclear facilities in operation and also radiation measurements in the surrounding environment. Such measurements are presently performed at Swedish nuclear facilities, in accordance with a programme formulated by SSM (the Swedish Radiation Safety Authority), and could be required also in connection with planned waste repositories at Forsmark.

Regarding self-monitoring (first bullet above), it should be noted that the underlying legislation is formulated such that the activity operator is required to have the necessary knowledge about the activity and how it affects human beings and the environment. This implies a clear connection between legal requirements, site understanding and monitoring for many environmental problems.

Finally, it should be mentioned that the European Union Directive regarding environmental impact assessments/statements has been revised recently (EU 2014), and that this revision, among other things, strengthens requirements concerning monitoring. Since Swedish regulations (in principle) follow EU regulations, a stronger emphasis on monitoring in connection with environmental impact assessment practises in Sweden can be expected when the new regulations and associated recommendations are transposed and implemented in Swedish legislation during 2017.

2.3 Monitoring within other nuclear waste programmes

This section gives a brief account of monitoring within two other nuclear waste programmes that investigate possible repository sites and run extensive monitoring programmes at these sites, the Finnish and the French programmes, considered to be of particular relevance for the monitoring at Forsmark. This is not to say that these are the only programmes and sites that could provide useful information. However, no attempt has been made to produce an exhaustive review, not even within the relatively small world of nuclear waste management organisations. It should also be noted that the focus here is not on describing the other programmes in detail, but rather on the identification of ingredients that deserve to be studied more closely and possibly be considered also at Forsmark.

2.3.1 Finland (Posiva)

The Finnish nuclear waste programme is run by Posiva Oy and has many similarities with the Swedish one, both in terms of technical solutions (e.g. the same KBS-3 spent fuel repository concept) and the selected site. The Finnish repository for spent nuclear fuel will be located at Olkiluoto near Pori in Southwestern Finland; this also hosts a nuclear power plant and a repository for low- and intermediate-level waste. Furthermore, Olkiluoto is a coastal site situated just some 220 km northeast of Forsmark across the Bothnian Sea (a northern part of the Baltic Sea), which implies similarities with respect to bedrock geology and landscape development. A comparison between the site descriptive models for the two sites is presented in Geier et al. (2012).

An important difference with implications for the monitoring programme is the fact that the first part of what is intended to be the Finnish spent fuel repository already has been built at Olkiluoto. Specifically, the access tunnel has been excavated down to its final depth of c. 450 m where technical facilities for research and development activities are constructed; this plant is commonly referred to as the Onkalo. This means that the monitoring currently is in the construction stage (rather than pre-construction), when groundwater abstraction from the tunnels is affecting bedrock hydrogeology and possibly also the conditions on the surface (cf. Chapter 3). The existence of tunnels and rock caverns in (parts of) the rock volume planned to host the repository also means that monitoring can (and must) be performed in and from these underground constructions.

Posiva is running an extensive multi-disciplinary monitoring programme at Olkiluoto as part of the repository project. This programme was recently evaluated and updated (Posiva 2012). The updated programme is divided into six sub-programmes or disciplines, as summarised below.

- Rock mechanics. This part of the programme consists of seismic, displacement, surface levelling and temperature measurements outside the underground construction, and measurements and visual observations in the tunnels (see Johansson 2014, 2015 for annual reports for 2013 and 2014, respectively).
- Hydrology. The hydrological monitoring is based on groundwater pressure and flow measurements in numerous deep and shallow boreholes drilled in the Olkiluoto bedrock, groundwater monitoring wells in the overburden, and measurement weirs in the tunnel system (see Vaittinen et al. 2014, 2015). The monitoring also includes meteorological and surface water measurements; these are reported within the Surface environment programme (cf. below).
- Hydrogeochemistry. This sub-programme consists of monitoring of shallow and deep groundwater through sampling in shallow and deep regolith and bedrock boreholes from the surface, and sampling of inflowing groundwater and in boreholes from the tunnels (e.g. Penttinen et al. 2014). It also includes sampling and analyses of "process water" and gas.
- Surface environment. The reporting of the monitoring of the surface environment (e.g. Haapanen 2014, Pere et al. 2015) is divided into a number of sub-disciplines representing a variety of issues and types of monitoring: evolution of the geosphere (e.g. changes in elevation and regolith composition), input data to biosphere modelling (e.g. surface water chemistry and ecological parameters), interactions between surface and bedrock (which includes landscape properties and meteorology), "conventional" environmental impact (e.g. noise and air quality), and radioactive releases.
- Foreign materials. This part of the monitoring programme is about control and registration (i.e. bookkeeping) of foreign materials introduced into the underground facilities, either deliberately or inadvertently (see Sacklén 2015).
- The engineered barrier system. The updated programme also includes a new discipline of monitoring, concentrating on research and development of monitoring techniques, methods and strategies needed to start monitoring of engineered barriers (bentonite buffer around waste canisters and backfill of tunnels) during the operational phase.

Apart from activities performed in or directly connected to the underground facilities, the scope of the Olkiluoto programme is to a large extent similar to that of the Forsmark monitoring (cf. overview in Chapter 3). However, rather than further exploring similarities and differences between the two programmes, some features of the Finnish programme that SKB should consider (now and/or in the future) are summarised in following.

The Posiva monitoring reports (e.g. those referred to above) are annual reports that provide relatively detailed descriptions of monitoring and monitoring results. They also contain data evaluations, at least comparisons with earlier measurements, and appear to be organised in terms of issues/objectives (to some extent). It can also be noted that they are published as open reports. SKB should study the Posiva monitoring reports carefully when developing the reporting policy and report structures coupled to the updated Forsmark monitoring programme. With regard to monitoring of the engineered barrier system, SKB and Posiva are now jointly developing this work. As a part of this work, SKB and Posiva are strongly involved in the new EC project Modern 2020, which is a sequel to the Modern project described earlier. Conclusions and actions from these undertakings will not be further discussed in this report.

The monitoring at Olkiluoto is already today dealing with an existing underground facility, which means that Posiva are at the stage when they have to have, or very soon need to develop, methods for evaluating which disturbances are caused by the facility and which are due to other factors. This is central to the forthcoming SKB monitoring too, and SKB should follow the Posiva work on this issue (or perhaps co-operate with Posiva).

Since Posiva has carried out part of the construction work for the planned repository, there should be monitoring experiences that could be useful for SKB. In particular, the Posiva monitoring and data handling during the construction of the underground facility should be studied by SKB as a part of the continued development of the Forsmark programme. In this context, it would be interesting to find out whether and how environmental monitoring data were communicated to the construction crew, how these data were used by them, and which measures were taken to protect the surrounding environment from potential effects of the construction.

Also the general organisation and implementation of the present monitoring and data handling at Olkiluoto should be studied in more detail than has been done for the present study. Of particular interest would be to investigate if and how data flows and reporting routines have been changed during and after the construction of the existing facility.

The monitoring at Olkiluoto contains some categories and parameters not covered by the present Forsmark programme, where SKB possibly could get valuable input when setting up corresponding measurements. For example, air quality is not monitored at Forsmark today (except for radioactive releases).

2.3.2 France (Andra)

French nuclear waste is managed by the public agency Andra. Surface facilities for low- and intermediate-level waste types have been in operation since the 1960s, and potential sites for near-surface and deep geological repositories for higher-level wastes are currently being investigated. The site primarily considered for the deep geological repository for spent nuclear fuel and long-lived intermediate-level waste is located at Bure in Northeastern France. Similarly to Olkiluoto, a research facility has been built at the intended disposal depth, where scientific research and technical development are carried out. If results are favourable and the necessary licences are obtained, the nuclear waste facility will be built in the same geological formation as the present research facility.

An extensive programme for environmental monitoring has been implemented in the surroundings of the research facility at Bure. In 2007, Andra set up the Perennial Observatory of the Environment (OPE, see Andra n d). One aim of the OPE is to establish the initial state of the current environment around the future repository (scheduled for a ten-year period), and then to track its evolution during the repository construction and operational periods. The region studied by the OPE monitoring covers a surface area of 900 km^2 around the potential repository site. Within this area, more detailed studies are being conducted in a "reference sector" of around 240 km^2.

The monitoring network in place consists of several hundred observation points supplemented by collection of data from satellite and aerial photographs, and continuous monitoring at forest, agricultural, atmospheric and surface water stations. The monitoring includes fauna and flora, crops and soil quality. Among the monitoring installations are a 45-metre flux tower used to quantify exchanges of CO_2, water and energy between the atmosphere and surface ecosystems, and an atmospheric station with a 120-metre mast equipped with weather sensors and air samplers connected to analysers on the ground that can be used to continuously measure air quality and greenhouse gases.

To ensure the traceability and preservation of the samples collected by the OPE, Andra is building a sample archive called the Andra environmental specimen bank (also referred to as the "écothèque"), see Leclerc et al. (2015) for a description. This is a long-term store of environmental samples intended to be operated for at least 100 years to ensure proper monitoring and access to reference samples throughout the repository operation period. In this facility, all kinds of samples taken within the monitoring programme will be preserved and stored. The related scientific tasks are carried out within the framework of national and international partnerships, using a certified observation system.

The significant effort made by Andra to secure and preserve samples for possible future use as reference samples when evaluating effects and consequences of waste deposition is an important part of a strategy to prepare for the operational period. SKB needs to consider similar measures in relation to its monitoring programme for Forsmark, which need to be initiated soon if method development and sufficient baseline sampling are to be finished before construction of planned repositories commences.

Another aspect of the OPE programme that SKB should consider and try to reproduce is the apparently extensive co-operation with scientific institutions and state agencies. OPE monitoring programmes for different disciplines have been developed and are operated together with such organisations, and several monitoring installations are included in national and international monitoring networks. Andra also has as an objective of the OPE to make the monitoring installations available to the scientific community. These kinds of co-operation and partnership could be beneficial also for SKB, as a means of obtaining access to up-to-date knowledge and reference data, and would also result in goodwill and scientific confidence.

3 Monitoring needs, experience and methodology for the Forsmark programme update

After the presentations of various inputs from elsewhere in the preceding chapter, this chapter focuses on the monitoring performed by SKB and especially at Forsmark. Using conceptual models of how an underground repository affects the surrounding environment as a starting point, the intention is to describe why monitoring is needed in different stages of a repository project and what needs to be monitored (Section 3.1). Monitoring for environmental impact assessment, including site-specific implications of nature values observed in the Forsmark area, is discussed in Section 3.2. Section 3.3 describes monitoring programmes managed by SKB, with emphasis on the development of monitoring at Forsmark. Finally, Sections 3.4 and 3.5 give a more technical background to the discipline-specific descriptions and evaluations in Chapters 4 through 7, in terms of key issues, data uses and users, organisation and methodology.

3.1 Conceptual models and monitoring needs in different stages

This section seeks to explain why monitoring is needed at the Forsmark site and what parameters and states need to be monitored. To this end, a brief description of existing and planned repositories at Forsmark is first given, followed by conceptual models for repository impact during different phases in repository development. Subsequently, a summary of needs for supplementary information or continuous monitoring that were noted in conjunction with earlier site descriptive modelling is presented. Finally, some of the planned monitoring activities not covered by the current monitoring programme are described, i.e. primarily monitoring of "conventional" construction-related disturbances.

Taking the effects of a geological repository on its surroundings as the starting point for the description of conceptual models of repository impact, the following three main periods are distinguished and discussed in the following (cf. Section 2.1.3).

1. *The pre-construction period* when the site is still undisturbed by the repository planned to be built, and at the end of which a proper baseline should be established.
2. *The construction and operation period* during which an underground construction exists and is kept drained, whereby it affects its surroundings by acting as a sink for groundwater flow and solute transport. Also direct effects of construction and operational activities (e.g. noise and air pollution) may occur during this period.
3. *The post-closure period*, when the repository has been closed and abandoned, and gradually becomes saturated by water (reinstated groundwater level) such that the various radioactive and other materials emplaced there may act as sources of (primarily) groundwater-borne transport up to surface ecosystems.

Conceptual models and monitoring needs for these three periods are discussed in Sections 3.1.1 through 3.1.3, whereas observations and remaining uncertainties in site descriptions are described in Section 3.1.4. It should also be noted that the periods distinguished above are separated by transients, such as the re-saturation phase following repository closure. These periods may be long (e.g. Selroos and Follin 2010), but are not described specifically here; the stages outlined above represent "extremes" that are sufficient for the purposes of the present discussion. Furthermore, conditions may obviously vary significantly also during each period, especially during the post-closure period, which in safety assessments may last up to one million years. Variations may be large also during the preceding construction and operation period, due to differences in size and location of open repository parts between different stages in repository development.

3.1.1 The pre-construction period

During the pre-construction period, the site is undisturbed by the repository to be analysed (since it does not exist), but not necessarily by other impacts of human activities. This implies that one important objective of the monitoring during this period is to collect data that provide an adequate basis for distinguishing ongoing natural processes and human activities from the impact of repository construction and operation once the latter activities commenced. Collection and analysis of time series of relevant parameters are central to achieving this objective. Trends and short-term variations need to be identified and evaluated for natural processes and effects of human activities operating on a variety of scales.

Before repository construction, groundwater flow and solute transport towards, within and from the intended repository volume take place as determined by prevailing, (generally) slowly changing boundary conditions describing the conditions on the ground surface, in the sea and in adjacent rock volumes. This means that also under undisturbed conditions there are ongoing processes changing hydrological and hydrogeochemical conditions in the repository volume and its surroundings.

As discussed above, this is the period for initial collection of information about the site, including monitoring data. This information is then used to develop site understanding and various models, and to establish a baseline that can serve as a reference in assessments of future disturbances. In Forsmark, site investigations for the spent fuel repository commenced in 2002 and were completed in 2007. These investigations were both preceded and followed by site investigations for SFR, i.e. for the existing SFR 1 in the 1980s and for the planned extension of SFR (SFR 3) in 2008–2010. Based on these investigations, site descriptive models have been produced (SKB 2008, 2013b), which constitute the latest multi-disciplinary integrated descriptions of the pre-construction conditions at Forsmark.

An example of a conceptual model developed for the Forsmark site is shown in Figure 3-1, which shows a hydrogeological conceptual model developed as a part of the site descriptive modelling performed for the spent fuel repository. This means that it shows undisturbed flow conditions and that it is primarily valid for the part of Forsmark where that particular repository is planned to be built. The essentially horizontal structures labelled "Horizontal fractures/Sheet joints" in the figure act, as a consequence of ambient boundary conditions, as drains for groundwater flow from both above and below them. They are typical of the "target area" where the spent fuel is planned to be located, but are not found everywhere in the Forsmark area. The conceptual cross-section presents several basic features of the studied system that are of importance for groundwater flow and associated transport of dissolved components, and hence also for potential disturbances of these processes.

In particular, Figure 3-1 illustrates the relatively small-scale flow systems associated with groundwater flow in the regolith, where flow goes from local recharge areas to low-lying discharge areas that coincide with surface waters or wetlands. However, as indicated below the lake in the left part of the cross-section, there are exceptions from this pattern; under certain conditions lakes may act as recharge areas for groundwater (Johansson 2008). For site understanding and monitoring needs, the main implications of this and similar observations made during the site investigations are that

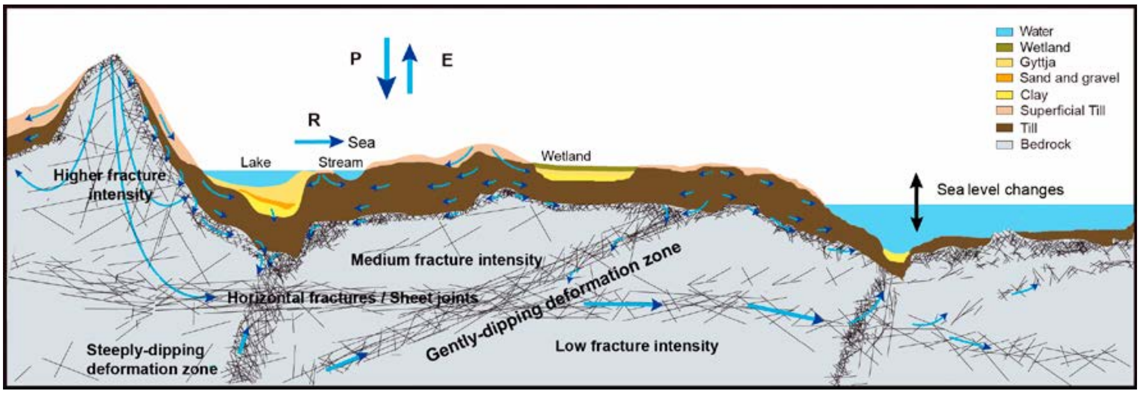

__Figure 3-1.__ Conceptual hydrogeological model for the pre-construction period showing general flow directions between recharge and discharge areas in regolith (brown to yellow layers) and larger-scale flow patterns in bedrock (grey part) determined by fractures and deformation zones. P, E and R denote precipitation, evapotranspiration and runoff, respectively. Figure from Follin (2008).

the hydrological conditions are complex and that temporally and spatially coordinated monitoring of several hydrological sub-systems is required to understand present interactions and how they may develop in the future.

In this context, it should be noted that knowledge about near-surface and surface hydrological processes is not only (or perhaps not even primarily) of interest as such, but also/mainly due to the important role of hydrology for chemical and biological processes in surface ecosystems. Water acts as a carrier of different forms of matter and many abiotic and biotic processes take place in or are otherwise dependent on water. This calls for a coordination of monitoring activities within different disciplines, such that all the different types of data needed for modelling or evaluation of consequences are available from the same locations or objects.

Figure 3-1 also illustrates the larger-scale groundwater flow systems in bedrock, and especially the importance of different types of structures (fractures and deformation zones) for groundwater flow and solute transport. Most of the flow in the crystalline rock at Forsmark occurs along large deformation zones, which also constitute the main hydraulic connections between deep bedrock and the surface. This means that hydrogeological disturbances associated with underground constructions mainly propagate along such structures. Thus, baseline monitoring should be performed where disturbances from a planned repository volume are expected to propagate towards surface objects of interest and can be measured in terms of changes in pressure and/or flux.

During the pre-construction phase, relevant hydraulic connections between planned repository volumes and objects on the surface are by necessity identified based on modelling rather than observed hydraulic interferences. These models must, in turn, be based on preliminary designs and hydrogeological descriptions obtained from boreholes and other investigations from the surface. This introduces uncertainties as to whether the monitoring programme implemented during the pre-construction stage covers the structures and sections that are relevant for monitoring the impact of later construction and operational activities. Clearly, the main approach to reducing such uncertainties is to have a well-developed site understanding and to make sure that the monitoring includes the main structures and connections in the system, since these most likely will be affected by future disturbances.

3.1.2 The construction and operational period

During the construction and operational period, underground constructions are developed and are kept virtually free of water and air-filled through abstraction of incoming groundwater. This implies that atmospheric conditions prevail in all open tunnels, shafts and other parts of the repository, such that the underground parts of the repository constitute a sink in the groundwater flow system. Thereby, groundwater and dissolved chemical components in the water are transported towards the repository, driven by the hydraulic gradient from bedrock to repository that is induced by the atmospheric conditions in the open tunnels and caverns. This may lead to changes in hydrological and hydrogeochemical conditions in both bedrock and regolith, and to effects on various objects (e.g. lakes and wetlands) on the surface.

From the perspective of groundwater flow and solute transport, this means that the relatively short-term effects and consequences occurring during the construction and operational period arise under conditions that may be very different from those prevailing during the pre-construction period. In particular, flow and transport directions may be reversed such that areas on the surface that constitute discharge areas under undisturbed conditions may become recharge areas when groundwater is abstracted from the repository volume. Groundwater could also be drawn towards the repository from surrounding rock volumes. This could lead to changes in the chemical compositions of groundwater and solid phases (e.g. through precipitation/dissolution processes) in rock volumes affected by the groundwater diversion from the repository. Depending on whether these waters reach the repository during the construction and operational periods, these changes may or may not be observed by monitoring the hydrochemistry of the incoming groundwater.

Groundwater containing chemical components of importance for the assessment of long-term safety could be transported towards the repository, but not necessarily reach the repository itself. For the safety assessment, it is still be important to know whether and how the conditions in the surroundings of the repository differ from those described by the site descriptive model depicting the pre-construction situation. This implies that hydrochemical monitoring of both the groundwater entering the repository and that in the surrounding bedrock is needed during the construction and operational period.

Figure 3-2 illustrates inflow of groundwater to a tunnel and resulting hydrological effects and consequences in surface ecosystems. Effects related to flow and transport in the bedrock may be a problem in itself (cf. above), but the main focus of the environmental impact assessment is the consequences near and on the ground surface. These are primarily caused by the lowering of the groundwater level in the regolith, which may affect other parts of the hydrological system (e.g. surface water levels in lakes and wetlands), flora and fauna (by promoting species better adapted to dry conditions relative to those better suited for wetter conditions) and chemical conditions (by promoting oxygen penetration deeper into the soil), and may also cause land subsidence that could affect buildings and other constructions.

In particular, consequences related to rare habitats and species that need to be protected are central to the environmental impact assessment; these aspects of the Forsmark site are discussed in Section 3.2.1. The lowering of the groundwater level is usually referred to as drawdown (e.g. Figure 3-2). The drawdown at a particular location and time (or average for a given period) is the difference between the undisturbed groundwater level and that calculated or measured under disturbed conditions (usually defined as positive if the disturbed level is lower).

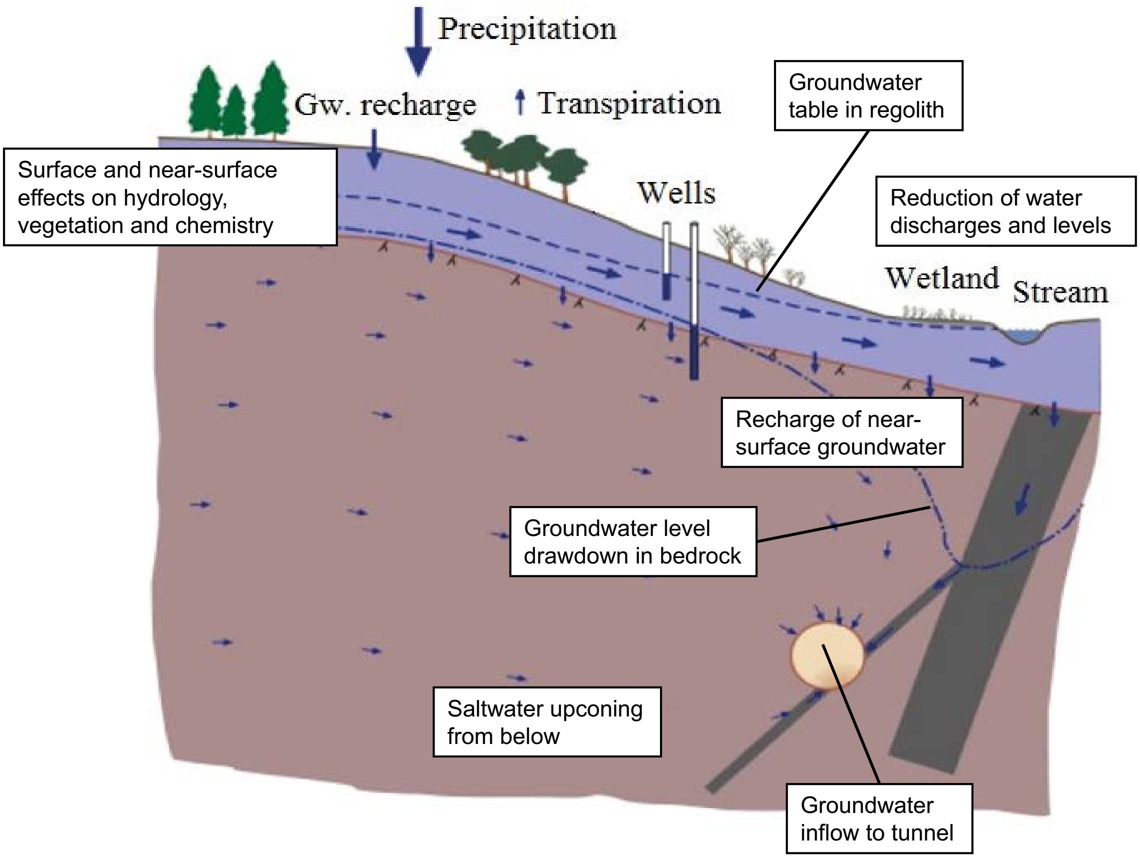

Figure 3-2. *Conceptual illustration of groundwater flow, with the darker brown areas indicating larger fractures and fracture zones in the bedrock, the groundwater table in the regolith (corresponding to a "water surface" in the porous medium of an open aquifer), and groundwater level drawdown in the bedrock, i.e. reduced groundwater pressure as indicated by the "cone" in the curve representing the groundwater pressure at some level in the bedrock. The figure also shows some of the possible effects of groundwater level drawdown on the bedrock and surface systems during the construction and operational period of an underground construction (indicated by the circular tunnel cross-section). Changes of physical, chemical and biological conditions in the regolith could lead to subsidence of buildings and changes in water availability and chemistry affecting flora and fauna. Figure modified from Axelsson and Follin (2000).*

Of particular importance for the evaluation of hydrological conditions and associated effects and consequences of the repository are the areas where deformation zones outcrop and groundwater could be transferred from bedrock to regolith or vice versa. Lakes, wetlands and other objects are more likely to be affected by groundwater drawdown-related changes if they are located within or close to such areas and if the bedrock and regolith materials in the contact zone are permeable. The fact that deformation zones often outcrop along lower-lying stretches in the terrain, which also tend to be the wetter part of the landscape where lakes and wetlands are located, implies that areas where changes in bedrock hydrogeology could affect objects on the surface are not uncommon.

Especially in early assessments made in the pre-construction stage, locations of lakes and wetland areas potentially affected by bedrock hydrogeology are determined solely by modelling. An example from this type of modelling exercise is shown in Figure 3-3, which shows modelled groundwater drawdown for a particular calculation case studied in the assessment of the planned spent fuel repository at Forsmark. The drawdown pattern (darker red colours correspond to larger drawdowns) follows a set of lines that essentially coincide with outcropping vertical and sub-vertical deformation zones and fractures. Thus, as explained above, these are also the stretches where hydrology-related effects primarily are expected to occur.

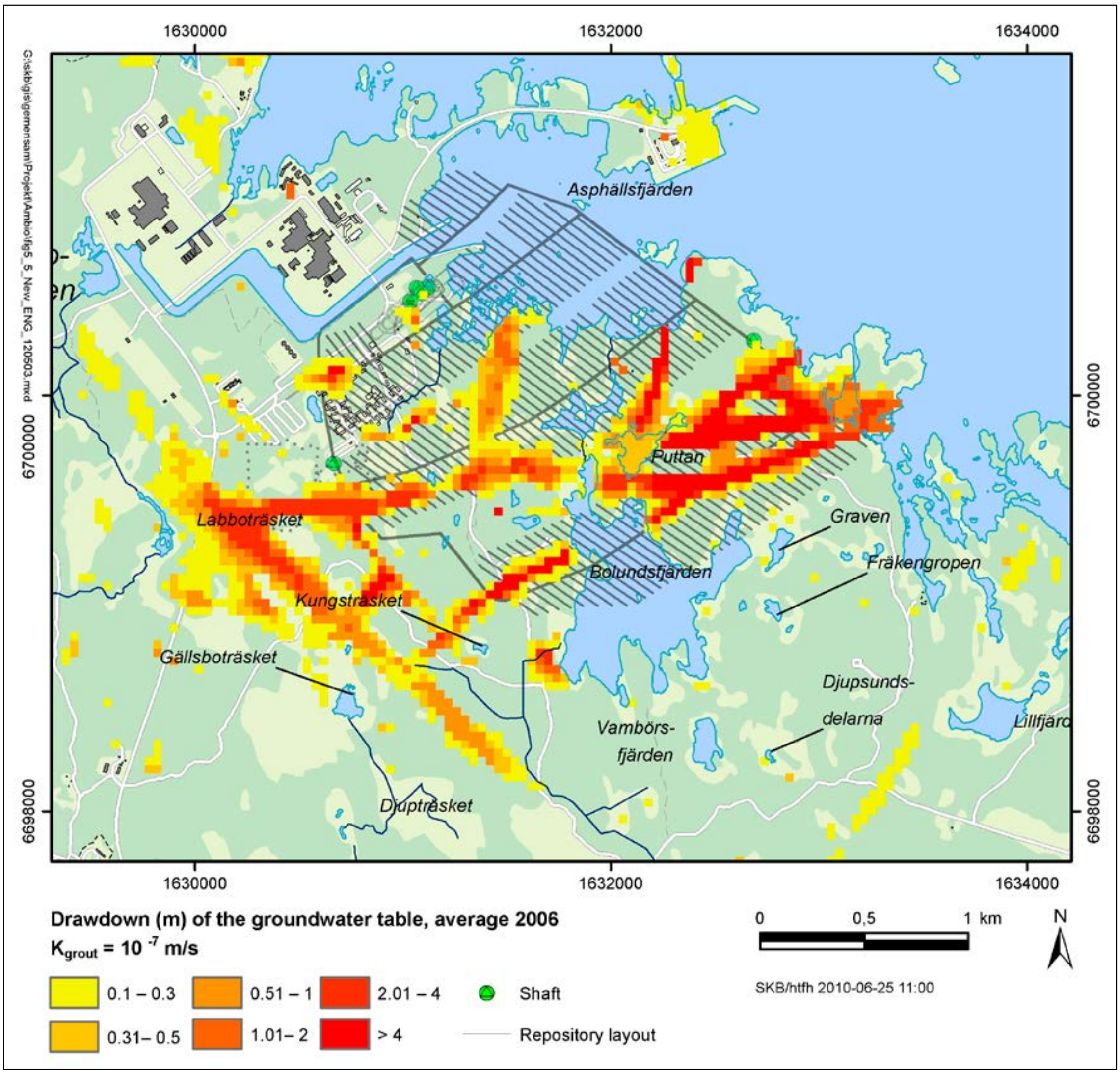

Figure 3-3. *Example of calculated annual average drawdown of the groundwater table at Forsmark (from Werner et al. 2013).* K_{grout} *denotes the hydraulic conductivity of the grouted zone around the repository and is a parameter that is varied between the calculation cases. Note that this is just an example of results for a particular type of repository (that for spent fuel) and for a particular combination of hydrological model and repository design. The results are typical of those obtained in the assessment of the spent fuel repository but need not be identical to those derived based on other assumptions or later versions of the repository design.*

This type of model-based identification of areas affected by groundwater drawdown is subject to the same uncertainties as the modelling discussed above. Similarly, the main approach to reduce the uncertainties is to increase the confidence in the model by collection of relevant data, e.g. by monitoring already before construction commences. In this case, monitoring data from regolith and bedrock that enable joint evaluations of co-variations and responses to various events would be of special value. Such events could be man-made (e.g. groundwater sampling or interference tests) or natural (e.g. precipitation events or large changes in sea level). The important thing is that the monitoring network makes it possible to evaluate whether and where these disturbances propagate from surface to bedrock and vice versa.

The monitoring during the construction and operational period should be able to capture the disturbances caused by the activities in the repository and also provide supporting data, primarily from reference areas, to help separating the effects of the repository from other natural and human activities that may affect the measured quantity. For reasons outlined above (and indicated in Figure 3-2), hydrochemical monitoring is also vital during the construction and operational period. Data from hydrochemical monitoring are important for assessments of both short-term effects during the construction and operational phase (primarily on the surface) and long-term effects during the coming post-closure phase (e.g. on safety indicators of repository conditions).

Since many of the consequences that may occur in the surface system concern ecological conditions, ecological monitoring, e.g. in the form of direct observations of habitats and species, is also an important part of the monitoring programme. It should be noted that monitoring of this type primarily implies repeated observations that could be performed at relatively long intervals (i.e. annually or even less frequently). Not only the protected habitats or species are of interest in this context, but also observations of other species or ecosystems that could indicate ongoing changes related to the repository. For example, it may be easier to establish an ongoing dry-out of a wetland based on species that are common there, irrespective of whether they are protected, or by observing species more sensitive to dry conditions than those primarily to be protected.

3.1.3 The post-closure period

The post-closure period is initiated by the termination of groundwater abstraction from the repository volume, which is then closed and abandoned. Once the repository has been closed, it will be re-saturated with water by natural groundwater inflow, with the site eventually returning to a situation similar to the undisturbed conditions prevailing during the pre-construction period. However, the conditions early in the post-closure period, but after resaturation, are not identical to those of the pre-construction period, but differ in at least three respects.

- The repository has been excavated and then re-filled with various materials, i.e. the geological materials used as backfill in tunnels, caverns and shafts, the engineered barriers (if any), and the nuclear waste in its canisters or containers. This means that a source consisting of a variety of radioactive and other materials has been emplaced in the bedrock and that potentially harmful components of this source can be mobilised and transported away by the groundwater. In addition, the chemical and hydraulic properties of construction, backfill and buffer materials will differ from those of the natural materials that were excavated.
- Hydrogeological and hydrogeochemical conditions in the bedrock have changed during the construction and operational period of open repository conditions (i.e. “reversed” groundwater flow towards the repository), which creates new initial and boundary conditions for any kind of modelling or model-based assessment of the post-closure period (compared to using the pre-construction conditions). This implies that near-surface hydrochemical conditions could prevail in a larger part of the bedrock than before construction commenced, and/or that the recharging groundwater undergoes chemical reactions that create new water compositions. In either case, this needs to be considered when assigning initial and boundary conditions and transport parameters in, for instance, hydrogeological models and models for post-closure radionuclide transport. The complexity of post-closure bedrock conditions and whether they return to those before repository construction are also affected by changes in hydraulic and chemical properties within the repository (cf. above).

- During the construction and operational period, which according to present plans will last 60–70 years (SKB 2016a), conditions may have changed also independently of the open repository, especially on the surface. In particular, climate change, shoreline displacement and landscape development processes may cause changes in site conditions that could be of importance. Obviously, much larger changes will occur during the remainder of the very long assessment periods that normally are considered (cf. below), but the initial period needs to be considered in some studies of the relatively near-future development of the site.

It is important to realise that whereas there exist no definitive plans for monitoring during the post-closure period, earlier monitoring is required to develop the necessary basis for the assessments of long-term safety during this period. Thus, the present report does not discuss monitoring to be carried out during the post-closure period, but monitoring required for the assessment of this period.

Figure 3-4 shows a conceptual model of solute transport following a release from a nuclear waste repository in bedrock; the figure indicates a KBS-3 type (spent fuel) repository but the principle is also valid for an SFR type repository consisting of larger caverns at shallower depth. Specifically, the figure illustrates the flow path of a "water parcel" that receives contaminants (primarily radionuclides) as it passes through the repository volume and then travels along fractures and deformation zones to a discharge area (in this case in a mire), from which it is transported by surface water flow through a set of surface ecosystems where man and non-human biota could be exposed to the contaminants. This implies that characterisation of all bedrock and surface systems along such flow paths is needed to obtain an adequate basis for modelling of the flow paths and the processes affecting "water parcels", i.e. the chemical components they contain and their interactions with surrounding geological and biological materials.

Monitoring of hydrological, hydrogeochemical and ecological processes and parameters is central to the development of the necessary site understanding and to obtaining relevant parameters for the models used in the assessment of post-closure safety. In particular, monitoring is required to understand and describe processes that display significant short-term (seasonal and/or from year to year) variations. This is the case for many parameters related to processes associated with flow, transport and surface ecosystems, where the analysis of the variations themselves, e.g. transient responses and interactions between hydrological and/or chemical subsystems, also could be an important part of the basis for process understanding.

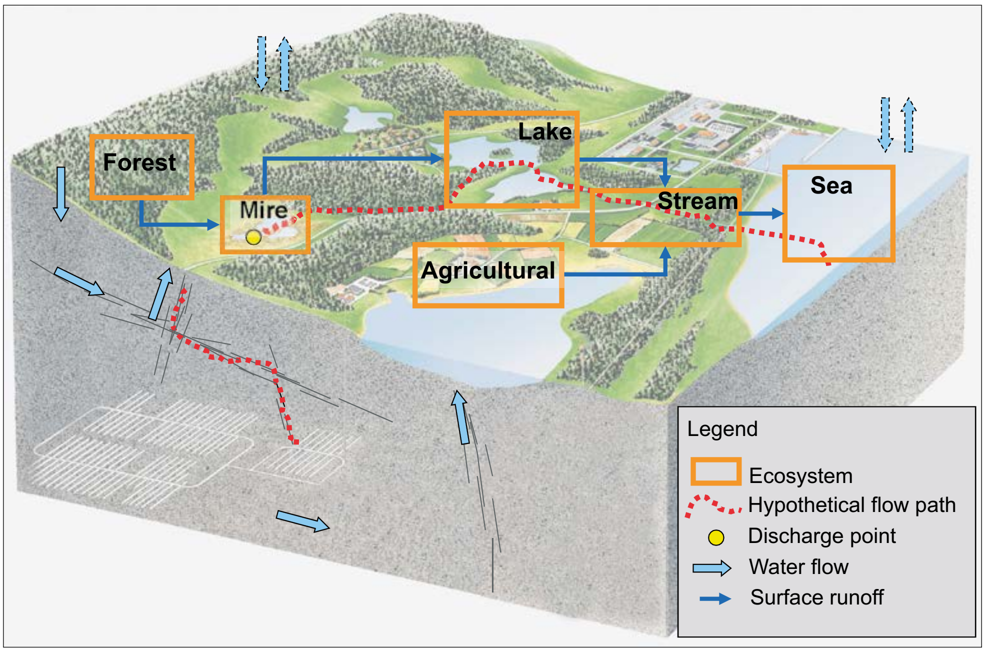

Figure 3-4. *Conceptual model of solute transport along a hypothetical flow path from a nuclear waste repository, which is indicated by the white lines in the grey bedrock part of the model, up to a discharge area (indicated by the yellow "discharge point"), and further through different types of ecosystems to the sea. Figure from Lindborg (2008).*

Since safety assessments of nuclear waste repositories consider very long time periods (i.e. up to 100 000 years and one million years for low/intermediate and high-level waste, respectively), future site development and the succession of landscape objects that may receive contributions of radionuclides in the future need to be described in these long time perspectives. Specifically, continuing shoreline displacement promotes a process of landscape development in which the present sea bays are cut off from the sea and become lakes, which then turn into wetlands and then, under certain conditions, become areas suitable for agricultural production (e.g. Lindborg 2008, 2010). In some cases, there is no lake stage in the succession, such that the sea bay directly changes into a wetland after cut-off from the sea. It should also be noted that other types of terrestrial areas, e.g. forests or non-arable open land, may develop after the wetland stage.

In the context of collecting data for description of a site that changes in time, monitoring of a present-day object at the site, e.g. a lake, may serve the dual purpose of providing data for modelling that particular lake and also future lakes resembling the one monitored today. Figure 3-5 shows an example of modelled landscape development at Forsmark between 2000 AD and 5000 AD, where shoreline displacement has led to the development of new land areas and a succession of landscape objects has taken place within present (2000 AD) land areas. In the figure, the succession of a specific object is exemplified by Lake Bolundsfjärden, which is a lake today and a potential agricultural area in 3 000 years. This means that monitoring of Lake Bolundsfjärden today will provide initial conditions and other input data for modelling the continued development of the lake, and hence contributes to the description of future agricultural land in the same area.

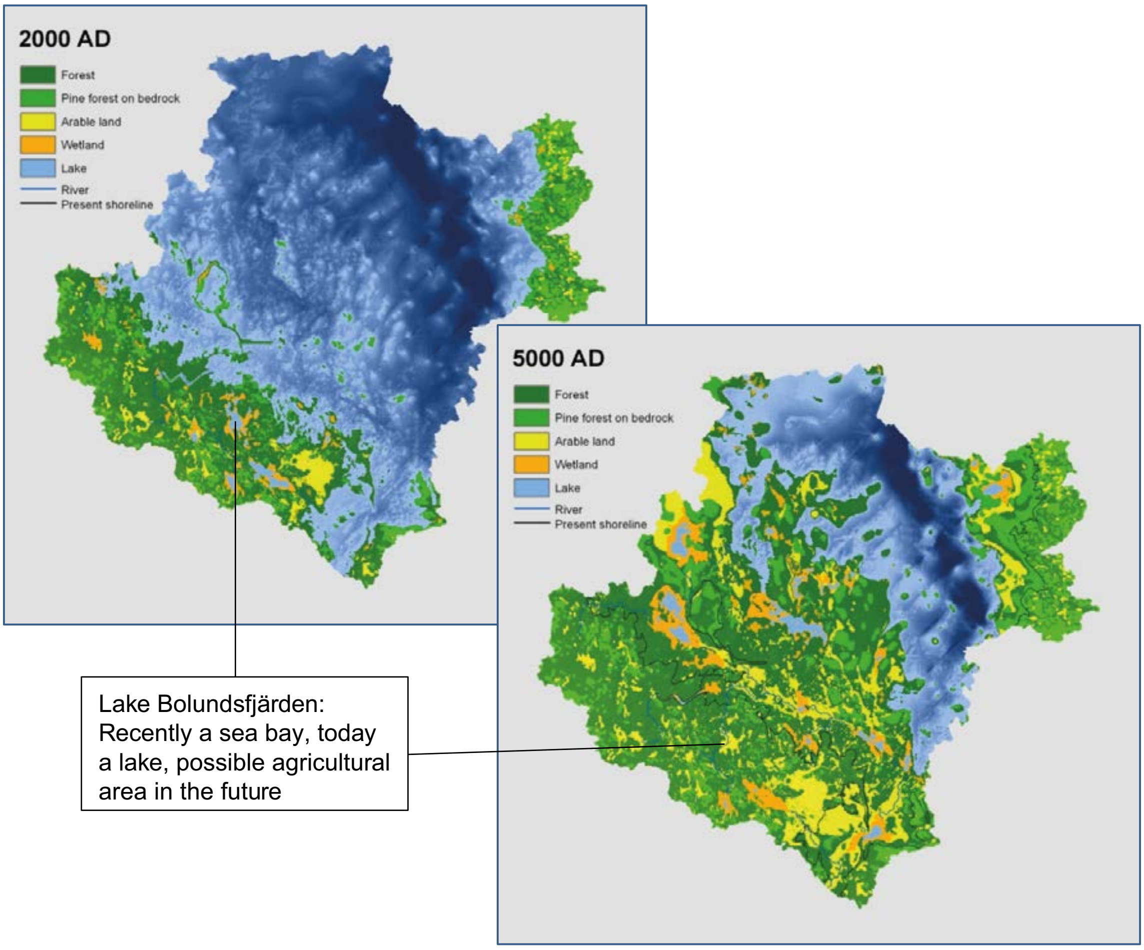

Figure 3-5. *Modelled landscape development at Forsmark between 2000 AD and 5000 AD (example of results presented in Lindborg 2010) showing the emergence of new land and landscape development within present land areas. Lake Bolundsfjärden changes from lake to agricultural area during the modelled period (see text).*

The description of present-day Lake Bolundsfjärden may also be useful as an analogue for future lakes with similar characteristics that form outside the present shoreline. Similarly, the description of the future terrestrial “Lake Bolundsfjärden” area may benefit from data collected today in terrestrial areas further inland, where the succession has advanced further. In addition, monitoring of Lake Bolundsfjärden and adjacent objects will help understanding present-day and future interactions between the lake and, for instance, the sea and the groundwater below and around the lake.

As indicated by the conceptual model in Figure 3-4, the assessment of long-term, post-closure safety relies on the identification and description of discharge areas for groundwater that has passed through the repository volume. Since groundwater discharge generally takes place in the low-elevation parts of the terrain where wetlands and lakes are located, much of the effort in site investigations and safety assessments is focused on these types of areas. The emphasis on these areas is also motivated by the fact that this is where most of the agricultural production of human foodstuffs and fodder for animals takes place, which means that the most important exposure routes in the assessment of dose and risk related to radionuclides often depend on the descriptions of present and future processes within these discharge areas. This implies that the monitoring programme to some extent should focus on these areas; it also explains why some of the present monitoring installations (e.g. groundwater observation wells in regolith) preferentially are located there.

The very long time perspectives associated with post-closure safety assessments imply that also changes in climate need to be taken into account, and that the changes expected to occur during the assessment periods are large. Essentially, periods of both warmer and much colder climates are included in the assessments. As an example of possible conditions during a period of colder climate, Figure 3-6 illustrates a landscape with permafrost where the only connections between large (repository) depths and the surface are the so-called “through taliks” that develop through the whole depth of the permafrost below larger volumes of surface water. This means that the safety assessment and associated data needs related to these conditions are focused on lower-lying (discharge) areas, implying that a subset of the discharge areas monitored and described for present and near-future conditions is relevant also for the assessment of colder far-future conditions.

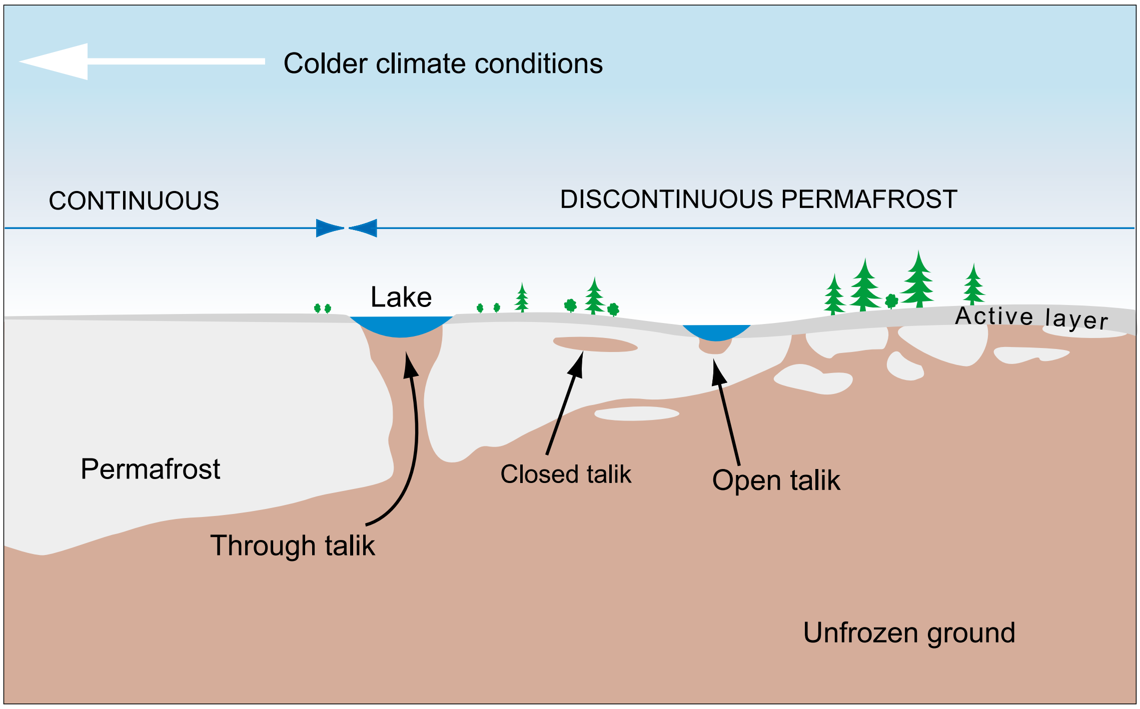

Figure 3-6. *Illustration of a generic permafrost landscape where the larger lake maintains a through talik, which is a “window” in the permafrost that enables groundwater flow and transport from below the permafrost to the surface (and vice versa). Figure from Lindborg (2010).*

3.1.4 Uncertainties with implications for monitoring

The site descriptions of Forsmark not only presented what was known about the site at the time of reporting, but also the uncertainties and needs for additional information remaining after each modelling step. In this section, some of the uncertainties and needs identified in the site descriptive modelling are summarised, i.e. especially those with implications for monitoring. Most of the following points were discussed in the final site description produced for the spent fuel repository application, SDM-Site (SKB 2008, Lindborg 2008, Johansson 2008); some have been considered also in the later site description for the extended SFR, SDM-PSU (SKB 2013b).

The flat and comparatively young Forsmark landscape is subject to ongoing development governed by processes that are known in principle but not in full detail, and which are observable within the time frame of the monitoring to be undertaken. This means that monitoring of both landscape-forming processes and underlying drivers such as hydrology could reduce uncertainties related to the understanding of landscape development and the parameters representing it in quantitative models.

The regolith at Forsmark is characterised by a high content of calcite. Depletion of the calcite is an ongoing process, but the time scale of this process is uncertain. Since calcite has a large influence on the overall chemistry and on properties affecting radionuclide retention, further hydrogeochemical investigations focusing on processes related to calcite depletion are needed to improve the basis for quantification of process rates and time-scales. These investigations could include hydrochemical monitoring, in combination with geochemical studies.

In the site investigations at Forsmark, large-scale horizontal connectivity and hydrogeological responses were observed in the upper 100–150 metres of the bedrock. However, the hydraulic connections between the existing SFR repository and the rock volume planned to host the spent fuel repository constituted a remaining uncertainty, which could be reduced by continued monitoring and evaluation of various mutual hydrological interactions. In particular, the integrity and properties of the Singö deformation zone are of key importance in this context.

Concerning large-scale hydrological connections where monitoring could provide needed additional information, it was noted that the studies of interferences between the groundwater level variations in the deep bedrock and various “events” in bedrock and other hydrological subsystems were associated with uncertainties. In addition to the groundwater abstraction from SFR, these “events” included changes in sea-level and evapotranspiration processes during dry periods.

Evidence of deep groundwater discharge could confirm the existence of flow and transport paths between planned repository depth and the surface, and could also be used in the testing of hydrogeological models. Such evidence, which primarily could be obtained from chemical analyses of specific parameters, has been sought during the site investigations and the possibilities for obtaining useful data in this regard should be considered also in forthcoming monitoring. It may be noted that the available hydrogeological field data, i.e. measured hydraulic gradients between regolith and bedrock, indicate that there are no discharge areas for flow systems involving deep bedrock groundwater in present land areas where the spent fuel repository is planned to be located (Johansson 2008). However, it cannot be excluded that such discharge areas exist.

During the site investigations, it was observed that lakes in Forsmark could function as recharge areas for groundwater under certain conditions (i.e. dry summers with extensive evapotranspiration from surrounding land areas). Improved understanding is needed regarding lake-groundwater-atmosphere interactions, and concerted monitoring would be a key part of the data collection to achieve this. The shallow groundwater levels mean that there is a strong interaction between evapotranspiration, soil moisture and groundwater. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, were evident in the data from many of the groundwater monitoring wells in the regolith, which indicates that a high temporal resolution of the monitoring is required, at least during certain periods, to understand the processes.

Measured relationships between lake water levels and groundwater levels indicate that the lake sediments, the underlying till, and/or the uppermost bedrock have low vertical hydraulic conductivities in the lakes from which such data are available. The hydraulic contact between the surface water and the groundwater below it is important both for the effects of groundwater drawdown and for future radionuclide releases to the surface water. Data suitable for evaluation of the hydraulic properties of sediments and underlying regolith are therefore needed also from other objects, including smaller lakes and ponds.

High salinities were found in the groundwater below several of the lakes at Forsmark. The hydrological and hydrochemical interpretations indicate that these waters are relict, essentially stagnant and of mainly marine origin. However, no absolute conclusion could be drawn from the existing data regarding the key question of whether they are evidence of an ongoing upward flow of deep saline water; further hydrogeological and hydrochemical monitoring could help answering this question.

Episodes of saltwater intrusion into lakes in connection with high seawater levels were recorded during the site investigations. Monitoring would be required to improve the understanding of when this occurs and how the lakes respond.

Observations of corrosion damage to monitoring equipment have been made during and after the site investigations. The corrosion is caused by earth electrical currents, which in turn are due to a number of sources, most notably the nearby high-voltage direct current cable connecting Sweden and Finland (see Section 4.3 and Thunehed 2017). Monitoring of earth electrical currents would help understanding the causes of corrosion and the effects of protective measures.

3.2 Monitoring for environmental impact assessment

3.2.1 Objects and species of high nature values

The presence of rare species and habitats that require protection or other measures is an important pre-condition for the assessment of the environmental consequences of any activity in Forsmark. Identified nature values and examples of how they were handled in recent environmental impact assessments are therefore described below. However, the description is more of an overview of protected areas and objects that need monitoring than a description of the actual monitoring needs.

The environmental impact statement produced for the spent fuel repository application (SKB 2011a) describes the Forsmark area as having a wilderness character with high natural values caused by an interaction of several factors, including the shoreline displacement, the flat topography, the calcite-rich regolith, and that the area is situated in a boundary zone between vegetation zones and also relatively undisturbed (outside the industrial areas). The Forsmark area has a high fraction of wetlands compared with the rest of the County of Uppsala. Much of the area around the nuclear power plant is of national interest for nature conservation and is surrounded by four Natura 2000 sites, two of which are also nature reserves (Natura 2000 is the EU network of nature protection areas and associated nature types).

Based on inventories performed as a part of the site investigations for the spent fuel repository, the area south of the nuclear power plant was shown to contain numerous valuable environments, especially around Lake Bolundsfjärden. They mainly consist of different rich fen environments and calcite-rich ponds where red-listed species occur. There are also various kinds of coniferous forests on calcite-rich soil, some of which are of a natural forest character. Many of these environments, particularly the wetlands, are assessed to have very high natural values (see classification of wetlands in Figure 3-7). Furthermore, some of these environments contain habitats covered by the EU Habitats Directive, and Sweden has pledged not to reduce their area.

During the inventories, red-listed species of mammals, bats, insects, amphibians, vascular plants, mosses, fungi and fish have been encountered within the investigation area, including pool frog, fen orchid, Geyer's whorl snail and flea sedge. The pool frog is, in Sweden, found only along the northern coast of Uppland, and the environments south of Forsmark are an important part of the total habitat of pool frog in the country. Several of the ponds also host an interesting dragonfly fauna. In the environmental impact assessment, identified nature values are combined with an analysis of impact and effects, which in this case involves the simulated groundwater drawdown and its effects on the ecological conditions in the wetlands to be assessed, to yield a classification of the consequences (Figure 3-8). This assessment of consequences is then used as a basis for decisions on whether the proposed disturbance can be allowed, and on protective and compensatory measures.

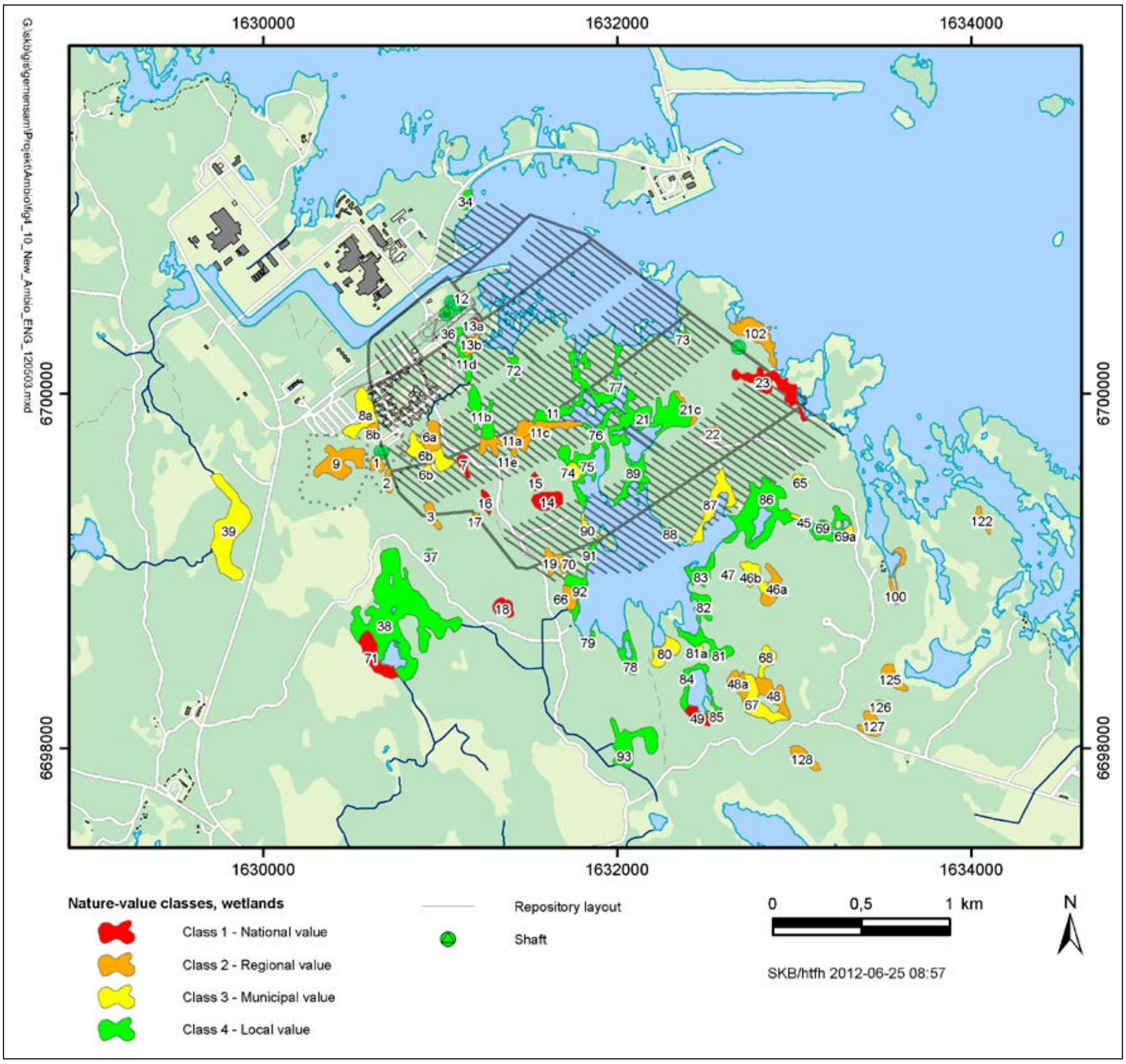

Figure 3-7. *Overview map showing locations and nature-value classifications of delineated wetland objects at Forsmark. The figure is an example produced for a particular assessment, i.e. of the spent fuel repository indicated by a network of lines representing the layout, and does not necessarily show the final classification or all wetlands in the area. Figure from Werner et al. (2013).*

Despite the influence of forestry, there are also older forest stands in Forsmark, some with such high natural values that they have been classified as key forest habitats or sites of natural value. In the forest environments, more than 20 red-listed species of fungi have been encountered. The area around Forsmark is very rich in birds, including numerous red-listed species (e.g. the white-tailed eagle). Some of the lakes in the area, such as Lake Norra Bassängen and Lake Bolundsfjärden, are also of importance for spawning fish.

3.2.2 Construction-related monitoring

The present report is for the most part focused on disciplines and measurements already included in the Forsmark monitoring programme, and how they should be developed to meet future needs. As described below, there is ongoing monitoring in and around existing nuclear facilities in Forsmark (SFR and the nuclear power plant). However, most of the present monitoring is directed towards the undisturbed natural system in areas some distance away from existing facilities, and primarily serves the purposes of advancing site understanding and establishing baseline conditions at the site.

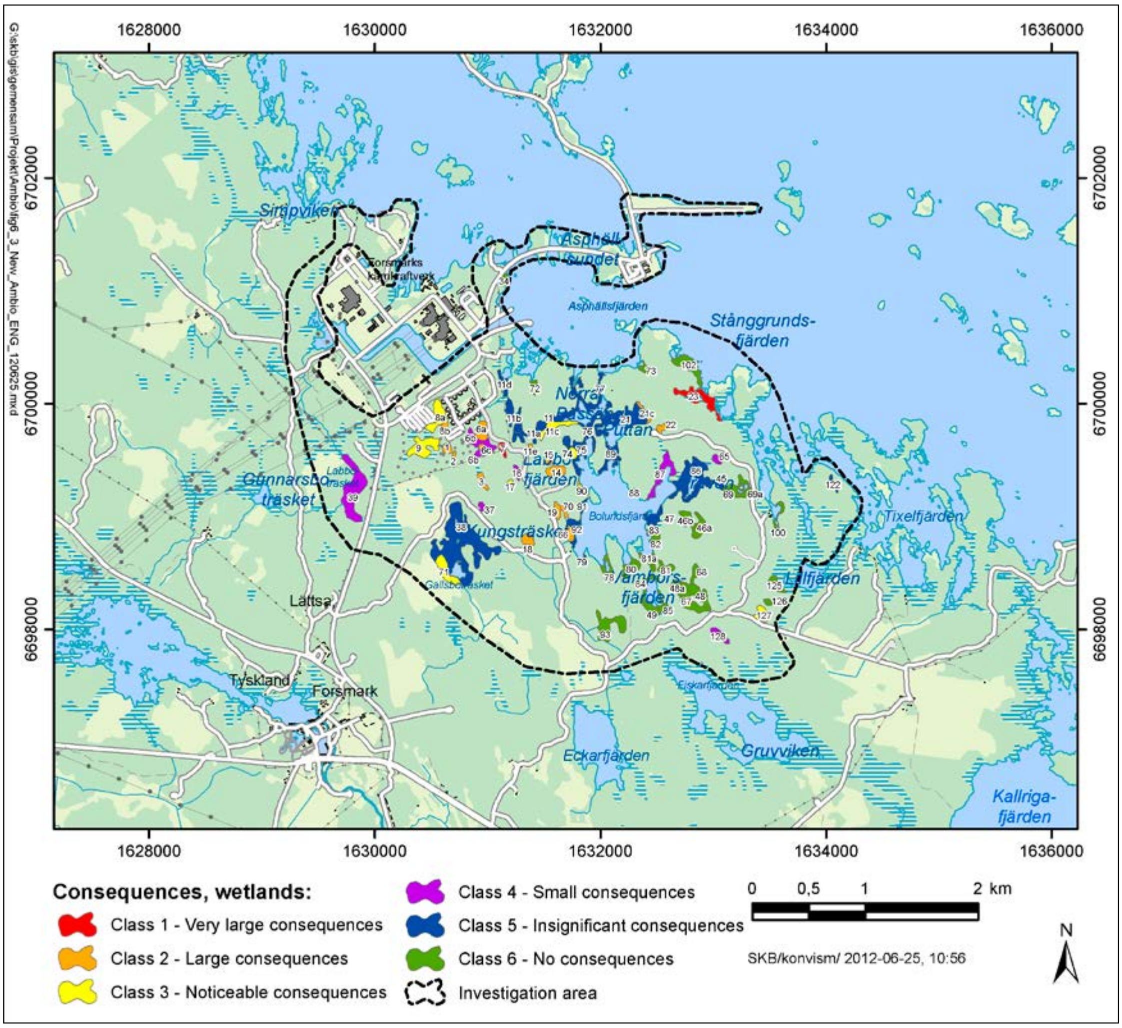

Figure 3-8. *Classification of ecological consequences of the planned spent fuel repository for wetland objects at Forsmark. Note that the figure is included as an example, and that it refers to a particular calculation case and repository design; it neither represents a final classification nor all ecological consequences of present and planned repositories. Figure from Werner at al. (2013).*

Once construction of a new facility at Forsmark commences, irrespective of whether it is the spent fuel repository or the new part of SFR that gets started first, a new set of monitoring activities not included in the present programme is needed. These activities are mainly what could be categorised as "conventional monitoring" in conjunction with large underground construction works, and consist of monitoring of various disturbances related to the construction activities themselves and their effects on man and the environment.

According to environmental regulations, a permit application should include a proposed monitoring programme, and the recent applications submitted by SKB include proposals for monitoring programmes. These are initial proposals that will be refined and made more detailed as the application process proceeds. Currently, they describe the planned monitoring only in general terms. New construction-related activities summarised in SKB (2011a) include monitoring of noise, vibrations and air shock waves, and subsidence of buildings (see also Andersson 2013).

The applications also describe measures and monitoring related to the spreading of dust, handling of water from rock piles and tunnels, and handling of chemical products and waste. Concerning the handling of drainage water from deposits on the surface and the underground constructions, the proposed monitoring includes the surface water recipients where water is discharged. Surface water monitoring is also required in connection with construction work in water, such as creation of new land through artificial fill.

Most of the monitoring outlined in the present section is "conventional" in the sense that it is similar to that performed at many construction sites, and will be specified in detail later in consultation with the supervisory authorities. The details of these activities are not discussed in the present report. However, the construction-related monitoring that requires a baseline (e.g. recipient conditions) is considered in the programme updates presented here, as far as possible with respect to presently available information.

3.3 Present SKB monitoring and monitoring experiences

This section provides an overview of monitoring experience and ongoing monitoring activities within SKB, including a summary of the development of the programme for monitoring at Forsmark. In addition, monitoring end-users and key issues are presented, and the organisation of the following discipline-specific chapters is described.

3.3.1 Overview of SKB monitoring programmes

Geoscientific monitoring at Forsmark started in the early 1980s, in connection with the investigations and later construction and operation of the first stage of SFR. A significant increase in the monitoring activities was initiated in 2002 with the start of the site investigations for the spent fuel repository (see next section for more information about Forsmark). In the Simpevarp–Laxemar area, which is located in the Oskarshamn municipality in Southeastern Sweden, SKB is performing monitoring at the interim storage for spent nuclear fuel (Clab) and in and around the Äspö Hard Rock Laboratory. Also in Laxemar–Simpevarp, site investigations, including an extensive monitoring programme, for a spent fuel repository started in 2002. However, most of these activities were decommissioned after the selection of Forsmark in 2009 as the repository site to be proposed by SKB.

The monitoring at Clab started in the early 1980s during the construction period. The facility was taken into operation in 1985 and later extended with a new part that became operational in 2008. The monitoring of Clab is described in a self-monitoring programme (Carlstedt 2015), which includes monitoring of cooling and process waters, abstracted groundwater, groundwater in private wells, noise and release of radioactivity to the atmosphere. In addition, monitoring of groundwater levels is performed in a set of bedrock boreholes surrounding Clab (Werner 2010). Radiological environmental monitoring carried out on the Simpevarp peninsula, where both Clab and the Oskarshamn nuclear power plant are located, is performed by the operator of the nuclear power plant, and is essentially similar to that at Forsmark described in Section 3.3.3.

The Äspö Hard Rock Laboratory is a research facility situated adjacent to the Simpevarp–Laxemar area. The facility has been used primarily for research related to various aspects of the spent fuel repository and reaches a depth of approximately 460 m (i.e. about the same depth as the planned repository). Geoscientific monitoring related to the Äspö laboratory started in 1987, as part of the pre-investigations preceding excavation of the ramp access tunnel. Experiences from investigations during the construction of the laboratory are presented in Almén and Stenberg (2005), where a wide range of investigation methods are discussed and evaluated regarding their usefulness for detailed characterisation and related modelling needs. This means that the Äspö programme offers data and practical experience from investigations and monitoring during pre-construction and construction phases, as well as from a following "operational" phase.

Thus, much of the SKB knowledge on monitoring, concerning installations, data handling and overall methodologies, has been developed at Äspö. The Äspö monitoring network, which primarily consists of boreholes drilled from tunnels and from the surface, has been extended as the construction and subsequent research in the underground laboratory developed. The still ongoing Äspö groundwater monitoring has generated a large database of hydrological and hydrochemical data, see e.g. the annual reports for 2013 and 2015 on the monitoring of groundwater levels/pressures in boreholes and inflows to tunnels (Wass 2014d and Wass 2016d, respectively). Other monitoring organised within the framework of the Äspö laboratory is the meteorological and surface water monitoring on the island of Äspö and nearby island and mainland areas (see e.g. the 2013 report, Sehalic et al. 2014).

Between 2002 and 2008, site investigations for a spent fuel repository were conducted in the Laxemar–Simpevarp area; the final site descriptive model is reported in SKB (2009). A monitoring network consisting of installations for measuring meteorological parameters, surface water levels and discharges, groundwater levels in bedrock and regolith, and chemical sampling of surface waters and groundwater was developed during the course of the site investigations and used as a basis for the site descriptive modelling. Following the decision to select Forsmark as the site for the spent fuel repository in 2009, most of the monitoring was terminated and most of the boreholes were deinstrumented. The monitoring that continued was included in the programme for the Äspö laboratory, which thereby was extended by surface water (e.g. additional discharge stations) and meteorological monitoring, and a set of regolith and bedrock boreholes for groundwater level and hydrochemical monitoring.

3.3.2 Present monitoring organisation and data management at SKB

As a preparation for the evaluation of the present monitoring at Forsmark, this section presents a brief description of how environmental monitoring is organised at SKB. The description is primarily focused on the operational aspects of the monitoring at the sites SKB is responsible for in the Forsmark and Laxemar–Simpevarp–Äspö areas. Hence, it describes who does the actual monitoring, but it does not present the related "higher-level" administrative systems and procedures within SKB (such as the routines and method descriptions related to monitoring).

The monitoring performed by SKB can be divided into four activities corresponding to four sites and organisational units.

1. Monitoring of the Clab intermediate storage for spent nuclear fuel in Simpevarp is performed by the unit responsible for the operation of Clab (unit DC within the Operations department in the present (2016) SKB organisation).
2. Monitoring of the SFR repository in Forsmark, for which the SFR operation unit is responsible (presently unit DS within the Operations department). As explained in more detail in the next section, this monitoring consists mostly of measurements made in the repository and in boreholes drilled from the repository.
3. Monitoring of the Äspö Hard Rock Laboratory and the Laxemar–Simpevarp area. This monitoring involves a large number of boreholes in and along the Äspö tunnels and some meteorological, hydrological and hydrochemical monitoring installations from the Laxemar–Simpevarp site investigations. Responsible for this monitoring is a unit within the SKB Technology department (unit TD).
4. Monitoring of the area for the Forsmark site investigations, including some later additions to the monitoring network (see next section). This monitoring is performed by the Forsmark site management unit (unit BP), which is part of the Nuclear fuel department at SKB.

It follows that environmental monitoring is carried out by four units representing three different departments within SKB. Note that the SFR monitoring is partly carried out by the Forsmark site management unit, but evaluated and reported by the SFR organisation. Monitoring responsibilities within SKB are divided between these units/departments, and there is no central or common function responsible for all monitoring within the company. However, there are common resources for monitoring in the form of method descriptions for some monitoring activities and technical resources for development and purchase of measurement devices and other equipment within the Technology department.

Research and development related to monitoring equipment and methods is presented in the SKB RD&D programme, which considers both environmental monitoring and monitoring performed within existing and planned nuclear waste repositories. SKB produces an RD&D programme every third year. The latest was published very recently, in the autumn of 2016 (SKB 2016a), and consequently the preceding one, and the latest to be fully and officially reviewed by the authorities, in 2013 (SKB 2013a).

The monitoring outlined above can be divided into two broad categories. Activities 1 and 2 in the list above represent monitoring directly associated with the operation of existing nuclear facilities. This monitoring is driven by external requirements according to environmental legislation (Section 2.2) and the specific permits for operating the facilities, and external reporting of the results is usually required. The underlying monitoring programme is part of a legal process and is generally changed only if required by or in consultation with the authorities.

The second monitoring category, activities 3 and 4 in the list, is driven by SKB-internal requirements and needs, which emanate from research and development needs (Äspö) and from data needs for the establishment of a baseline or complementary investigations (Forsmark). For Forsmark, this means that until permits with conditions specifying monitoring outside the present SFR facility have been received, SKB must formulate requirements internally and design a monitoring programme based on present and expected future data needs. Such data needs could arise within several activities and parts of the SKB organisation, i.e. units within the departments for operations of nuclear facilities, technology (including research), spent fuel, low- and intermediate waste, and safety and environment, which indicates a somewhat diverse situation regarding the handling of monitoring at SKB.

Data management, including planning, handling of data flows, quality control and organisation of databases, is of crucial importance for the collection and utilisation of monitoring data. As described in more detail in the main SDM reports (SKB 2008, 2013b), all primary data collected by in the field and from laboratory measurements are stored in the SKB databases Sicada and SKB-GIS (GIS stands for geographic information system). Before delivery to the database operator, the data are reviewed and approved by the person responsible for the field activity providing the data (the activity leader). The database operator transfers the data to the database and then makes an order of the same data from the database. The data export from the database is then checked by the database operator and the activity leader to ensure that no mistakes are made in the transfer of the data to the database. The data are then approved by the activity leader by signing the data.

According to present routines, modelling should be based on quality-controlled and approved data stored in the SKB Sicada and GIS databases only. All orders and deliveries of data from the databases are registered, making all data transfers, and hence all inputs to modelling, traceable. Error handling is an important part of the data management system at SKB. It is the responsibility of all data users to report all errors found and to keep up-to-date on the data errors reported. For all errors reported, the type of error is identified and corrective actions are taken.

3.3.3 Past and present monitoring at Forsmark

Overview and stages in programme development

Similarly to Laxemar–Simpevarp, the monitoring at Forsmark has three main starting points and objectives: radiological monitoring of nuclear facilities and the environment, geoscientific monitoring of a nuclear facility (SFR, in the Forsmark case), and a site investigation for the planned spent fuel repository. One major difference is that since Forsmark was selected by SKB as the site for the spent fuel repository, a much larger portion of the monitoring activities initiated during the site investigation are still ongoing; furthermore, new measurements have been added to the programme.

Radiological measurements are performed regularly around the nuclear facilities in Forsmark, both directly on outgoing process water and exhaust air and in the form of radiological environmental monitoring, with sampling of water, plants and animals (SKB 2011a). The radiological monitoring is required by the radiation protection legislation. In particular, the environmental monitoring is performed in accordance with a programme prescribed by the Swedish Radiation Safety Authority, SSM (or actually by one of its predecessors, SSI), which specifies measurements at all sites with nuclear facilities in Sweden (Lindén 2004).

The environmental radiological monitoring includes measurements in marine and terrestrial ecosystems, with locations and species/media to be sampled and radionuclides to be analysed specified in the above-mentioned programme, and consists of a basic programme carried out every year and an extended programme of marine measurements every four years. It is the responsibility of the operator of the nuclear facility to perform the monitoring, which in practise for the most part is carried out by independent agencies such as universities. SSM performs quality assurance, e.g. by spot checks. There is also a programme for biological monitoring focused on the effects of intake and release of cooling water on fish, birds and bottom fauna in the sea (see Chapter 7 and Adill et al. 2016).

The establishment of the existing network of installations for geoscientific monitoring, i.e. primarily (but not exclusively) equipment for hydrological and hydrochemical measurements, can be separated into the following three periods when most of the additions were made.

- The construction and initial operational phase of the existing of SFR repository (i.e. SFR 1, see Figure 1-5). This monitoring consists of measurements in SFR (including boreholes from the tunnels) and in surface boreholes in the vicinity of SFR, and was established in the 1980s.
- The site investigations for the spent fuel repository. An extensive monitoring network was developed during the site investigations 2002–2007. The investigations were mainly conducted within an area referred to as the "candidate area", and were in the later stages focused on its northwestern part (Figure 3-9), the so-called "target area" (sometimes referred to as the "prioritised area").
- The later period of supplementary investigations and installations. During the period after completion of SDM-Site in 2008, new investigations including the provision of additional monitoring installations have been performed in the SFR area for the SFR extension project (Figure 1-5), for design and other construction-related preparations in the planned surface facility area of the spent fuel repository (Figure 1-7), and in connection with objects identified as having high nature values (see example in Figure 3-7).

Details concerning monitoring installations, such as where, how many and what kind of equipment, how and how often measurements are made and how data are handled, are given in the discipline-specific descriptions of the present programme in Chapters 4 through 7. In the following, some main characteristics of the development and "sub-programmes" outlined above are summarised.

The SFR monitoring programme

This section describes the official monitoring programme for SFR, i.e. the programme providing the basis for the reporting to SSM that is associated with the operation permit. Boreholes and other installations used in this monitoring originate mostly from the pre-investigations and construction of the existing SFR in the 1980s. As described in Odén et al. (2014), additional boreholes have been drilled in the SFR area during later site investigations for the spent fuel repository and the extension of SFR. These boreholes are included in the overall monitoring programme for Forsmark, see Chapters 5 and 6 for hydrological and hydrochemical monitoring, respectively, but not in the SFR-specific programme reported to SSM.

The SFR monitoring programme is described in a general programme document (Skogsberg 2008) and a more detailed SKB-internal instruction that describes how the measurements are to be performed. The programme consists of surveillance of tunnels and rock caverns, including rock support, and monitoring of a bentonite barrier, rock deformation, groundwater inflow, and groundwater pressure and chemistry in boreholes drilled from inside the facility. The programme is reported in a short annual report (e.g. Lind (2015) for 2014 and Åström (2016) for 2015), with appendices describing results from the different monitoring activities (see Jonsson (2015) for all 2014 monitoring except measurements in boreholes, and Lundqvist (2016) for the corresponding report for 2015).

The hydrogeological monitoring included in the SFR programme consists of automatic pressure registrations in 38 sections distributed between 12 boreholes (see e.g. Harrström (2015, 2016) for the 2014 and 2015 monitoring reports). The hydrochemical sampling is performed once a year in four borehole sections. The analysed parameters include pH, electrical conductivity, a set of major components and three isotopes. More extensive measurements have been performed with a time interval of 4–6 years, see Nilsson (2015, 2016) for the 2014 and 2015 annual reports, respectively, where 2015 was a year of more extensive monitoring. The time series from the SFR monitoring provides a relatively long-term record (c. 30 years) of the hydrogeological and hydrochemical effects of an open repository in the Forsmark bedrock. Among the interesting observations than can be made is that the groundwater inflow to the underground facility has decreased to 1/3 of the inflow in 1988 when the repository was taken into operation (Jonsson 2015).

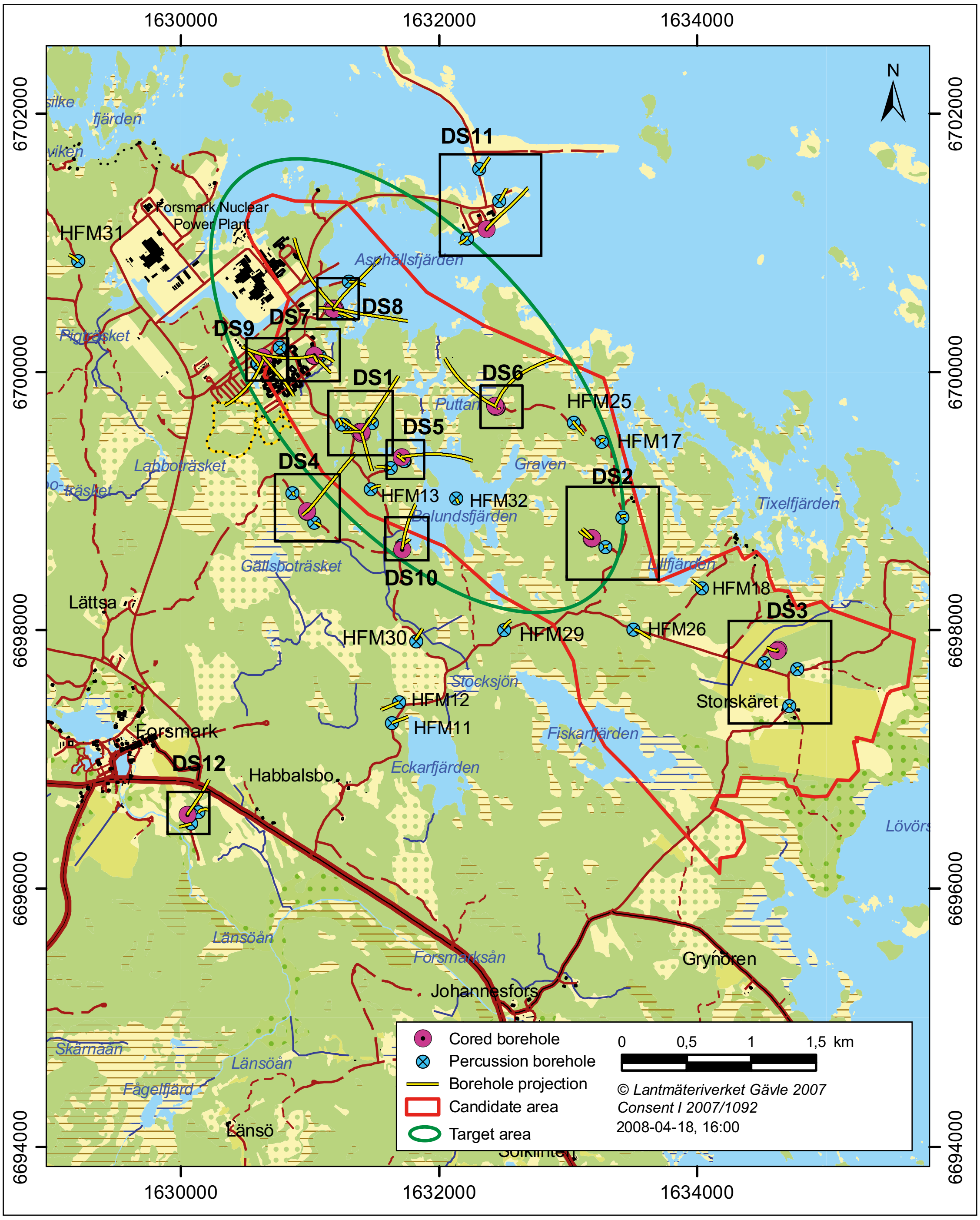

Figure 3-9. *Map showing candidate and target areas and drill sites (DS) associated with the site investigation for the spent fuel repository. The SFR repository is located below the eastern part of the SFR pier (i.e. to the right of the "DS11" label, see also Figure 1-5), whereas the area marked "DS8" essentially corresponds to the area of the surface facility of the spent fuel repository (cf. Figure 1-7).*

The site investigations for the spent fuel repository

The site investigations for the planned spent fuel repository began in 2002 and ended in 2008 with the publication of the SDM-Site version of the Forsmark site descriptive model (SKB 2008). These site investigations generated the majority of the monitoring installations that exist in the Forsmark area. Essentially, the investigations and the associated monitoring network can be (and were) divided into bedrock and surface parts, which is not to say that they are (or were) treated as completely separate items – integration and joint interpretations were central to data evaluation and modelling. Following the generic site investigation programme published in 2001 (SKB 2001a), site-specific programmes describing the different stages in the Forsmark site investigations were presented in a series of SKB reports (SKB 2002, 2005, 2007). A framework programme for site investigations during the forthcoming construction and operational phases has also been presented (SKB 2010b).

The bedrock monitoring is mainly based on a number of percussion- and core-drilled boreholes (Figure 3-9). The deeper core-drilled boreholes (most of them 500–1 000 m long), and also many of the shallower (100–300 m long) percussion-drilled holes, are organised in terms of twelve drill sites (DS), denoted by DS1 through DS12 in Figure 3-9. Each core-drilled borehole was labelled in accordance with the number of the drill site where it is located, and letters are used to distinguish boreholes at the same drill site (i.e. boreholes KFM01A and KFM01B are both at DS1). The percussion-drilled boreholes were numbered chronologically (labelled HFMxx, where "xx" is the number) and did not follow the DS numbering.

The borehole network was developed gradually during the site investigations, with the objectives of the boreholes changing from more general characterisation issues to specific questions during the course of the investigations. The design of each borehole (i.e. its location, length and inclination) was determined by specific characterisation and monitoring needs, such that many boreholes targeted intercepts with specific geological structures (fractures or deformation zones) with the aim of establishing borehole sections where hydraulic testing and long-term monitoring could be performed. However, some boreholes were drilled with the main objective of sampling and otherwise investigating specific rock units, i.e. the bedrock volumes between the larger structures that together with the structures provide the geometric framework of the bedrock models. Figure 3-10 shows an example of a bedrock model with deformation zones and rock units (in this case the so-called "fracture domains"); some boreholes are also indicated.

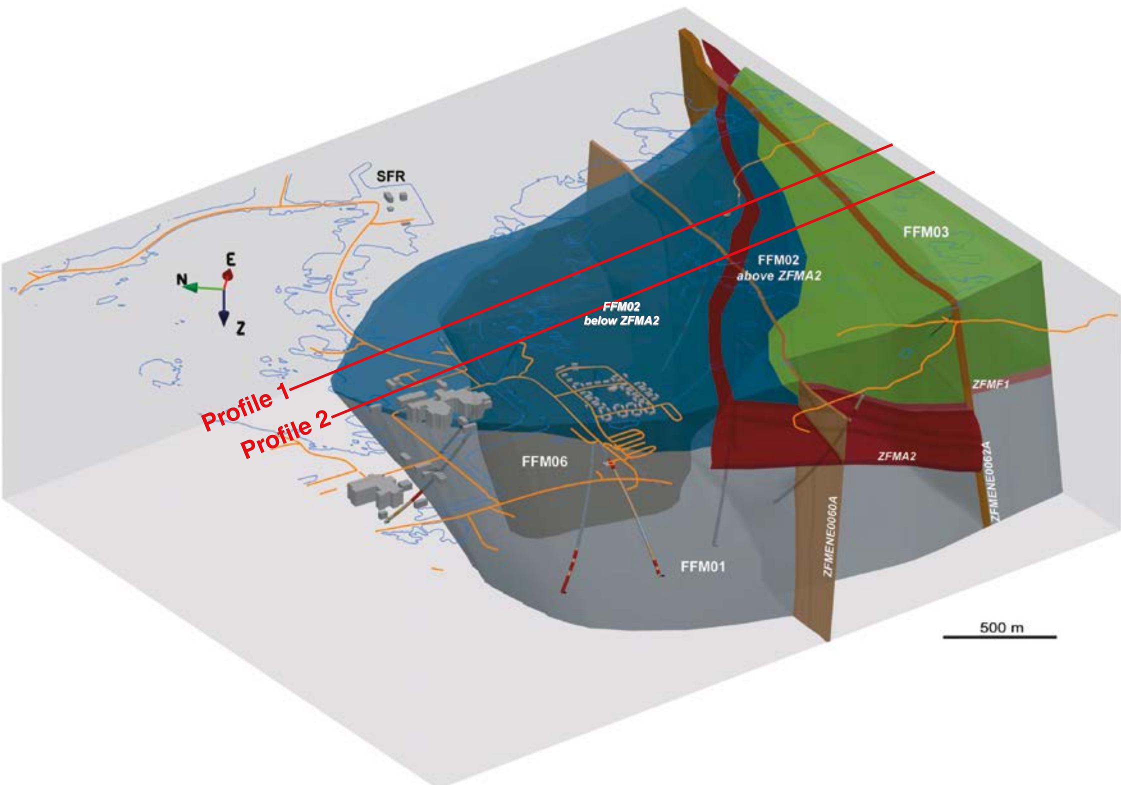

***Figure 3-10.** Example of geological-geometrical model of the Forsmark bedrock where units with labels "ZFM…" are deformation zones and those labelled "FFM…" are "fracture domains", which is one of the subdivisions of the rock mass that was used in the bedrock modelling. Figure from Selroos and Follin (2010), where also the profiles indicated in the figure are shown.*

Thus, the site understanding, the site-specific database and a monitoring network were developed through successive drilling, testing, modelling and monitoring during the site investigations. The then established monitoring network is the basis for the present hydrogeological and hydrogeochemical monitoring of the bedrock in most of the Forsmark area (with the SFR area as the main exception). For reasons discussed above (Section 3.1), the main hydraulic connections in the bedrock, especially those that can propagate hydraulic disturbances and enable connected pathways for solute transport between repository depths/volumes and the surface, have been of particular importance for the development of the bedrock monitoring network. Joint interpretations of monitoring data from the bedrock and the surface (including surface water and meteorological data) turned out to be very important during the site investigations for the development of site understanding related to hydrology/hydrogeology and solute transport.

Whereas the network of connected fractures and deformation zones constitutes a common framework for the bedrock monitoring (except for parts of the geological monitoring, see Chapter 4), the monitoring of the surface systems was to some extent developed using different subdivisions or subsystems for different disciplines, models and/or parameters. These included catchment areas and other hydrological subdivisions such as groundwater recharge and discharge areas, different types of ecosystems (terrestrial, limnic and marine), areas of different vegetation types or land uses, and geologically or chemically based subdivisions into different regolith layers and/or areas. Furthermore, monitoring may also be motivated by data needs coupled to specific objects (e.g. certain lakes, wetlands or forest areas) due to their present nature values or their potential use as analogues for presently sea-covered objects to be considered in the assessment of long-term safety.

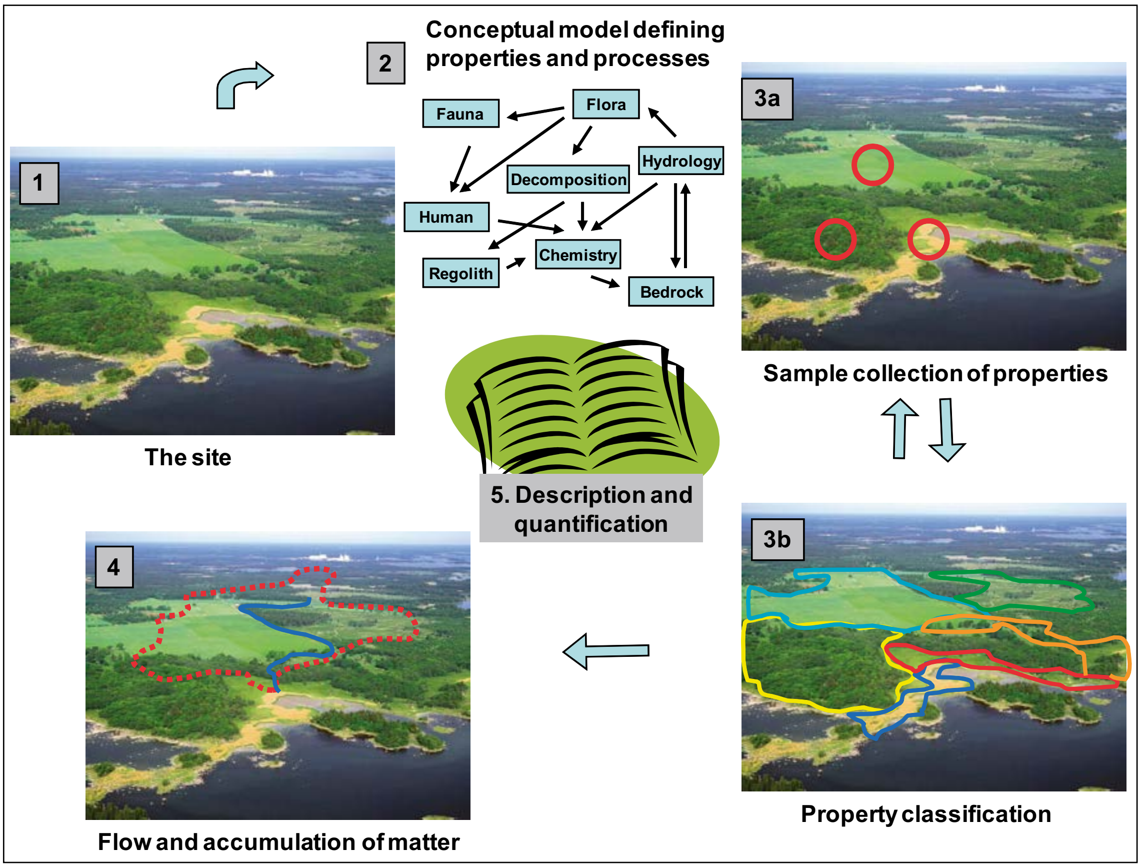

Figure 3-11. *Modelling process and data needs for developing a site descriptive ecosystem model. The site (1) is defined. A conceptual model (2) is produced describing functional units, their properties and the fluxes of matter/energy between them. Samples and monitoring data are collected at the site (3a) to describe the biotic and abiotic properties and processes in the conceptual model. The landscape is divided into a number of distributed model domains using site data and GIS (3b). Flows and accumulations of water and matter are described using hydrological tools, catchment areas and site data (4). All information is compiled into the site descriptive ecosystem model (5). Figure from Lindborg (2008).*

Figure 3-11 gives an overview of the process of developing a site descriptive ecosystem model, which also illustrates data needs from monitoring and other data-generating activities (such as sampling for various characterisation purposes). In order to provide the necessary data, the surface and near-surface monitoring network established during the site investigations at Forsmark was developed to produce time series data on a variety of parameters, including abiotic (e.g. meteorology and hydrology) and biotic/ecological parameters (e.g. population dynamics). Essentially, the present monitoring of the surface system at Forsmark mainly consists of two types of measurements: automated measurements of meteorological and hydrological parameters producing data with high temporal resolution (minutes to hours, if needed), and manually measured data from sampling campaigns (chemistry) and inventories (ecology) that provide data with much lower temporal resolution (months to years).

As indicated in Figure 3-11, the spatial structure provided by surface water catchment areas is of particular importance for the modelling of hydrology and transport of matter in connection with surface ecosystems. Based on topography and the surface water system, a total of 25 "lake-centred" catchments, specifically eight main catchments with their sub-catchments, were delineated in Forsmark (Brunberg et al. 2004). However, the catchments associated with the stream discharge stations in the area (see Section 5.4) are the catchments used in the quantitative analyses of water and chemical mass balances.

The small streams (brooks) that connect lakes and wetlands to the sea serve as drains and collect discharging groundwater with its content of dissolved chemical substances from the land area surface, and transport it further downstream to lakes and the sea. Data from hydrological (discharge) and chemical monitoring of the stream network are therefore key inputs to water and mass balance calculations performed to test models and develop process understanding. Furthermore, the monitoring network for surface water and groundwater was developed to include major discharge areas such as larger lakes and wetlands, including groundwater below lakes, and groundwater in different regolith materials/layers, at different depths, and in the regolith/bedrock interface zone.

Recent modifications of the monitoring programme

After the completion of SDM-Site in 2008 and the decision to select Forsmark as the site for the spent fuel repository in 2009, monitoring has continued largely unchanged. However, some changes, planned as well as unplanned, have taken place since 2008. The unplanned changes include reductions of the programme due to malfunctioning equipment that was not replaced, see Chapter 5 for details. However, there are also many examples of equipment that has been replaced.

Most of the recent changes are additions to the monitoring network resulting from various new investigations in the area. These are either supplementary studies related to the spent fuel repository, i.e. to address external requests for supplementary information and to prepare for coming design and construction stages, or in the context of the site investigation for the SFR extension. Recent additions of monitoring installations at Forsmark can be summarised as follows:

- The site investigations for the SFR extension resulted in a set of new boreholes in bedrock (SKB 2013b, Odén et al. 2014). These boreholes were drilled within the relatively small model domain considered in SDM-PSU, most of them from the eastern part of the SFR pier and from a nearby islet, and are hence located close to SFR (Figure 1-5). In addition, groundwater monitoring wells were installed in the regolith on the SFR pier. All new boreholes and monitoring wells are included in the 2015–2017 hydrogeological monitoring programme for Forsmark, which is described in the activity plan AP SFK-10-083 (SKBdoc 1464444, internal document in Swedish).
- As a preparation for the design and construction of the access tunnel and surface parts of the spent fuel repository, a series of investigations involving drillings in bedrock and regolith were carried out from 2010 to 2012 within and in the vicinity of the planned area for the surface facility (Figure 1-7, cf. location of "DS8" area in Figure 3-9). The aim was to produce more detailed descriptions of topographical, geological and hydrogeological conditions within the relatively small surface facility area than provided in SDM-Site (the investigations are reported in a number of SKB-internal documents). The investigations were focused on the upper bedrock and the regolith; the longest boreholes are c. 150 m, and most of them are in the interval 60–100 m. All monitoring wells in the regolith and a majority of the bedrock boreholes from these investigations are included in the monitoring programme for 2015–2017 (cf. above). These bedrock boreholes are monitored as open wells, i.e. are not subdivided into several monitoring sections.

- Additional investigations preparing for the design of shafts, ramp and surface facility of the spent fuel repository have been carried out during 2016. These investigations included the drilling of a new core-drilled borehole to a depth of c. 540 m, a large number of drillings in regolith (Henriksson 2016), and installation of groundwater monitoring wells. Most reports describing boreholes, installations and investigations in the boreholes, and planned monitoring activities were not available when the present report was finalised.
- As described above (Section 3.2.1), the environmental impact assessment of the spent fuel repository identified important nature values in the Forsmark area that could be negatively affected by repository construction and operation. Therefore, activities directed towards preparations for the construction stage and compensatory measures have been performed during the years after the application was submitted. Activities involving monitoring and/or new monitoring installations can be summarised as follows:
  - Monitoring of red-listed species associated with wetland/pond environments (pool frog, great crested newt and fen orchid) has been carried out as repeated inventories (Collinder 2013, 2014, 2015, Collinder and Zachariassen 2016). Groundwater monitoring wells have been installed in wetlands with fen orchid populations, such that relations between population dynamics and hydrological variations can be monitored.
  - Surface water level gauges and groundwater monitoring wells have been installed in a number of wetland/pond environments of high nature values. Hydrological and hydrochemical monitoring have been performed and these installations are included in the present monitoring programme for Forsmark (cf. above).
  - As a compensation for nature values that according to present plans will be lost during the construction of the surface facility, new ponds designed to be suitable for the red-listed species have been constructed and monitored hydrochemically and through repeated inventories focusing on the development of vegetation and bottom fauna (Qvarfordt et al. 2013, 2014a, b, 2015). Surface water level gauges have been installed in the new ponds and are included in the monitoring network.
  - Mitigating measures in the form of water supply to ponds and wetlands have also been studied theoretically (through modelling) and experimentally. A field experiment with water supply to one of the Forsmark ponds classified as possessing high nature values was performed in 2013 (Werner et al. 2014), and groundwater monitoring wells were installed in connection with this experiment. These monitoring wells are not included in the present monitoring programme.

Other recent modifications of the monitoring at Forsmark include a move of the meteorological monitoring station, changes in locations and methodology of the bedrock groundwater flow measurements, and addition of boreholes in the SFR area to the hydrochemical monitoring. It is noted that comprehensive presentations and evaluations of monitoring data have not been performed after the SDM-Site and SDM-PSU efforts (of which the latter was largely focused on areas in the vicinity of SFR). This means that data from recent additions to the monitoring network have not been evaluated, and that a substantial amount of data from both new and "old" monitoring devices has accumulated in recent years.

3.4 End-users and key issues

As a somewhat more technical and detailed background to the discipline-specific analyses reported and synthesised in the remainder of the report, this and the following sections describe key issues to be addressed by means of monitoring data. Furthermore, an outline of a methodology and a set of general aspects that need to be considered when developing the programme are presented.

The key issues that require monitoring data in order to be resolved are divided into the following groups.

1. Site understanding and site-descriptive modelling: Monitoring data used as input to further developments of the site understanding and updates of the Forsmark SDM.
2. Assessment of long-term radiological safety: Monitoring data used as input to the safety assessments to be produced in the coming stages of the licensing processes.
3. Assessment of environmental consequences of construction and operation: Monitoring data used to provide an adequate baseline and otherwise prepare for the construction and operation period, and to assess consequences of construction and operation activities.
4. Repository design and construction: Monitoring data used as input to the design of repositories and management of monitoring systems associated with construction and operation.

Another task that may require changes in the monitoring programme is to support the ongoing licensing processes with additional information about the site. As the monitoring associated with this task is largely unknown, it is not further described here. Furthermore, it should be noted that the listed key issues, which also could be referred to as data uses or data users, are associated with a set of overarching supporting activities that involve issues related to data handling, communication of data and results, and storage of data and reference samples.

3.4.1 Site understanding and site-descriptive modelling

Continuous developments of the site understanding and associated site-descriptive models form the scientific basis for the assessment of long-term radiological safety, assessment of environmental impacts of construction and operation, and repository design. At present, there is an overall well-developed scientific knowledge of the Forsmark site. Furthermore, the detailed investigations to be carried out from the underground during repository construction will provide additional knowledge and will allow adaptation of the layout to ensure that deposition holes will be placed in suitable locations (SKB 2016b). Data gathered through the updated monitoring programme will provide additional means to further address remaining uncertainties, and to refine the knowledge of the Forsmark site and its natural and anthropogenic development. Table 3-1 provides a list of overall key issues related to the Forsmark site understanding that need to be considered in the updated monitoring programme.

Table 3-1. List of overall key issues related to site understanding and site-descriptive modelling.

Key issue	Comments
Baseline (for the pre-construction period)	Basis for conceptual models, process understanding and quantitative models (see below).
	Basis for assessment of natural and anthropogenic trends and changes during the construction and operation period.
	Various aspects of baseline datasets need to be evaluated well before initiation of the construction and operation period, e.g. to determine data gaps, data quality (uncertainties/errors), and whether the spatial and temporal distributions of datasets are relevant and representative.
Conceptual models and process understanding	Description of abiotic subsystems and interactions between sub systems.
	Interactions between abiotic and biotic systems.
	Conceptual models and process understanding related to type areas and objects in the biosphere, i.e. areas/objects of importance for environmental impact assessment and/or analogues for future biosphere objects.
	Assignment of basic parameters to be communicated between disciplines.
Quantitative models	Assignment of initial and boundary conditions, input and calibration data.

3.4.2 Assessment of post-closure radiological safety

The assessment of long-term radiological safety is a cornerstone of a licence application for a nuclear waste repository. As explained in Section 3.1.3, the present programme does not consider monitoring that is to be performed after repository closure, but includes data needs for earlier assessments of the post-closure period. Table 3-2 provides a list of overall key issues related to assessment of post-closure radiological safety where the monitoring programme can provide some further insights. However, the key source for further information about the site at the repository level will come from the detailed investigations carried out as the repository is constructed.

In addition to data needed to describe and assess the domains where the monitoring takes place, geosphere-biosphere interactions are included in the "Issues" column to emphasise that some monitoring activities are motivated by the need to link the two domains, or to describe the one domain based on data from the other. Examples of such issues include the recharge of near-surface (regolith) groundwater into the bedrock and surface/near-surface discharge of bedrock groundwater (i.e. discharge of groundwater from large depths in surface water or regolith groundwater).

Table 3-2. List of overall key issues related to long-term radiological safety.

Domain	Issues
Near repository	Assessment of hydrogeological and chemical conditions in the vicinity of the repository that are of importance to long-term radiological safety (e.g. canister and buffer integrity).
Geosphere	Characterisation of groundwater flow paths in the rock, and chemical properties along the flow paths.
	Providing data for models of radionuclide transport and accumulation in the geosphere, including tests of alternative models and motivations for model simplifications.
	Geosphere-biosphere interactions.
Biosphere	Characterisation of groundwater and surface-water flow paths in the biosphere, and chemical properties along the flow paths.
	Providing data for models of radionuclide transport and accumulation in the biosphere, including tests of alternative models and motivations for model simplifications.
	Providing data to support descriptions of landscape development.
	Geosphere-biosphere interactions.

3.4.3 Environmental impact assessment

In the updated monitoring programme for the pre-construction period, it is of utmost importance to identify those (indicator) parameters and locations that require a baseline prior to initiation of construction. The vast majority of the impact cases listed below are multi-disciplinary. The impact cases and associated monitoring needs are further described in the discipline-specific chapters on meteorology and hydrology (Chapter 5), chemistry (Chapter 6) and ecology and nature values (Chapter 7). For each of these disciplines, assessment of environmental consequences requires access to reference data (Section 2.1.6). Hence, identification and evaluation of potential reference data sources is an integrated part of the development of an updated monitoring programme.

The impact cases of relevance for different types of monitoring activities can be divided into the following:

- Construction of surface facilities (e.g. in- and up-filling of water and land areas, construction activities and associated drainage, rock crushing, and road and boat transport).
- Operation of surface facilities (e.g. handling of drainage water, storm water and sewage water, rock crushing, and road and boat transport).
- Drainage of subsurface facilities.
- Management of wetlands, forests and agricultural areas.

Table 3-3 describes general data needs for environmental impact assessment and input to design.

Table 3-3. Aspects of impact cases of relevance for an updated monitoring programme.

Aspect	Issues
Impact-case description	General description.
	Measures and conditions proposed in permit applications.
	Definition of source, recipient and pathway.
Source description	Physical-hydrological processes and parameters.
	Chemical processes and parameters.
Recipient description	Physical-hydrological characteristics.
	Chemical characteristics.
	Ecological characteristics.
	Conservation values and benchmarks.
Pathway description	Hydrological processes and parameters.
	Chemical processes and parameters.
	Ecological processes and parameters.
Potential recipient effects and consequences	Physical-hydrological effects.
	Chemical efffects.
	Ecological (or other revelant) consequences.
Recommendations for monitoring programme	Source, recipient and pathway monitoring.
	Hydrological parameters.
	Chemical parameters.
	Ecological parameters.
	Baseline data.
	Reference monitoring.

3.5 Methodology and general considerations for programme update

3.5.1 Organisation of present programme and evaluation

The monitoring disciplines consider a wide range of parameters, where different aspects and conditions are important for assessment of different parameters. Since each discipline tends to primarily consider parameters of fairly similar general characteristics, it follows that different aspects dominate the evaluations in the different disciplines. For instance, there is a multitude of parameters that could be included in the hydrochemical monitoring, whereas the choice of parameters is not that much of a question for the hydrological monitoring. Furthermore, most of the hydrological monitoring is carried out by automatic measurements, which implies that it is relatively simple to change the temporal resolution of the dataset, whereas manual sampling is the norm in the hydrochemical programme, implying that sampling frequency is an important strategic (and economic) question. (The increasing availability of automated sensor systems for hydrochemical monitoring will probably change this to some extent; this development should be followed by SKB.)

These examples indicate that there are differences in the methodologies employed by the different disciplines when updating the monitoring programme. However, the basic steps are the same and the overall methodology for evaluating the Forsmark programme can be summarised as follows.

1. Identification of monitoring needs through an analysis of data users, key issues, and specific data needs derived from these and additional information. This implies that the key issues in Section 3.4 are assessed and formulated in terms of operational data needs. Thus, this step is about defining the questions to which the monitoring should provide answers.
2. Identification and description of monitoring parameters/targets, i.e. what to measure or otherwise observe in the monitoring programme to fulfil the needs identified above. This part of the analysis is about what should be measured to answer the questions. Note that this is not only a matter of what to measure in terms of parameters. Also where, when and how often monitoring must be performed, as well as the required precision of the measurements, can be important for specification of what needs to be measured to provide the necessary information.

3. Evaluation of whether the present programme fulfils the needs identified in the preceding steps, i.e. whether there is ongoing monitoring of the parameters/targets identified in the preceding step. This means that the presently ongoing programme is checked against the identified needs, such that it can be concluded whether the required monitoring is carried out, in terms of parameters, locations, number of points and frequency. Note that it should also be evaluated whether all parts of the ongoing monitoring are needed.
4. Evaluation of the present programme with respect to problems related to measurement methods and data handling. This means that data and experience are collected and evaluated with respect to what might need to be changed in the practical methods and procedures. The aim is to determine whether methods for measurements and data handling are adequate.
5. Compilation and further development of the results from the preceding steps into a list of concrete recommendations describing how to handle the present monitoring, needs for new monitoring and monitoring that can be terminated, and proposed changes in supporting activities (e.g. maintenance and data handling). In the cases where additional studies are required to specify how to proceed, those studies should be described.
6. Formulation and presentation of an integrated monitoring programme and a set of prioritised investigations.

The subsequent chapters describe and evaluate the current monitoring programme (Chapter 4 through 7), provide recommendations for programme updates and further studies (Chapter 8) and provide a condensed presentation of the proposed updated programme (Chapter 9). Essentially, they present the current monitoring and use the general and site-specific information summarised above in order to assess the need for modifying the programme, either by expanding ongoing monitoring activities, by introducing new activities/monitoring localities, or by terminating (parts of) ongoing activities.

The structure of the discipline-specific analyses follows the current organisation of the programme, as outlined in Section 1.6.

Geological monitoring is described in Chapter 4, with recommendations summarised in Section 8.1. The monitoring discussed there includes rock deformation, and measurements of earth electrical currents and the global magnetic field.

Meteorological and hydrological monitoring is covered in Chapter 5 and Section 8.2. The monitoring includes meteorological parameters and observations, groundwater levels and fluxes in bedrock, groundwater levels in regolith, surface water levels in lakes, ponds and the sea, and surface-water discharges in streams.

Hydrochemical monitoring is described and evaluated in Chapter 6 and Section 8.3. This part of the monitoring programme consists of hydrochemical sampling and analyses of various waters in the surface, near-surface and bedrock systems.

Monitoring of ecology and nature values is described and analysed in Chapter 7, and the resulting recommendations given in Section 8.4. This monitoring includes general monitoring of mammals and birds, and monitoring of threatened species and specific objects of particular interest for assessment of environmental consequences of planned repositories.

As described in Section 3.3, ongoing monitoring in the Forsmark area includes measurements in the existing SFR repository, e.g. groundwater inflow to the facility and groundwater pressures and hydrochemistry in boreholes drilled therefrom, and radiological measurements in air and water leaving the nuclear facilities and in surrounding ecosystems. In the following, these measurements are described when relevant, but no specific evaluation is made of whether they are appropriate and sufficient for the monitoring of the SFR repository itself.

3.5.2 Additional inputs and considerations

The planned update of the Forsmark monitoring programme is to large extent motivated by the fact that the programme for the establishment of a spent fuel repository in Forsmark is about to enter a new stage, as construction works are expected to commence in a not-too-distant future. Another important change with implications for monitoring is that the construction of the SFR extension is also planned to start relatively soon. As an input to the discipline-specific analyses in the following chapters, some important aspects of the present stage in the waste management activities at Forsmark that could be reflected in the evaluation of the monitoring programme are summarised as follows:

Existing monitoring programme. The current programme serves as a starting point and main reference for the evaluations and updates. This is by far the most important input to the present work. The evaluation of the present programme is required to cover all aspects, including data needs,equipment, measurements and data handling.

Baseline. An important aspect of monitoring in the present pre-construction stage at Forsmark (pre-construction with respect to the spent fuel repository and the SFR extension) is the establishment of a baseline representing the "undisturbed" conditions prior to the initiation of construction works or the conditions during some other designated "baseline period" (Section 2.1). Clearly, the relevance and meaning of a baseline will vary among disciplines and parameters, but in many cases, such as for water levels in ponds and wetlands of high nature values, both mean values and variations characterising "undisturbed" conditions must be quantified. However, for each discipline or type of data it must be specified what to achieve during the baseline period, and proper documentation of the baseline knowledge or state is necessary.

Long-term monitoring. The time horizon of the monitoring programme changes from being that of a "normal programme" (years up to a decade) to become one of a "long-term programme" (several decades up to one hundred years). This raises issues related to sustainability of, for instance, installations and systems for documentation and data management, and continuity in programme management. A related consideration is that the quality of similar measurements may change, e.g. decreasing limits of detection in chemical measurements, which would require careful consideration in the treatment of time series data. However, it could also imply that the actual meaning and contents of what is considered a monitoring programme changes. With a significantly longer observation period, there might be processes or parameters otherwise considered irrelevant in monitoring (usually because they would not change during the observation period) that should be included in the programme.

Ongoing licensing processes and other external contacts. The process for licensing of a spent fuel repository was initiated in the spring of 2011 and in December 2014 SKB submitted an application for extending SFR. These processes will give rise to comments from those participating in the review process and likely also to demands for complementary investigations that could affect the monitoring programme. Eventually, the licensing processes will entail that monitoring programmes need to be coordinated with the other monitoring at the site. There may also appear other questions or issues with implications for monitoring that SKB decides to address, for goodwill or other "non-compulsory" reasons.

Repository designs, and plans and preparations for construction works. The monitoring programme should be general in terms of collecting information to support site understanding, but should also take current knowledge on repository design and construction plans into account. This implies that developments in these areas need to be checked continuously, including address of possible interferences between existing monitoring installations and planned construction works.

The descriptions of monitoring installations and data in this report use the coordinate systems RT 90 2.5 gon V/0:15 (X, Y) and RHB 70 (Z), i.e. vertical (Z) coordinates are expressed in terms of elevation (m) above the RHB 70 datum (0 m elevation).

4 Geological monitoring

4.1 Overview of present monitoring programme

Monitoring activities at Forsmark within the geologic discipline are presented in the following three sections and include:

- Monitoring of rock deformation, Section 4.2.
- Monitoring of earth electrical currents, Section 4.3.
- Monitoring of the global magnetic field, Section 4.4.

4.2 Monitoring of rock deformation

4.2.1 Background

The Eurasian shield is subject to strains arising from tectonic crustal shortening and glacio-isostatic recovery after the retreat of, mainly, the Weichselian continental ice sheet. Ever since the bedrock was first segmented by large-scale orogenies and rifting events, strains have been increasingly localised to deformation zones. Such deformation zones occur at all scales, ranging in size from mesoscale fractures (trace lengths of tens to hundreds of metres) to regional scale zones (trace lengths of up to hundreds of kilometres). The imposed strains are dissipated along the block boundaries/deformation zones either seismically, i.e. as earthquakes of various magnitudes, as aseismic slip, i.e. the stick-slip mechanism is less pronounced or, to a far lesser extent, as plastic deformation of the blocks themselves.

For nuclear waste disposal concepts based on storage in bedrock, earthquakes endanger the safety of the repository due to their potential of causing reactivation of sealed fractures or planes of weakness caused by ductile deformation during earlier periods of the geologic evolution or slip along suitably oriented fracture planes with low physical or chemical friction and/or high hydraulic pressure. Earthquakes may also under certain circumstances deteriorate the repository shelter capacity by causing brittle rock deformation, i.e. fracturing of solid rock. The safety can also be endangered by reactivation of sealed fractures or planes of weakness caused by ductile deformation during earlier periods of the geologic evolution or slip along suitably oriented fracture planes with low physical or chemical friction and/or high hydraulic pressure. Within the planning and preparation process prior to construction of an underground repository, it is therefore of utmost importance to characterise the current seismic activity at the selected site including its regional surroundings. Further, if possible, it is important to quantify the amount of strain, and in particular the strain rate, i.e. the velocity with which the rock is deformed. The latter enables a long-term estimation and understanding of the stresses necessary to generate earthquakes and earthquake recurrence times (Ekman and Ekman 2013).

Intraplate strain rates are extremely low and, therefore, very difficult to measure. Intraplate strain rate estimates range between roughly 10^{-12} per year (Anderson 1986, Muir-Wood 1995) and $1.5 \cdot 10^{-9}$ per year (Slunga 1991, Sandiford et al. 2004, Scherneck et al. 2010). However, Slunga (1991) argues that most of the strain energy is continuously released aseismically. Hence, only a fraction of the tectonic strain would be effective for accumulating energy and restoring stresses. This implies that the strain rate effective for local stress regeneration is much lower than the large-scale strain rate across the Fennoscandian Shield.

A strategy has been elaborated for monitoring of current rock deformation at Forsmark. This strategy is essentially the same as for the corresponding site for disposal of nuclear waste at Olkiluoto in Finland, although details regarding measurement design and instrumentation applied to some extent differ between the sites (see Section 4.3 and Posiva 2013). The basic principle of the deformation measurement strategy for Forsmark is to combine equipment designed for detecting rock deformation manifested as seismic events with instruments suitable for measuring aseismic slip along, primarily, major deformation zones in the vicinity of the planned repositories. Most instruments should be located in the immediate and close (within a few kilometres) surroundings of present and planned repositories. However, the character of local seismic events at Forsmark have to be analysed in a regional, or even nation-wide context, which also lays claim to data from a large number of seismic stations dispersed over most of Sweden.

From the aspect of measuring technique, the monitoring of rock deformation at Forsmark is a considerable challenge, firstly because the process of repository design and construction, as well as the long-term safety assessment, calls for data not only from conventional, but also from a local network of non-conventional seismometers capable of detecting earthquakes of very low magnitudes. Secondly, advanced technology with the potential of quantifying and characterising the nature of extremely small aseismic horizontal and/or vertical deformation of rock blocks is demanded in order to achieve the needed data accuracy.

Deformation measurements of too short duration may, in spite of employment of sophisticated technology, deteriorate data quality and enhance the risk of misinterpretation of the magnitude and character of rock deformation at the investigated site. It is therefore essential that these types of measurements are performed as long-term monitoring, where the data sampling period preferably should be extended over several years, or even decades. Furthermore, the monitoring should encompass two fundamental periods (cf. Chapter 2), the *pre-construction* or *baseline* period, which is the monitoring phase prior to any induced disturbances related to the repository construction, and the *construction and operation* period, respectively. The construction and operation period is formally ended by the closure of the repository. Plans for post-closure monitoring are not discussed in the present report.

The baseline period is essential for different purposes. Firstly, monitoring instruments need to be calibrated and adapted to local conditions. Routines regarding their handling, and the data arising from the instruments, need to be established and documented with due education and training of the personnel. Secondly, the baseline period provides the necessary information that enables SKB to identify man-made disturbances induced by the construction of the repository, for instance subsidence, frequency of earthquakes, changes in water pressure (Chapter 5) or chemistry (Chapter 6). Lastly, the baseline period provides information on the natural variability of the geosphere so that monitoring during the operational phase might be adequately interpreted. We emphasise that the baseline monitoring must be initiated prior to initiation of construction work in the nearby SFR facility (Section 1.4).

4.2.2 Objectives, data use and data users

Monitoring of rock deformation, i.e. monitoring of different types of rock motion, is motivated by requirements from two principal activities: 1) *planning/projecting* associated to construction works and 2) research and development to evaluate *long-term safety* of the SFR and spent fuel repositories.

Data from long-term monitoring of current rock deformation, paired with knowledge of the previous geologic evolution and the structural geological setting of Forsmark, enable predictions of long term geological evolution of the site. For example, monitoring of strain rate enables estimation of the long-term prerequisites for earthquakes and their recurrence times which is necessary to assess seismic hazard in safety assessments covering periods of up to a million years.

Seismic monitoring provides information about the current pattern of natural seismicity in terms of magnitude, recurrence times and spatial distribution, but also about the response to stress redistributions, expressed as induced seismicity (Kisslinger 1976, Larsson 2004), due to e.g. blasting, excavation rate and grouting. Induced seismicity can also be used as input to constrain the geometry of geological structures (e.g. Valoroso et al. 2013), i.e. to improve the structural model and its various derivatives (e.g. DFN, radionuclide transport). The seismic monitoring is also used to increase operational safety by providing early warnings of e.g. rock bursts or spalling (Hudyma and Potvin 2010). Finally, a carefully set-up seismic network could provide fault plane solutions such that the local stress field and its variability can be quantified.

4.2.3 Present monitoring

Systems for deformation monitoring at Forsmark were successively established during the site investigation period 2002–2007 and involved two branches (SKB 2007):

- Seismic monitoring within the framework of the *Swedish National Seismic Network* (SNSN 2013).
- Aseismic deformation monitoring by GNSS (*Global Navigation Satellite System*) and DInSAR (*Differential Interferometry Synthetic Aperture Radar*) techniques.

The Department of Earth Sciences at Uppsala University has developed the Swedish National Seismic Network, SNSN, which in December 2014 included 67 seismometer stations distributed over most of Sweden (Figure 4-1). The function and methods used in the SNSN net are described in Böövarsson and Lund (2003) and Böövarsson et al. (2006).

Since the completion of the site investigations, preparations have been ongoing for establishing a local, high-resolution, seismic network at the Forsmark site. We here refer to such a network as a nano-seismic network (Joswig 2008), i.e. a system of seismometers with the capability of detecting seismic events of fundamentally lower magnitudes than those detected by the SNSN net.

Aseismic ground deformation has traditionally been measured and analysed by surveyors and geodesists using traditional sights and rods, various laser-based tools and, during the last decades, also high precision GPS instruments. The use of GPS networks has a good potential for measuring slow rock deformation, but is also associated with some limitations and drawbacks, for example that vertical movements are resolved less accurately than horizontal movements.

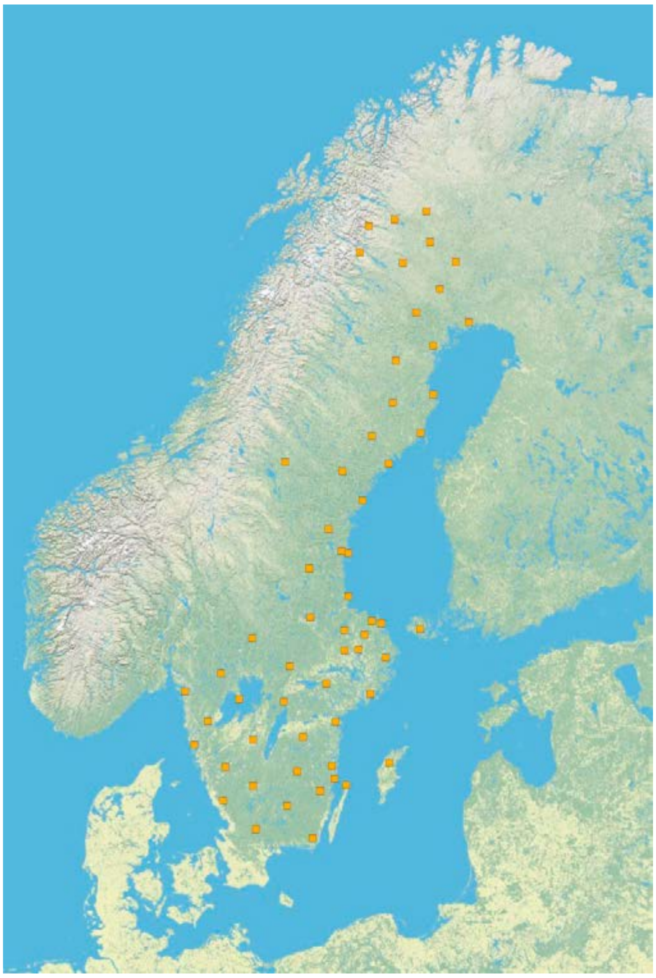

Figure 4-1. *Location of stations of the SNSN network.*

During the last decades, new techniques using radar images have been successively more elaborated, with new applications being discovered each year. One of these techniques, DInSAR, is able to resolve millimetre to, optimally, submillimetre vertical movements, and has been shown to be of great use in a number of geological applications (Samsonov et al. 2007, Guzzetti et al. 2009, Lanari et al. 2010). However, DInSAR has its limitations and, in contrast to GPS, measurements with DInSAR techniques resolve horizontal movements less precisely than vertical movements. Hence, a combination of GPS and DInSAR techniques constitutes a profitable approach for high-quality exploration of the 3D deformation characteristics of selected study areas, down to a submillimetre to millimetre per year resolution. This strategy has already been applied to the Forsmark site.

To sum up, the present section provides a presentation of the following four activities:

1. Seismic monitoring within the SNSN network.
2. Preparations for establishing a local, high-resolution seismic network.
3. GNSS monitoring.
4. DInSAR monitoring.

4.2.4 Seismic monitoring within the SNSN network

A project to condense and improve the national Swedish seismic monitoring network was initiated by the Department of Earth Sciences at Uppsala University in the late 1990s (Böðvarsson 1999). The first part of the network was put into operation in 1998 and consisted of six stations at approximately the same locations as those of the old, analogue, network constructed by Marcus Båth in the 1960s.

Twelve additional stations were installed along the coast of the Gulf of Bothnia in a separate project financed by the Swedish Natural Science Research Council (NFR), the Knut and Alice Wallenberg Foundation and SKB. Ever since, permanent stations have been installed at a steady pace with the latest permanent station installed at Ödesmark, near Burträsk in 2012. In addition, a number of temporary, mobile, stations are installed and currently in operation for specific studies beyond the general scope of SNSN (Karlsson et al. 2010, Juhlin and Lund 2011), at e.g. Pärvie and Burträsk.

One station, situated on the island of Gräsö, was in operation prior to the start of the Forsmark site investigations in 2002. During the first quarter of the year 2005, a new station was installed at drill site 4 within the Forsmark site investigation area, see Figure 4-2. The sensitivity of the SNSN network allows for complete recording of all earthquakes down to a magnitude of lower than 0.5 within the network and down to magnitude 0.0, or even a bit lower, near SKB´s investigation sites at Forsmark and Oskarshamn, after installation of the new stations.

The current long-term agreement (2012–2021) between SKB and Uppsala University states that the university (SKBdoc 1320451, SKB internal document) shall collect and analyse seismic data from the SNSN stations in operation and present the results to SKB in quarterly reports in the SKB P-series (e.g., Böðvarsson 2012). This has also, with a few exceptions, been the case since the third quarter of 2002 to the last quarter of 2011. After that, the same type of quarterly report has been written, but the reports have been assigned the status of SKB internal documents stored in SKB's file management system SKBdoc. For example, the quarterly reports of the year 2015 are found in Böðvarsson (2015a, b, c, 2016).

These quarterly reports provide fundamental information about seismic events including origin time, hypocentre location and information about the source parameters. At commencement of this commission for SKB in 2002, the number of SNSN stations was 34, and as mentioned previously the number had by the end of 2014 increased to 67 stations (Figure 4-1). With such a seismometer density, sensitivity and quality control, the network is state-of-the-art also with international measures.

An essential part of the routine analyses made by Uppsala University is the discrimination of explosions, caused by mining, infrastructure and military activities, from true earthquakes triggered by natural processes. Explosions and induced earthquakes are eliminated from the statistics of natural earthquakes and are not included in the routine reporting or the Sicada database. In the quarterly reports from Uppsala University the exact time, epicentre latitude and longitude, epicentre X- and Y-coordinates, hypocentre depth and local magnitude are presented for every registered earthquake during the three months that each report covers.

Figure 4-2. Top of concrete silo containing the SNSN seismic station near drill site 4 at Forsmark.

Table 4-1 summarises some important results from 13 years of continuous monitoring using the SNSN network (i.e. from late 2002 until the end of 2015). Because the number of seismic stations has successively increased during the monitoring period, consecutively more seismic data have been captured and the table demonstrates, with some scatter, a tendency for increasing numbers of registered events and real earthquakes, i.e. earthquakes not caused by e.g. blasting by the mining industry, which is the cause of the large majority of registrations. During the last 4 years, between c. 9000 and 12000 events (including blasting) have been registered yearly by the network stations. The number of real earthquakes is within the approximate interval 550–750 per year.

Table 4-1. Some important results from the seismic monitoring at Forsmark within the SNSN network between 2002 and 2015.

Year	Events	Real earthquakes	No. of magnitude ≥ 1.0	Maximum local magnitude (M_L)	Hypocentre depth intervals (km)	Epicentre positions of largest earthquakes
2002 Q3–Q4	–	121	22	3.3	0–34.6	100 km S Gotland
2003 Q1–Q2, Q4	–	237	54	3.0	0.1–34.6	Between Svenljunga and Tranemo
2004	7024	526	97	5.2	0.1–43.2	260 km SE Gotland
2005	4526	476	117	3.2	0–40.6	188 NW Östersund
2006 Q1–Q3	4137	346	118	2.5 (2)	0–35.8	25 km NV Vänersborg and 84 km NW Jokkmokk
2007	3966	335	98	2.7	0–37.3	12 km S Skara
2008	4617	315	86	4.4	0.1–49.6	20 km E Staffanstorp
2009 Q1–Q2,Q4	5101	425	69	3.1	0.1–49.3	13 km W Kalix
2010 Q2–Q4	7910	583	68	3.5 (2)	0.1–39.2	31 km SE Skellefteå
2011	9083	547	100	2.8	0.1–45.8	31 km SW Falkenberg and 22 km NW Robertsfors
2012	11722	725	95	4.1	0.1–43.7	40 km SW Falkenberg
2013	11495	724	89	2.9	0.1–49.5	3 km S Kiruna
2014	12658	643	115	4.1	0.1–34.5	18 km SE of Östansjö or 74 km north of Mora
2015 Q1	3154	200	33	3.0	0.1–32.9	19 km SE of Skellefteå

The number of annual earthquakes with a local magnitude $M_L \geq 1.0$ is relatively stable around 90–100. Magnitudes exceeding 3.0 are rare (Figure 4-3). The largest registered earthquake up to now was of magnitude $M_L = 5.2$ and occurred on September 21st, 2004, in Kaliningrad, outside the SNSN network, but only 260 km SE of Barshageudd on the island of Gotland. This earthquake was preceded by a fore-shock with magnitude 4.7 and one aftershock reaching magnitude 3.0. The main-shock and the fore-shock were felt in large parts of southern Sweden. The detected hypocentre depths from the SNSN monitoring vary within the interval 0–49.6 km (Table 4-1).

Finally, the following earthquakes may be worth mentioning due to their relative proximity to Forsmark:

- An earthquake with magnitude $M_L = 2.2$ and hypocentre depth 1.3 km occurred on Kungsholmen in Stockholm city on May 24th, 2006. This earthquake was felt by many persons living in the area.
- An earthquake occurring on June 6th, 2006, with magnitude $M_L = 2.0$ and depth 7.4 km, located 28 km east of Gräsö in Uppland.
- An earthquake in Gamla Stan in Stockholm on August 18th, 2007, with magnitude $M_L = 1.3$ and depth 2.4 km.
- An earthquake with magnitude $M_L = 2.1$ and the depth c. 15 km located in the Stockholm archipelago occurred about 11 km southeast of Blidö on December 10th, 2013.

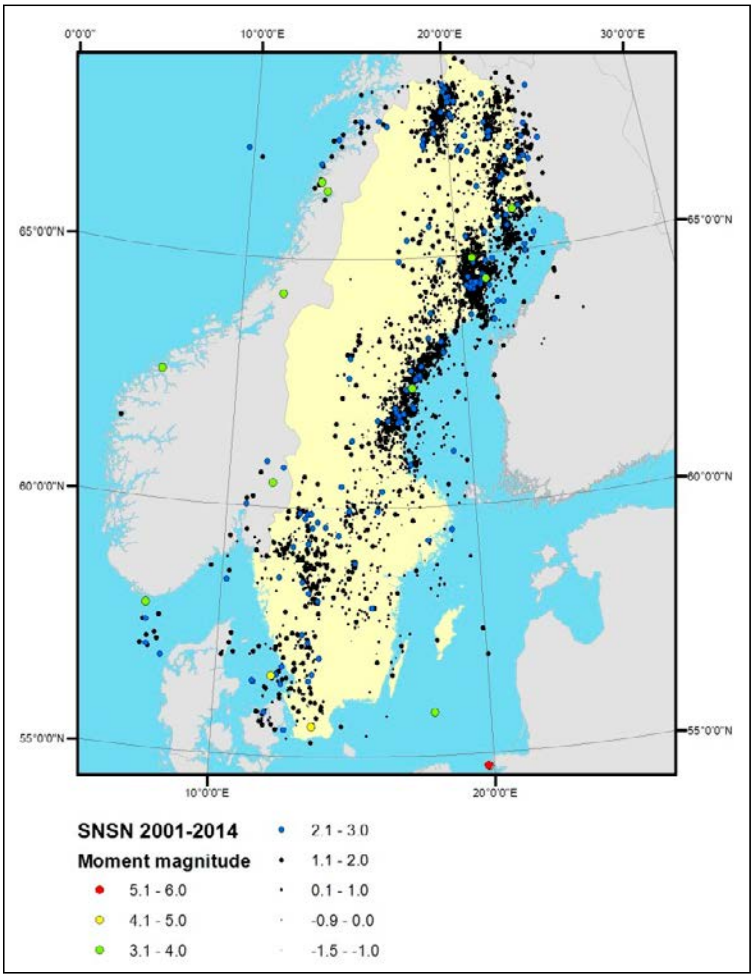

Figure 4-3. Earthquake activity recorded by SNSN during the period 2002–2014.

4.2.5 Preparations for establishing a nano-seismic network at Forsmark

The SNSN network is appropriate for the characterisation of seismic activity on a regional or nation-wide scale and has hitherto provided unprecedented insights into Swedish seismicity. Besides covering the major part of Sweden, the network is capable of capturing seismic events from a considerable part of the neighbouring countries Norway, Denmark, Finland and the Baltic states. The resolution of the system permits the study of earthquakes with as small a magnitude as down to, or even a bit below –1, with a reasonable level of completeness down to roughly magnitude 0. However, the Forsmark area is also by Swedish standards characterised by very low seismic activity (Böðvarsson et al. 2006) and in order to capture the natural seismicity within a reasonable timeframe, in terms of location and magnitude, it is essential to drastically increase sensitivity and resolution.

A local seismic network has multiple purposes and various, quite disparate, end-users will benefit from such monitoring in the following ways.

- The information is necessary to ensure operational safety related to the underground constructions, by monitoring precursors to spalling or rock bursts and evaluation of such events should they have occurred. Additionally, indirect information such as stress orientations and, optimally, stress magnitudes can be deduced from the network and used as input to refining the repository layout.
- The seismic information can be used to fine-tune/calibrate the structural model of the repository volume.
- Post-glacial seismicity and associated shear displacements are a significant issue in post-closure safety, and improvements to the structural model and in estimates of the long-term rate of strain with aid of the nano-seismic network can inform the estimation of post-glacial seismicity.
- The expected public interest in the repository and safety aspects related to its construction imposes high demands on transparency and scientific stringency on SKB in its communication with authorities, NGOs, media and the general public. There are no requirements from the regulator (SSM) in terms of nuclear safeguards.

The detailed and adequately handled seismic information emanating from such a network will therefore constitute a vital foundation. The local seismic network will fulfil the following goals:

- Provide detailed knowledge of naturally occurring earthquakes in the Forsmark area.
- Contribute to calibration and improvement of the structural model of the site.
- Contribute to increased understanding of the local stress field at Forsmark.
- Integrate with the operational safety system.
- Contribute to effective excavation of the repository components.

For this network we propose the term "*nano-seismic network*" (see e.g. Joswig 2008) since we aim for the acquisition and processing of seismic waves generated by sources which are two to three magnitudes below the target of the standard micro-seismic networks. In terms of seismic magnitude, it corresponds to ranges down to M_L –3.0, for source to sensor distances of 10 m to 10 km. During the last few years, SKB has planned and prepared for establishing such a nano-seismic network at the Forsmark site. However, this task is challenged by the following considerations.

- Seismometers with a sensitivity of this level are non-conventional devices that are produced only by a few specialised manufacturers in the world in short series. A first step in the preparations for establishing a nano-seismic network is to make an inventory of current producers of seismometer systems with sufficient sensitivity, long-term durability and data collection capacity to fulfil the demands for monitoring at Forsmark.
- Seismic and electric (electromagnetic) background noise needs to be quantified, possibly also monitored, to enable the construction of adequate filters.
- The seismometers need to be placed with due attention to the (local) geology, in terms of its deformation zones, fracture domains and inherent fracture networks to adequately account for attenuation of the seismic waves and distortions of signals, and optimally located with respect to planned repository components to maximise its intended purpose.

- Education and training of staff for long-term management of the network. This group of people shall supervise the system regarding functionality and data quality, and perform due maintenance and technical service. However, the emphasis should be to consecutively perform analyses, documentation and presentation of seismic data, possibly supported by expertise from Uppsala University.

In order to determine which type of seismic sensors will give optimum performance in the repository volume, and how these should be located in relation to local geology and repository layout, it is necessary to know the level and frequency content of the seismic background signals. Therefore a study of this complex of problems was made at Forsmark during 2010–2012 (Lund et al. 2012) and an additional study was performed in 2013 (Lund et al. 2017).

The instrumentation used in Lund et al. (2012) permitted study of frequencies up to 500 Hz. The seismic data show that the Forsmark nuclear power plant produces a significant amount of seismic energy. Most of this energy is emitted below 100 Hz, with pronounced peaks at 50 Hz and 100 Hz (Figure 4-4). However, there is both significant energy in narrow bands further up in the spectrum and a generally elevated level of background noise compared to normal Swedish background levels. It was also noted that the amplitudes of the power-plant-produced signals varied significantly in time.

Electromagnetic noise impacts the performance of electric cables and electronic components associated with the seismic equipment. Measurements of the horizontal magnetic field in Forsmark on December 29^{th}, 2009 (Lund et al. 2012) showed strong spectral peaks at 50 Hz and harmonics (100 Hz, 150 Hz, 200 Hz, and so on, see Figure 4-5), mostly due to the power generation in the nuclear power plant. There are also peaks at 16.67 Hz and harmonics, probably emanating from the closest electrified railway line, i.e. the one between Uppsala and Gävle situated about 37 km west of Forsmark, which adds energy also in the 50 Hz and associated harmonics peaks. The peaks at 66.7 Hz, 83.3 Hz, 116.7 Hz, 133.3 Hz, and so on, are all harmonics of the 16.67 Hz fundamental frequency.

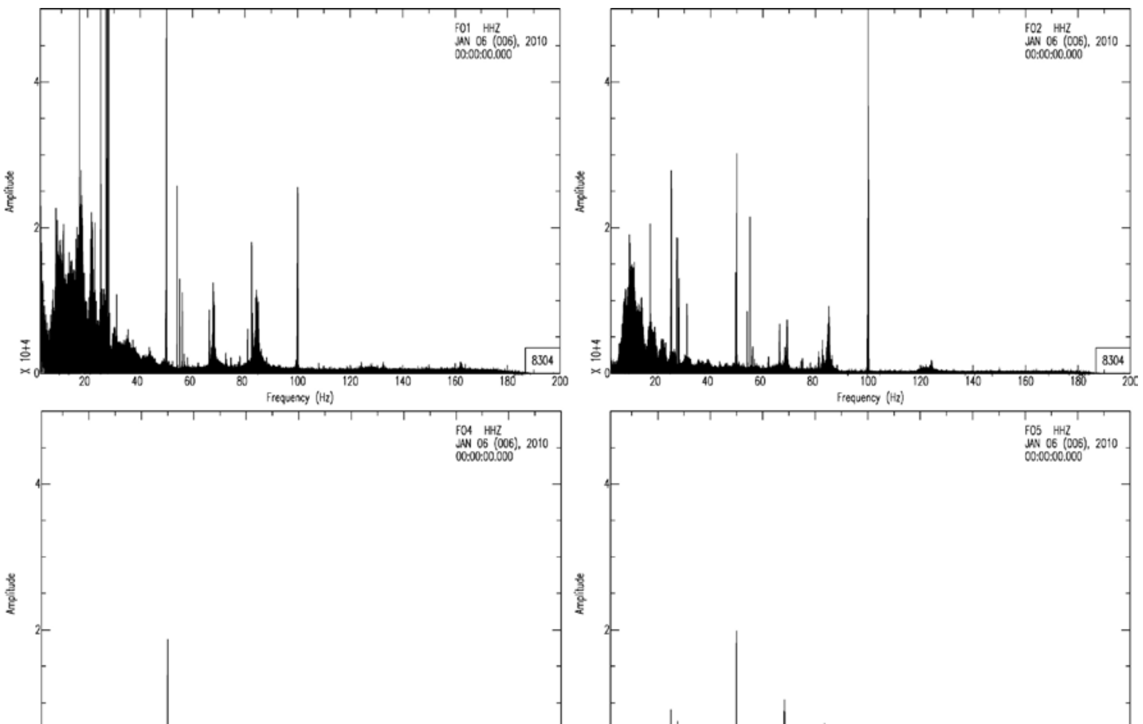

***Figure 4-4.** Frequency content of the seismic signal recorded during 24 hours on January 6th, 2010, at four temporary seismic stations at Forsmark, FO1 (upper left), FO2 (upper right), FO4 (lower left), and FO5 (lower right). The figures show true ground velocity in nm/s (Figure 3-2 in Lund et al. 2012).*

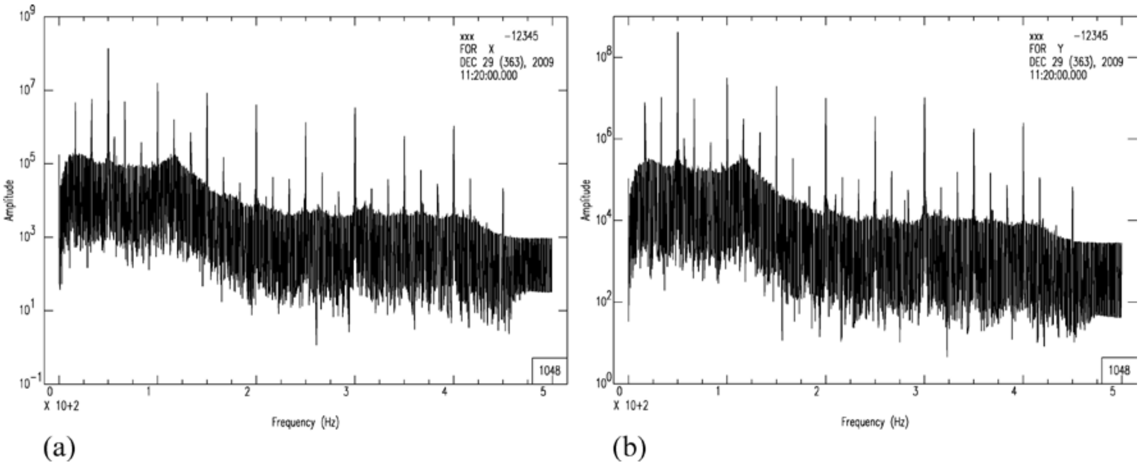

Figure 4-5. *Spectra (FFT) of the two horizontal components of the magnetic field at Forsmark at 11:20 to 11:40 on December 29th, 2009. (a) magnetic north, and (b) magnetic east (Figure 3-5 in Lund et al. 2012).*

It is obvious from the measurements that the noise in the Forsmark area is considerably higher than ideal for nano-seismic monitoring. In order to select adequate sensors, it is necessary to conduct instrument tests in the Forsmark area, see further Section 8.1.2. Only preliminary discussions have so far been held concerning preparations for management of the local seismic network. We emphasise that the recruitment process and training of the staff may be rather time consuming.

In 2013, a new study with geophones and accelerometers was performed in Forsmark (Lund et al. 2017). This project, which is part of a series of projects to prepare for the high resolution seismic network, had three objectives: (i) to investigate the seismic background signals in the Forsmark area at higher frequencies, up to about 10 kHz, (ii) to study what sensitivity the instrumentation would need in order to operate well in the noisy environment, (iii) to test how well custom-made sensors from IMS (Institute for Mine Seismology) perform in the Forsmark environment.

Three borehole sensors were bought from IMS, containing both a five-element geophone assembly and an accelerometer. The sensors were connected to data loggers rented from IMS, with 24-bit digitisers, GPS-timing and data storage on USB sticks. During the project the instrumentation was thoroughly tested in the laboratory at SNSN at Uppsala University and used in temporary installations in boreholes at six locations in Forsmark (Figure 4-6).

In response to objective (iii), Uppsala University found that the IMS geophone instrumentation picks up the high background noise levels around the Forsmark nuclear power plant and also registers the high amplitude spectral peaks emanating from the power generation at larger distances. However, due to the electronic noise in the digitiser, the instruments could not register the quiet background ground motion above approximately 200 Hz. The use of five-element coil geophones though implied a considerable improvement compared to single-element coils. The latter would have been restricted to record merely the highest amplitude spectral peaks of the background noise at the measurement point furthest from the power plants, and only those within the approximate interval 6–40 Hz. The accelerometers delivered by IMS, and their matching to the digitisers, were insufficient to register the quiet background noise in any frequency range.

For objective (i), the nuclear power plant emits significant seismic energy in a wide frequency band from the lowest frequencies detectable by the geophones (14 Hz natural frequency) up to at least 150 Hz. In addition, narrow band signals at 50 Hz and overtones all the way up to 950 Hz could be detected at all measurement sites, and there were additional high amplitude narrow frequency band signals coming from the power plants (example shown in Figure 4-7). No sustained wider-band high-amplitude signals above 400 Hz were detected. Above the frequencies where the geophones perform reliably, approximately 2 kHz, the results concerning the noise levels are uncertain as the accelerometer performed poorly. However, regarding the investigations of the accelerometer signals, it is unlikely that there would be sustained, high-amplitude, accelerations in the 2–12 kHz band.

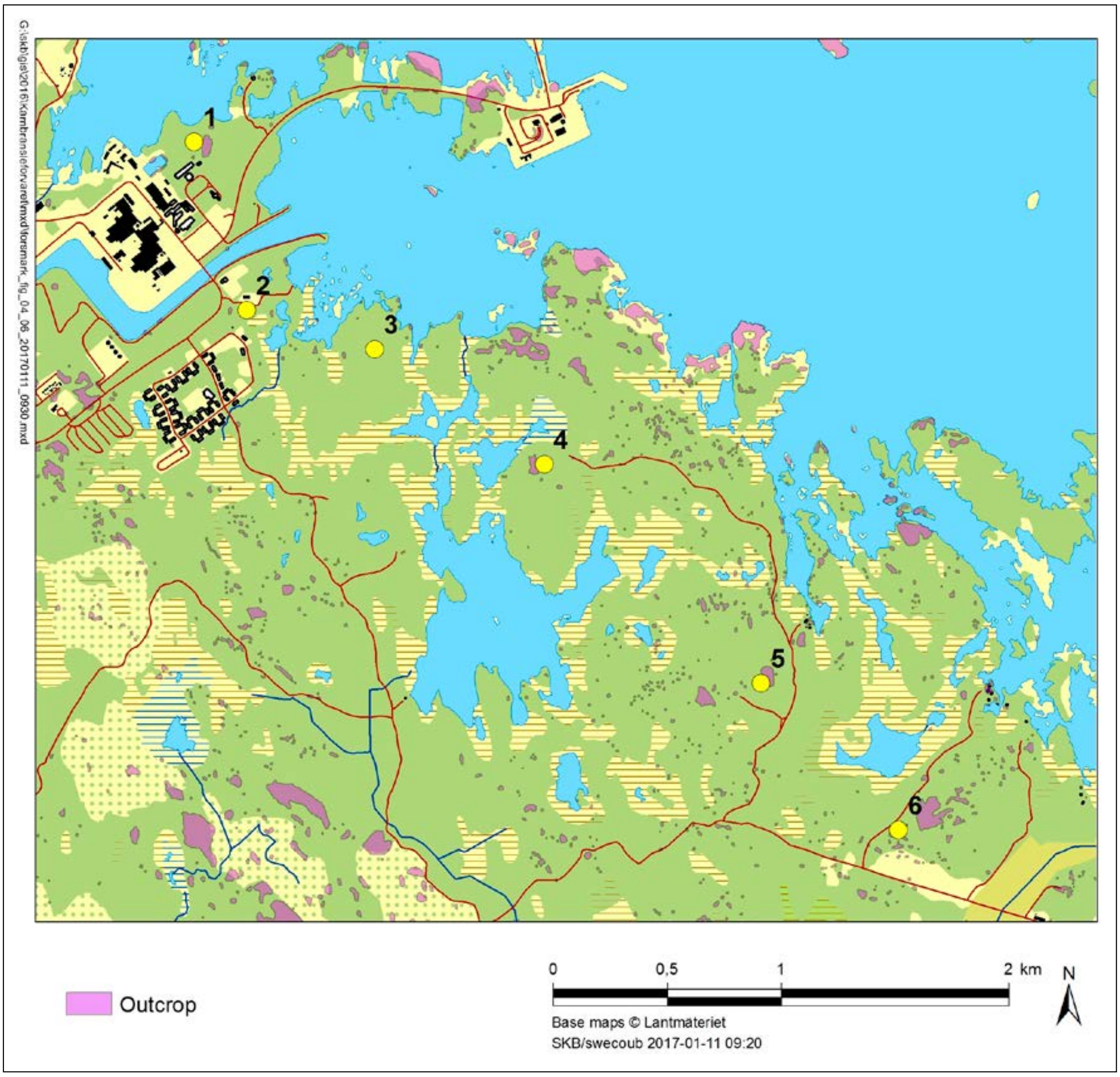

Figure 4-6. *Map of the Forsmark area with the six borehole-sensor measurement sites. Site 1 is very close to the nuclear reactors Forsmark 1 and 2. Site 6 is the most distant site from the power plants (Lund et al. 2017).*

As indicated above, in response to objective (ii) it was found, that in order to record true ground motion at higher frequencies, geophones need to have nominal sensitivity higher than the 80 V/m/s of single-element sensor coils used for standard IMS sensors. In order to record true ground motion over the whole proposed repository area, geophones should have a nominal sensitivity of at least 400 V/m/s, given the noise characteristics of the IMS digitiser. An additional, external high-quality pre-amplifier would also provide increased sensitivity. Geophones typically perform well up to frequencies of approximately 2 kHz. For higher frequencies accelerometers would be necessary. However, to record high-frequency accelerations well would need significantly better equipment than that tested in this project. Both the preamplifier/digitising step and the accelerometer sensitivity would need to be improved. The type of instrumentation needed for the repository network depends not only on the seismic background environment but also on factors such as the desired detection level, station density and rock type.

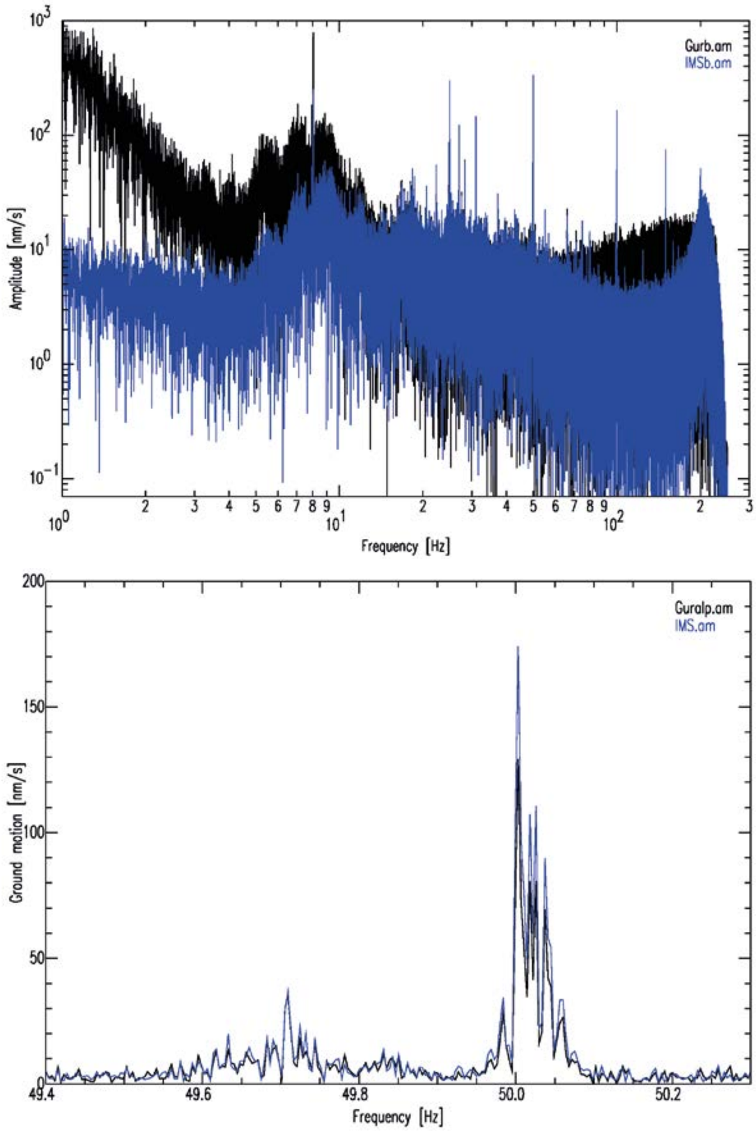

__Figure 4-7.__ Spectra of background seismic signals at site 6 in Forsmark, 10 minutes of data at 00:30 GMT on November 28, 2014. Vertical component of Guralp Compact (black) and IMS geophone (blue). Amplitude in ground motion [nm/s]. Top: Frequency content from 1 Hz to 150 Hz, logarithmic axes. Bottom: Zoom in around 50 Hz (49.4 – 50.4 Hz) with linear plot axes (Lund et al. 2017).

SKB has initiated a dedicated study to optimise the configuration of the network in terms of sensitivity and resolution, given the local conditions at Forsmark. The work is on-going, but preliminary results indicate that a first phase of monitoring may be proposed as in Figure 4-8. The first phase of monitoring is intended to cover a general area over the proposed repository and detect microseismic events down to moment magnitude (Mw) –1 or better. The intention of phase 1 is to better understand background seismicity and noise levels in the area before expanding the array to reach the final target magnitude detection of Mw > –3 or better.

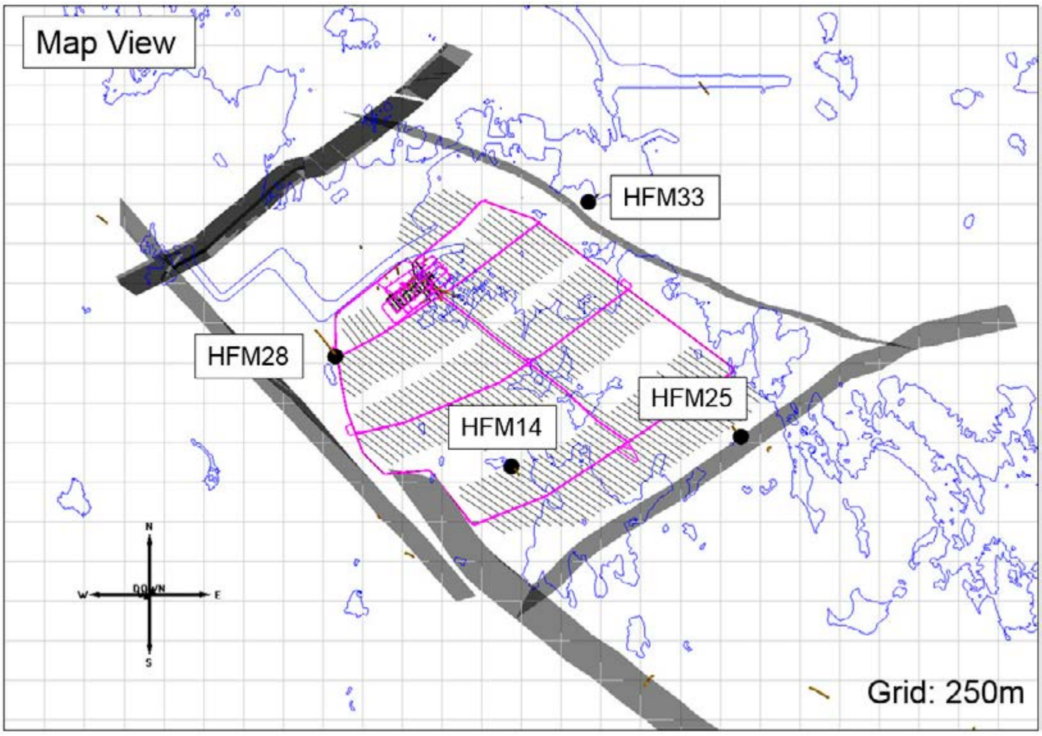

***Figure 4-8.** Map view of proposed array configuration 1 for phase 1. Four boreholes were selected for the sensors: HFM14, HFM25, HFM28 and HFM33. Near vertical deformation zones selected to guide sensor positioning are also highlighted; only HFM33 extends outside of the optimal area.*

4.2.6 GNSS monitoring

Method prerequisites and limitations

Registrations of horizontal and vertical bedrock movements using the GNSS (Global Navigation Satellite System) technique started at Forsmark in November 2005 (Figure 4-9). The specific system employed was GPS (Global Positioning System), which at the measurement period 2005–2009 was the only fully developed and maintained GNSS system. Today also GLONASS (Globalnaya Navigationnaya Sputnikovaya Sistema or Global Navigation Satellite System) is available. Furthermore, the European Galileo system as well as the Chinese Beidou system and the IRNSS (Indian Regional Navigation Satellite System) are under development. The GNSS technology makes use of electromagnetic waves within the radio frequency band 3 kHz–300 GHz. The commonly used GPS L1 and L2 bands operate at c. 1.6 GHz and 1.2 GHz, respectively. Distances between satellites and objects on the earth are determined by one-way measurements.

The main purpose of the aseismic deformation monitoring is to measure the rate of relative motion of larger rock blocks. The required accuracy is c. one millimetre per year, or preferably less, in order to thereby indirectly estimate the long-term slip along boundaries, i.e. the deformation zones. GPS monitoring is one of a limited number of methods suitable for this purpose. By positioning a GPS network such that individual sampling stations straddle major deformation zones, the crustal deformation along these ideally can be recorded with very high precision. This is due to several advantages associated with the GPS technique, e.g. that distances between data sampling stations are not limited to the local scale, there is no need for inter-station visibility and accuracies are normally superior to those of traditional methods (Poutanen et al. 2010).

However, the vertical accuracy is degraded by the fact that observing satellites are above, never below the horizon. This results in a known geometrical dilution of the accuracy for any specific satellite constellation (Levitan and Harte 2009). Averaged over all orbits, which is done by considering a period of 24 hours, the error is approximately a factor 1.5 larger in the vertical direction than in the horizontal plane near the equator. The horizontal locations at the latitude of Forsmark are also degraded due to satellite orbital inclinations of 55 degrees for all modern GPS satellites.

***Figure 4-9.** Sampling station at Forsmark with a choke ring antenna and GPS receiver mounted to the lower left. All stations are attached to a short steel rod anchored to the rock for good mechanical and thermal stability. The selection of the GPS sampling sites at Forsmark was based on geological assessments as well as on considerations about sky visibility and nearby natural or man-made reflectors (Figure 3-1 in Gustafson and Ljungberg 2010).*

Every other error source affects all directions equally, in practice, since effects of multipath and antenna phase centre are eliminated in the post processing. As a result, the accuracy is best in Easting, lower in Northing (although some satellites can be tracked over the pole), while the vertical is the least accurate (Ekman and Ekman 2013).

Field activities

A network of seven GPS sampling stations was established at Forsmark, on three major rock blocks, explicitly on different sides of the three major deformation zones that intersect the Forsmark region in a northwest-southeast direction, namely the Singö, Eckarfjärden and Forsmark deformation zones. The identification numbers and positions of all seven stations are marked on the map in Figure 4-10. GPS monitoring, performed as intermittent measurement operations with a duration of 3–7 days per campaign, was then initiated, starting in November 2005. During the following years the measurements were presented in annual reports (Gustafson and Ljungberg 2007, 2008, 2009). The GPS monitoring was discontinued after December 2009.

Data handling and preliminary evaluation

Data from all field campaigns are stored in Sicada. After the campaign in December 2009, the survey was interrupted for evaluation of the measurements performed so far, and the results were presented in a summary report (Gustafson and Ljungberg 2010), including assessment of measurement performance and an analysis of the validity of data from the entire four-year data collection period.

The data set displays a considerable scatter, indicating a complex, sinusoidal variability versus time, see examples in Figure 4-11. The goals of the Gustafson and Ljungberg (2010) study did, however, not include any comprehensive analysis of this phenomenon, and the interpretation of the long-term baseline motions was restricted to standard linear regression. Not only the GPS measurements at Forsmark, but also those at Äspö/Laxemar and the GPS measurements at several sites in Finland, Olkiluoto, Kivetty, Rumovaara and Satakunta (Ahola et al. 2008, Poutanen et al. 2010) indicate a sinusoidal variability which not yet has been unambiguously explained. This variability, the magnitude of which differs somewhat between sites, could be caused by still unknown random or systematic measurement or data processing errors, and hence not represent true changes of the baseline lengths.

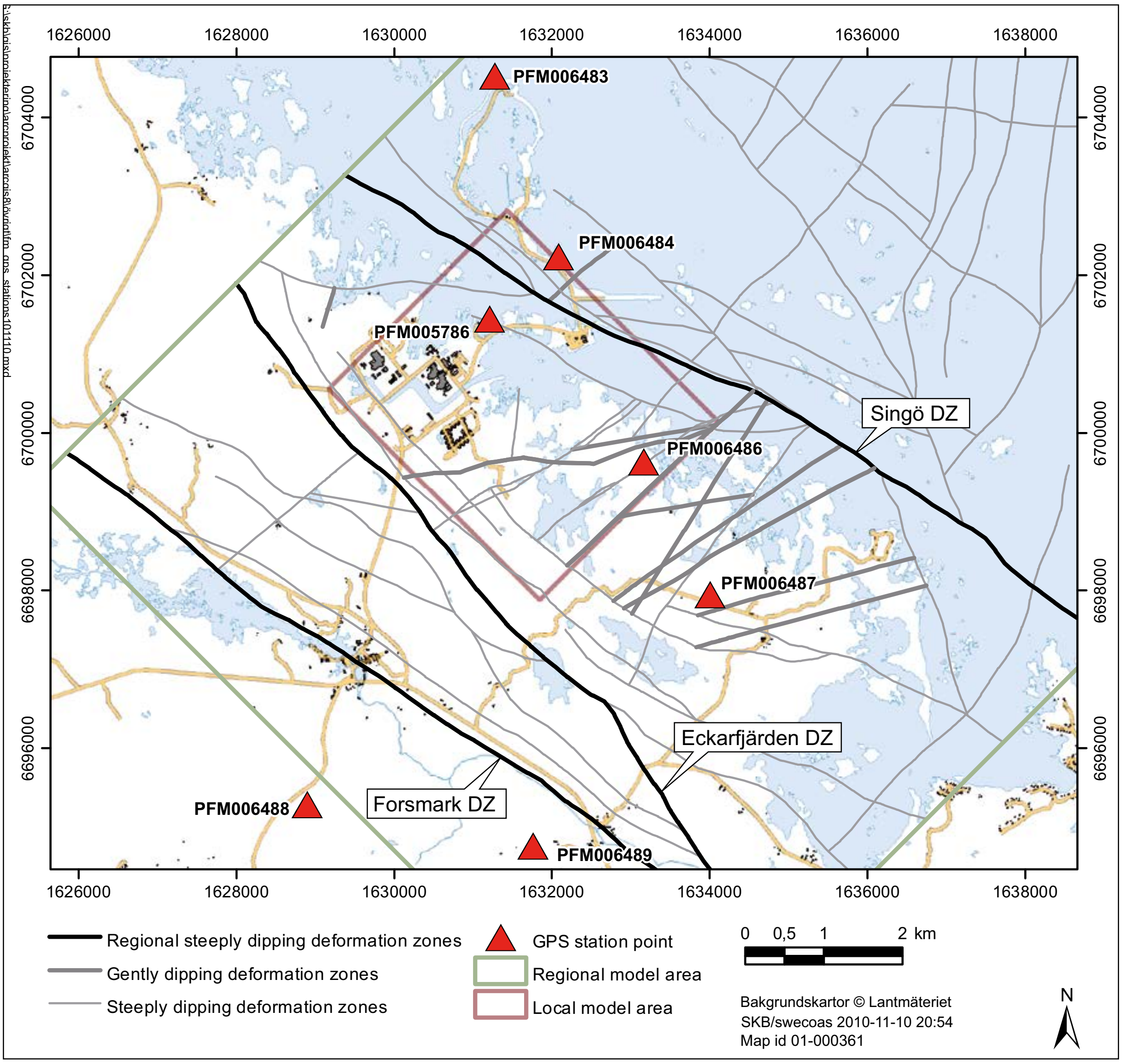

Figure 4-10. *General overview of the Forsmark site investigation area with the seven GPS sampling stations (Figure 1-1 in Gustafson and Ljungberg 2010).*

Another possibility, suggested by Ollikainen et al. (2004) is that the sinusoidal pattern may be explained by time-dependent, more or less cyclic meteorological and hydrological changes like variations in air pressure, snow cover, soil moisture and ocean water level. These factors may be regarded as a loading-unloading effect with a permanent but varying influence on the earth crust.

Also cyclic gravitational forces caused by the moon, the sun and some other planets, primarily Venus and Jupiter, exert an influence on the earth. Clear effects of these forces are observed as, for example, small variations (tidal effects) in groundwater levels in many boreholes at Forsmark, see e.g. Gokall-Norman and Ludvigson (2007). If the impact of these fluctuating stresses on the earth crust at Forsmark is indeed detectable by GPS technique is, however, a question not yet thoroughly answered.

The variability of the baseline lengths observed in the Forsmark results displays a similar sinusoidal pattern for all baselines, see Figure 4-11. It was judged to be of interest to make an effort to take the analysis of the Forsmark GPS data one step further than the analysis presented in Gustavsson and Ljungberg (2010), and a refined statistical analysis of measurement data by employing five different analysis techniques, three methods of linear regression and two methods of auto regressive modelling, was initiated and later presented in Ekman and Ekman (2013). The models applied differ regarding parametrization and model order.

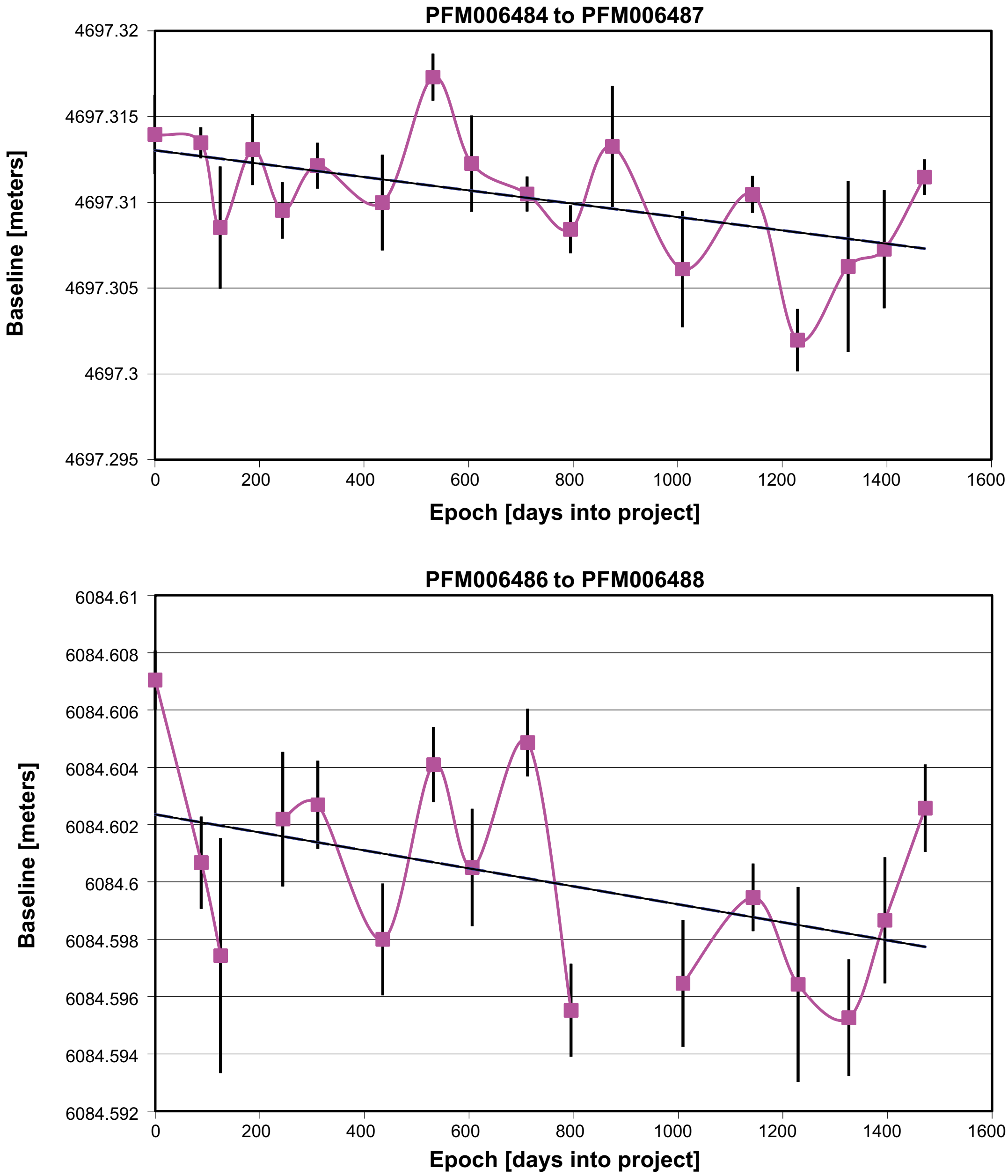

Figure 4-11. *Variation in baseline length between stations PFM006484 and PFM006487 (top) and stations PFM006486 and PFM006488 (bottom), which are two almost perpendicular baselines as a function of days into the project. A similar pattern of variations were observed for all baseline lengths (Figures 6-2 h and 6-2 m in Gustafson and Ljungberg 2010).*

The aim of this analysis was to test the robustness of the results obtained so far from the Forsmark GPS monitoring and, if possible, increase data confidence. In spite of applying different modelling methods, consistent estimates of the linear trend would be expected, even if the variances of the baseline motions are large, as long as they are driven by white noise processes. On the other hand, if data are not driven by white noise, i.e. if there still remains some unmodelled dynamics, or even if data are driven solely by white noise processes, but the time-series is too short, one would expect that analysis by different methods would entail more or less different results. This is due to the fact that different models may converge towards the "true" solution by different rates.

The working hypothesis in Ekman and Ekman (2013) is that the baseline velocities are characterised by a long-term linear drift, superposed by a non-linear sinusoidal motion of an origin not fully understood. This was a major challenge in the data analysis, which complicates the estimation of the long-term linear motions, especially as there appeared to be a shortage of data (see below). For instance, the disturbing impact of possible outliers in a data set is a more severe problem for short than for longer time-series of data. The main strategy in Ekman and Ekman (2013) was to model both the linear and the non-linear behaviour of the baseline velocities. In order to overcome data shortages as much as possible, the non-linear model was used to reduce the variance of the long-term linear trend estimates, thereby hopefully increasing reliability of the estimation of long-term rock-block motions.

Results

The statistical analysis described in the previous section resulted in rather big differences between the different analysis methods applied (Ekman and Ekman 2013), hence indicating a poor robustness of the Forsmark GPS results. The section "Data confidence" below highlights some disadvantages linked to the performance of the measurements at Forsmark, as well as to those performed at other sites employing the same methodology, and with which the results at Forsmark are compared. The main factors that may decrease data confidence are too short measurement period and the aliasing effect, i.e. that the sampling rate of the sinusoidal signal is not high enough. These factors in combination are supposed to have restricted the prospect of obtaining entirely satisfactory estimates of the long-term linear motions at Forsmark.

However, despite possible measurement, data processing and analysis shortcomings, the results obtained so far should be accounted for. In the present section the results gained by the five different analysis methods applied are presented and commented on together with brief remarks regarding the results from some other sites in Sweden and Finland.

The preliminary yearly changes of the Forsmark baseline lengths in Gustafson and Ljungberg (2010), representing the bedrock motion between the seven GPS stations illustrated in Figure 4-10, are in Ekman and Ekman (2013) compared to the corresponding results from the new analyses comprising linear regression according to LS[1], two varieties of BLUE[2] (BLUE-Berne and BLUE-RMS) together with results from AR[3]- and ARMA[4]-modelling, see Table 4-2.

The overall conclusion regarding linear regression (columns 3, 4, 5 and 6 in Table 4-2) is that the results from all three methods correspond well, which in spite of too short data series is to be expected, since the methodological differences between the calculations are small. Most baselines display motion rates larger than –1 mm/year, and several baselines point towards motions even exceeding or equal to –2 mm/year. All values except one (BLUE RMS between stations PFM006486 and PFM006487) are negative, indicating contraction of the investigated area.

Columns 7 and 8 in Table 4-2 present the linear trend results of baseline length changes after AR- and ARMA-modelling, including new linear trend estimates. The results confirmed that there are some sinusoidal motions that can be satisfactorily captured by the AR and ARMA models. The linear trend estimates demonstrate at least one order of magnitude smaller long-term linear motions for a majority of the baselines compared to the results from the linear regression trend estimations. Furthermore, the linear motions from the AR-modelling are for some baselines significantly different from the corresponding estimated linear trends from the ARMA-modelling. This is not surprising, because the structures of these two models differ relatively much. In the AR-modelling the slopes of the baseline curves are all negative (this is in line with the results from the linear regression estimations), whereas in the ARMA-modelling some of the slopes were positive.

1 Least Square model.

2 Best Linear Unbiased Estimate model.

3 Autoregressive model, a special case of the ARMA model.

4 Autoregressive–moving-average model.

Table 4-2. Comparison of baseline length changes at Forsmark.

From	To	Baseline change [mm/yr]					
		Gustafson and Ljungberg 2010	LS	BLUE-Berne	BLUE-RMS	AR-modelling	ARMA-modelling
PFM006483	PFM006484	–1.1	–1.37	–1.33	–1.20	–0.05	–0.06
PFM006483	PFM006486	–2.3	–2.40	–2.23	–2.25	–0.12	0.05
PFM006483	PFM006487	–2.5	–2.44	–2.43	–1.91	–0.09	–0.16
PFM006483	PFM006488	–2.0	–1.89	–2.11	–2.62	–0.04	–0.12
PFM006483	PFM006489	–2.1	–2.59	–2.79	–2.84	–0.05	0.22
PFM006483	PFM005786	–1.7	–1.96	–1.70	–2.53	–	–
PFM006484	PFM006486	–1.2	–1.33	–1.22	–1.44	–0.07	0.15
PFM006484	PFM006487	–1.4	–1.36	–1.36	–0.91	–0.04	–0.06
PFM006484	PFM006488	–1.7	–2.02	–1.92	–2.49	–0.03	0.05
PFM006484	PFM006489	–1.3	–2.01	–1.87	–2.28	–0.01	0.30
PFM006484	PFM005786	–1.9	–1.49	–1.24	–2.32	– *	– *
PFM006486	PFM006487	–0.3	–0.03	–0.10	0.46	– *	– *
PFM006486	PFM006488	–1.1	–1.36	–1.29	–0.83	–0.02	–0.07
PFM006486	PFM006489	–0.3	–0.89	–0.96	–1.93	–0.03	0.07
PFM006486	PFM005786	–2.3	–2.44	–2.34	–2.17	– *	– *
PFM006487	PFM006488	–1.9	–2.12	–1.83	–2.20	–0.06	0.05
PFM006487	PFM006489	–0.6	–1.33	–1.02	–1.71	–0.01	0.24
PFM006487	PFM005786	–1.8	–1.36	–1.64	–1.64	– *	– *
PFM006488	PFM006489	–1.1	–1.32	–1.31	–1.20	–0.04	–0.02
PFM006488	PFM005786	–0.3	–1.01	–1.29	–1.38	– *	– *
PFM006489	PFM005786	–0.6	–1.71	–1.98	–2.35	– *	– *

* Discarded due to non-significant linear trend.

The results from linear regression indicate, with some exceptions, bedrock motions at Forsmark of the same order of magnitude as for several of the baselines in the Äspö/Laxemar area as presented in Sjöberg et al. (2004). However, the AR- and ARMA-modelling indicate crustal motion rates at Forsmark of the same order of magnitude as at Olkiluoto, Kivetty, Romuvaara and Satakunta, Finland (Ahola et al. 2008, Poutanen et al. 2010), in other words motion rates at least one order of magnitude smaller than those presented in Gustafson and Ljungberg (2010) and some of the baselines in Sjöberg et al. (2004). Figure 4-12 is a graphical presentation of the estimated annual changes of the baseline lengths shown in Table 4-2.

It may also be of interest to compare the Forsmark results with those obtained in the so called BIFROST project (Scherneck et al. 2002). In this project direct observations of large-scale surface deformation have been carried out in Sweden since 1993, using permanent, continuous GPS receivers. The project has produced high quality estimates of deformation rates which correlate very well with those obtained from glacial rebound modelling. In the residuals between model and observations there are indications of relative displacement between the stations. Although these displacements are less than one mm/year, should they be fault movements they indicate deformations orders of magnitude larger than can be explained by seismic data. This deformation is therefore interpreted to be aseismic. Earthquake data from the 1980s have earlier been interpreted as indicating aseismic movement of the order 1 mm/year/100 km in southern Sweden (Slunga 1991, Böðvarsson et al. 2006).

Finally, the analysis in Ekman and Ekman (2013) demonstrated that the demanded accuracy for the GPS measurements was achieved by the GPS campaign 2005–2009, but that the motions are more complex than the linear drift supposed à priori. Possible cyclic variations with frequency maxima at c. 0.3, 0.8 and 1.8 cycles/year are implied. Whether these variations will remain stable over a longer period of observations is not known. The underlying causes are also unknown. Speculations about cyclic meteorological and hydrogeological changes as well as cyclic gravitational forces influencing the earth can be found in the literature (see section "Data handling and preliminary evaluation"), but other external perturbations or random errors cannot be excluded as explanations. However, data confidence can to some degree be doubted (see next section) and to improve reliability, future GNSS monitoring should be modified in a way described in Section 8.1.3.

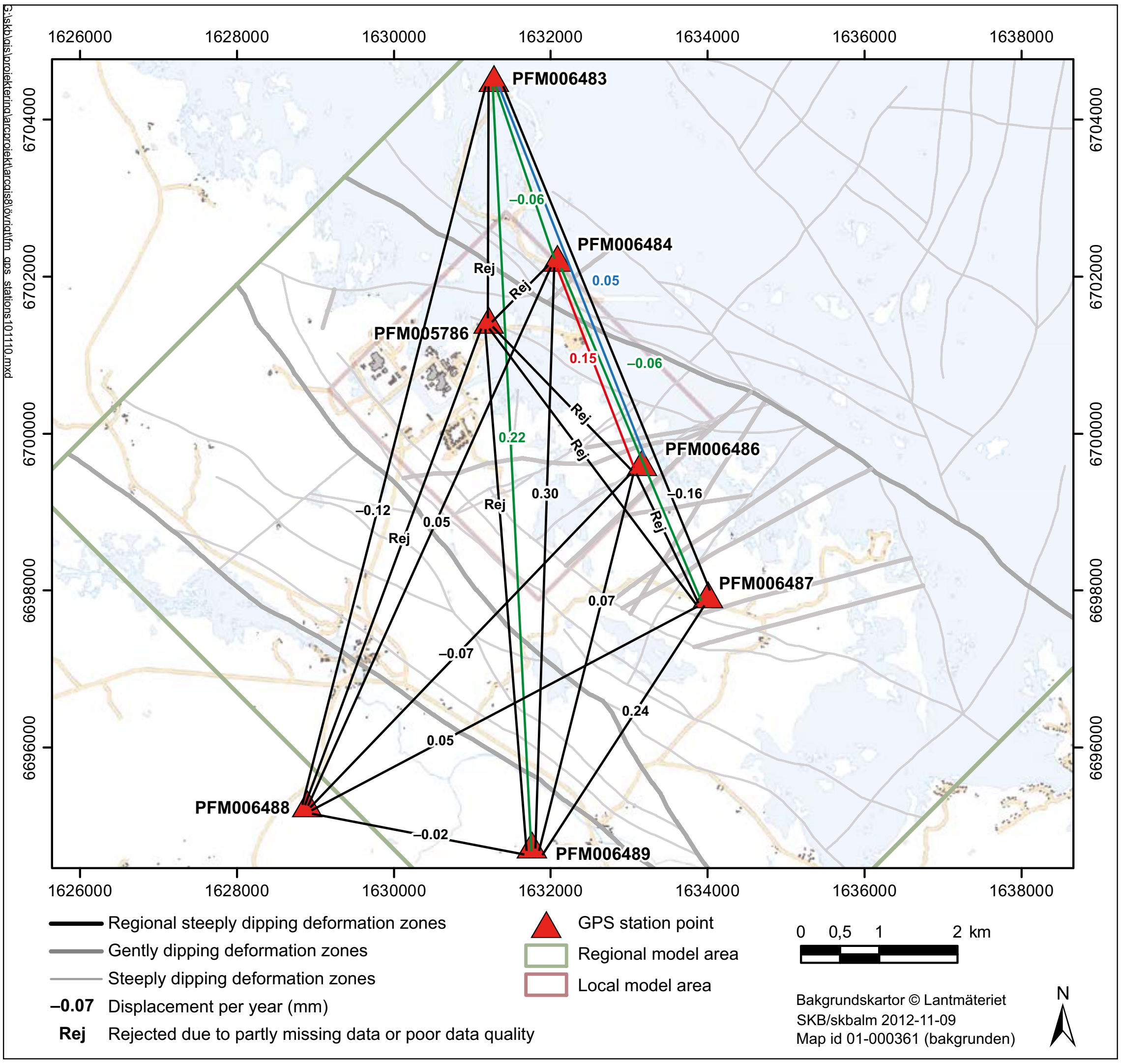

Figure 4-12. *Graphical presentation of the estimated annual changes of the baseline lengths according to Table 4-2, column 8 (ARMA-modelling). Green, blue and red colours are used for some baselines in order to help the reader to visualise these lines and separate them from closely situated black baselines (Figure 7-2 in Ekman and Ekman 2013).*

Data confidence

In the previous section, it is stated that the confidence regarding GNSS data from Forsmark to some degree may be mistrusted, and probable reasons for that doubt are suggested. In the present section, some additional comments on this issue are given.

As mentioned previously, it is in this context important to emphasise that the methods of linear regression explored in Ekman and Ekman (2013) as well as in Gustafsson and Ljungberg (2010) will in theory give consistent estimates of the linear trend, even if the variances of the baseline motions are very large, as long as they are driven by white noise processes. Moreover, the linear regression estimates will be consistent also if it is assumed that the measurements are originating from an AR or ARMA course, i.e. driven by sinusoidal processes. However, in both cases a consistent estimate requires that the number of measurements is sufficiently large. Thus, one could expect that the linear regression estimates and the linear trend estimates from the AR- or ARMA-modelling would give the same result if the number of measurements is adequately large, of course under the assumption that the actual sinusoidal process is correctly modelled by the AR or ARMA methods.

Furthermore, even if the AR or ARMA models are not able to exactly image the "true" underlying physical process, one would expect that the linear trend estimates should not differ very much between these two models, presupposed that the AR or ARMA models are at least reasonably approximating the sinusoidal motions.

Conclusively, the significant differences observed between several of the different estimation approaches of the baseline motions established in Ekman and Ekman (2013), see Table 4-2, clearly indicate that the number of measurements is too small in order to enable reliably consistent estimates of the long-term linear motions.

Another phenomenon which may deteriorate data quality is the so called aliasing effect, which is the term applied when the sampling rate of a sinusoidal signal is not high enough. The GPS measurements at Forsmark were not performed as continuous measurements but as intermittent campaigns (which was the case also for the measurement campaigns at the sites with which Forsmark was compared). It is therefore reasonable to assume that the aliasing effect may have had a negative impact on the GPS data quality. In Figure 4-13 an example is given which illustrates possible consequences for data evaluation of a too short measurement period, combined with too slow sampling rate.

The sampled curve in Figure 4-13 is almost continuous. However, a sequence of random noise with the standard deviation 1 mm is also added to the fast-sampled signal. In the same figure an estimated linear trend, based on the sampled signal, is illustrated as well. The sampling rate is shown as blue dots. Although the linear trend is zero, the estimated slope is in this case –0.58 mm/year, in spite of a mathematically correct linear regression. The deficiencies in sampling frequency and length of measurement period clearly indicate that if deformation measurements with GNSS technique would be resumed, there is an obvious potential for data improvement, presupposed that the measurements are performed continuously and during a sufficiently long period, together with some other method improvements suggested in Ekman and Ekman (2013). Recommendations for future GNSS measurements at Forsmark are given in Section 8.1.3.

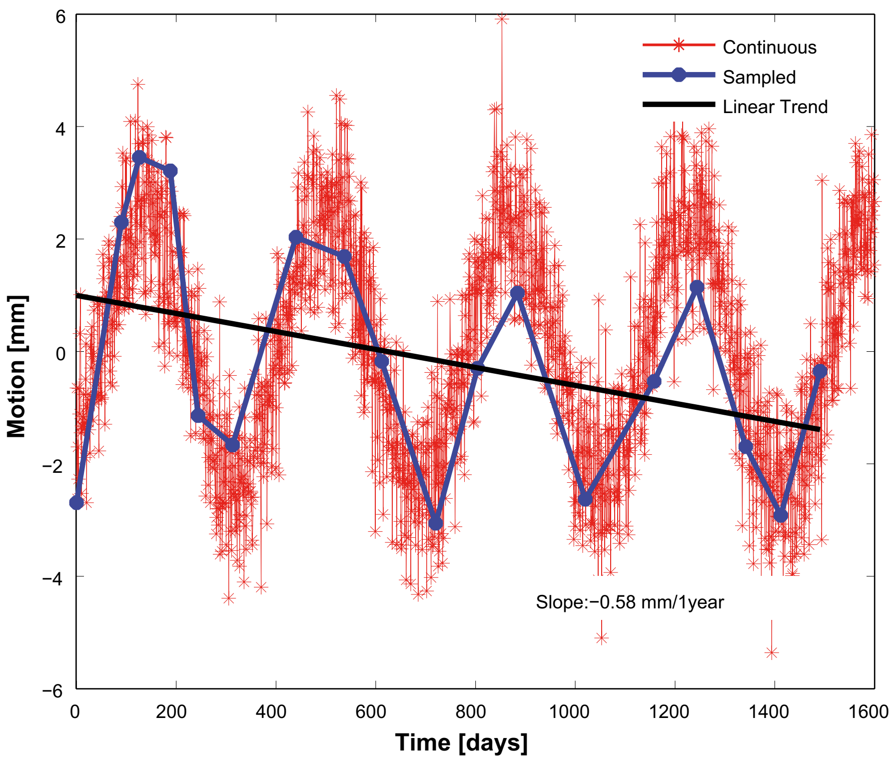

***Figure 4-13.** Illustration of consequences of the aliasing effect in combination with too short timeline for measurements (Figure 6-12 in Ekman and Ekman 2013).*

4.2.7 DInSAR processing

Method prerequisites and limitations

Radar (acronym for RAdio Detection And Ranging) systems operate using radio waves, and are often applied as object-detection systems for determination of the range, altitude, direction, speed and other characteristics of remote objects. Radar utilises microwave radiation with wavelengths within the interval 1 mm to 1 m. The microwave spectrum is usually defined as electromagnetic energy ranging in frequency from approximately 1 GHz to 100 GHz. However, most common radar applications lie within the 1 GHz to 40 GHz frequency interval.

DInSAR is a radar technique that compares the phases of multiple radar images of an area. The purpose is to resolve surface changes. Distances are determined by two-way measurements, which is a difference compared to the GPS one-way technique. In DInSAR radar, satellites emit pulses of radar energy, which are scattered by the Earth's surface. When such a pulse of radar energy is reflected back to the satellite, two types of information are recorded. The first is the amplitude of the signal. This is the information displayed in typical SAR images. The amplitude is influenced by factors such as the surface material, the slope of the surface and surface moisture content.

The second type of information recorded is the phase of the wave. The satellites used for the Forsmark investigations, the ERS-1 and ERS-2 (European Remote Sensing) satellites, work in the C band (4–8.2 GHz), which means that they have a radar wavelength of 5.66 cm. The phase of the wave upon return depends primarily on the distance between the satellite and the surface, but it is also affected by changes in physical properties of the atmosphere. However, this effect is small (Dehls 2006).

Differences in phase between two images are easily viewed by combining, or interfering, the two phase images. In the resulting image, the waves will either reinforce or cancel one another, depending on the relative phases. The resulting image is called an interferogram and contains concentric bands of colour "fringes" related to topography and/or surface deformation (see example in Figure 4-14).

If two images are acquired from different positions within a small period of time, the difference in phase can be used to determine the surface topography. If two images are acquired of the same area from exactly the same position, any difference in phase is due to motion of the ground surface towards or away from the satellite during the time between the two images (Figure 4-15).

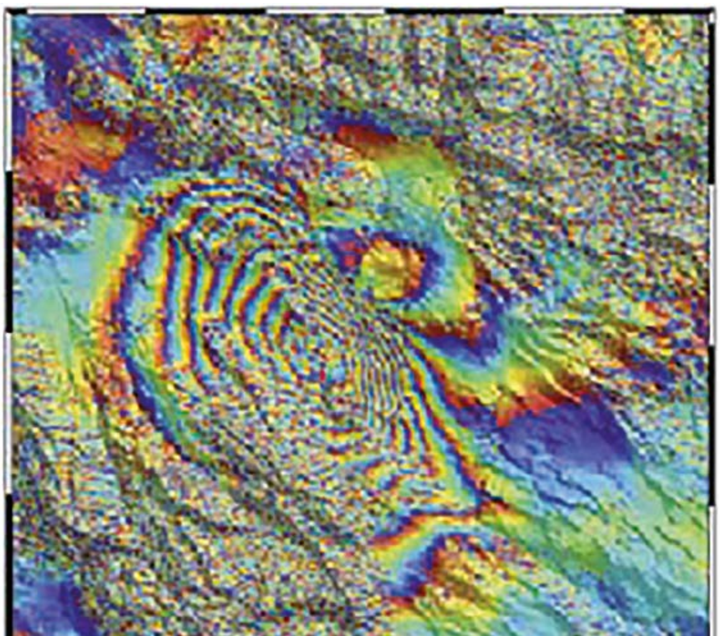

Figure 4-14. *Interferogram of the 2009 L'Aquila earthquake. From Walters et al. (2009).*

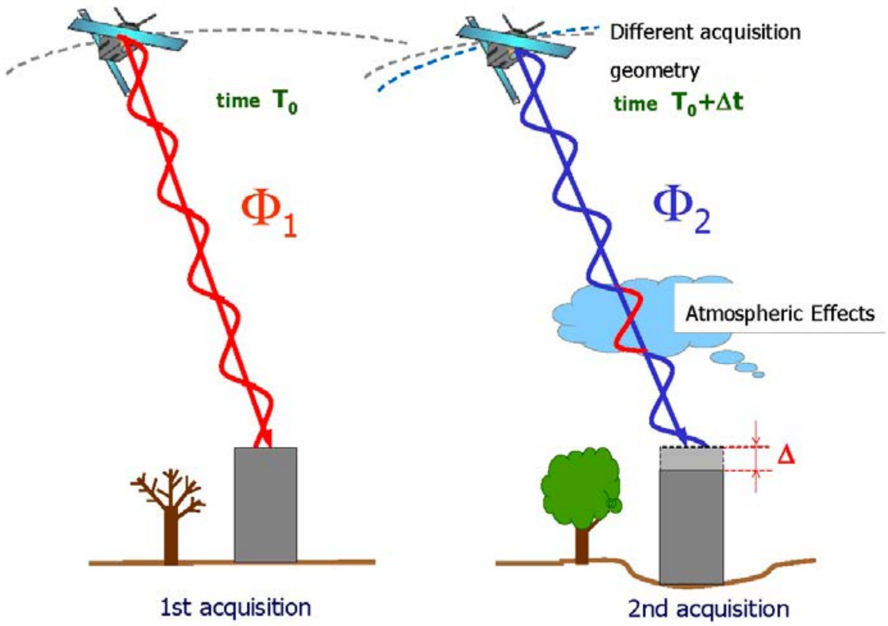

Figure 4-15. *If two radar images are acquired at different times from the same place, differential movement will result in a different measured phase (modified from Dehls 2006).*

Since it is nearly impossible to obtain two images of the same area from exactly the same point at two different times, three images are typically used to analyse surface change. Firstly, an image pair taken during a short interval is used to determine the topography. Secondly, an interferogram is created using two images with a longer time interval. The effects of topography are removed using the results of the first interferogram, and the resulting image contains fringes due to surface deformation. Each fringe represents one-half wavelength of surface movement. In the case of the ERS satellites, this is less than 3 cm. Based on the above described technological prerequisites, the DInSAR method is assessed to have the potential of detecting millimetre-scale surface deformation along the sensor–target line-of-sight (Dehls 2006).

Radar interferometry has one stringent condition that must be met for it to work. The many small reflective objects contributing to each pixel must remain unchanged, or coherent, between images. Decorrelation may occur due to variations in the complex reflectivity of individual sampling cells as a function of the acquisition geometry (geometric decorrelation) and/or time (temporal decorrelation). In addition, atmospherically induced phase changes, mainly due to the effect of the local water vapour content, can be difficult to discriminate from ground deformation (Dehls 2006).

New algorithms use many images acquired over a long time period to determine the motion history of individual objects, referred to as "permanent scatterers", PS, that are coherent over a long period of time (Ferretti et al. 2001). These permanent scatters can be identified and used in many images over a long period. Typical objects are corners of constructions, vertical structures such as fence posts, and natural reflectors such as sharp rocks or ledges in outcrops. This special application of the DInSAR technique, which was applied at Forsmark in 2006, is referred to as the PSInSAR (*Permanent Scatter Interferometry SAR*) method (Dehls 2006).

The PS approach is based on the exploitation of long time-series of interferometric SAR data (at least 25–30 images). The technique can overcome, or at least reduce (or estimate), the most important limiting factors associated with the DInSAR technique:

1) Decorrelation, i.e. when the small reflective objects contributing to each pixel change between images, due to variations in the complex reflectivity of individual sampling cells for geometric or temporal reasons.
2) Atmospheric phase effects, which are mainly due to changes in the local water vapour content.

The PS grid can be thought of as a high spatial density (up to 400 PS/km^2, in highly urbanised areas) geodetic network, allowing ground deformation measurements (along the line-of-sight direction) with millimetre accuracy (0.1–1 mm/yr on the average line-of-sight deformation rate and 1–3.5 mm on single measurements).

Since PS mainly correspond to portions of man-made structures, and a minimum PS density is required to guarantee the reliability of the measurements, most significant PS results have been obtained analysing urban areas and their immediate neighbourhood. The PS approach allows the identification of isolated phase-stable targets in low coherence areas. These provide precise surface deformation data in areas where a conventional DInSAR approach fails due to decorrelation noise (Dehls 2006).

Data processing

In the Forsmark PSInSAR project, standard processing was performed on 40 ERS-1 and ERS-2 scenes acquired during the period August 23rd, 1992, to August 5th, 1996. The areas of interest were specified by SKB, see Figure 4-16. However, in order to get a better understanding of regional trends, a larger area, comprising approximately 1 500 km^2, was processed. Slightly less than 20 000 PS were identified. Since a significant portion of the area is water, and due to the rural character of land area with much vegetation and few man-made structures, the real data density is estimated to be as low as between 15 and 20 PS/km^2. The highest densities were obtained along the coast and on the islands, where natural outcrops are more abundant (Dehls 2006).

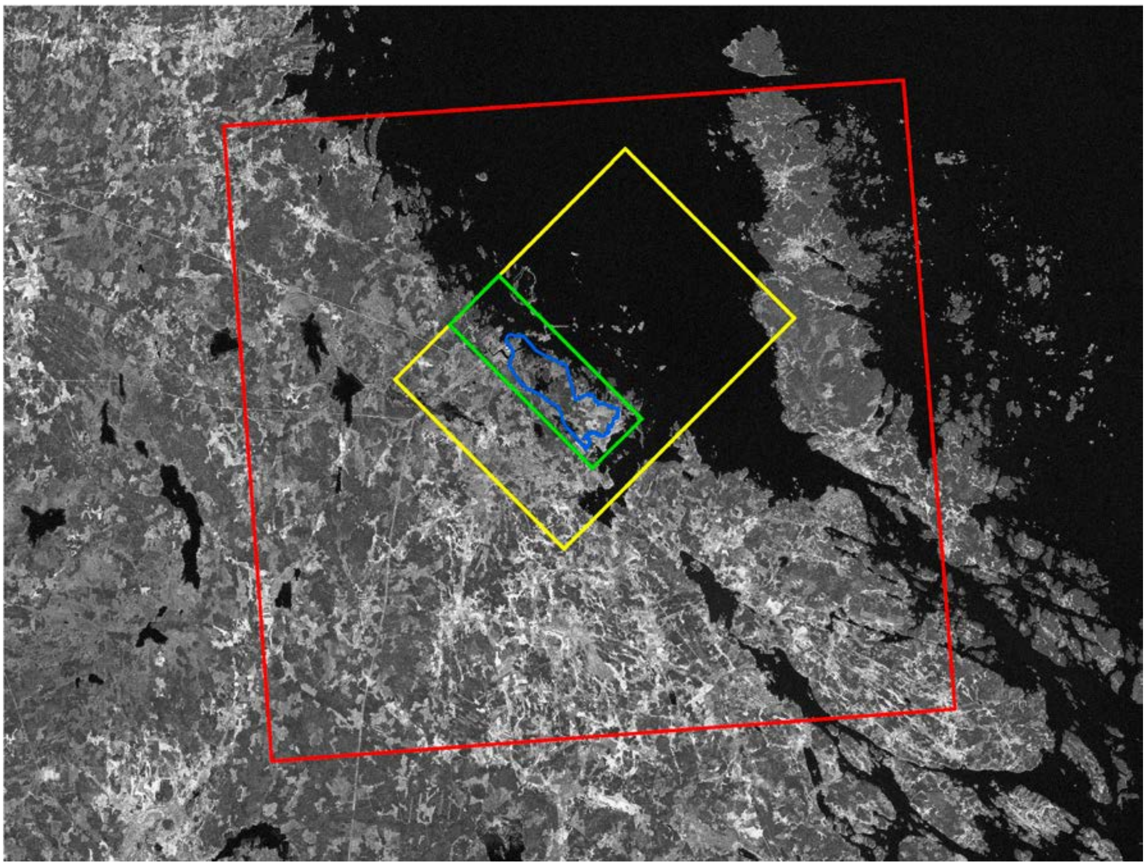

Figure 4-16. *The candidate area of the site investigation for the spent fuel repository is marked in blue. The green and yellow rectangles represent the local and regional model areas of the same investigation. The area marked in red is the area for which PSInSAR processing was carried out (from Dehls 2006, Figure 3-1).*

Results

Figure 4-17 presents the deformation observed around the nuclear power plant. While the buildings themselves are stable, there are a number of data points that show subsidence. Most of these are in areas of artificial fill along the waterfront. The deformation rate is constant, as shown by the displacement vs. time graph in Figure 4-17.

The left photograph in Figure 4-18 shows an area slightly southwest of the area illustrated in Figure 4-17. Vertical metal structures, such as those along the power line, are exceptionally good permanent scatterers, almost always visible. The right photograph in Figure 4-18 shows the town of Östhammar. Numerous buildings are obviously undergoing subsidence. They are not spatially correlated, however, suggesting that the subsidence is due to poor foundations and/or collapse of the buildings themselves.

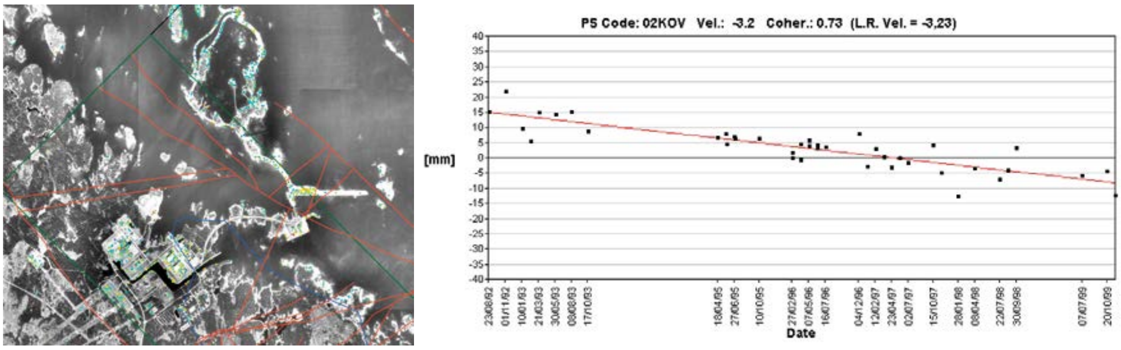

Figure 4-17. *Left: Deformation around the nuclear power plant (from Dehls 2006, Figure 3-2). Right: Displacement vs. time for one of the points on the pier behind the SKB building at Forsmark (from Dehls 2006, Figure 3-3).*

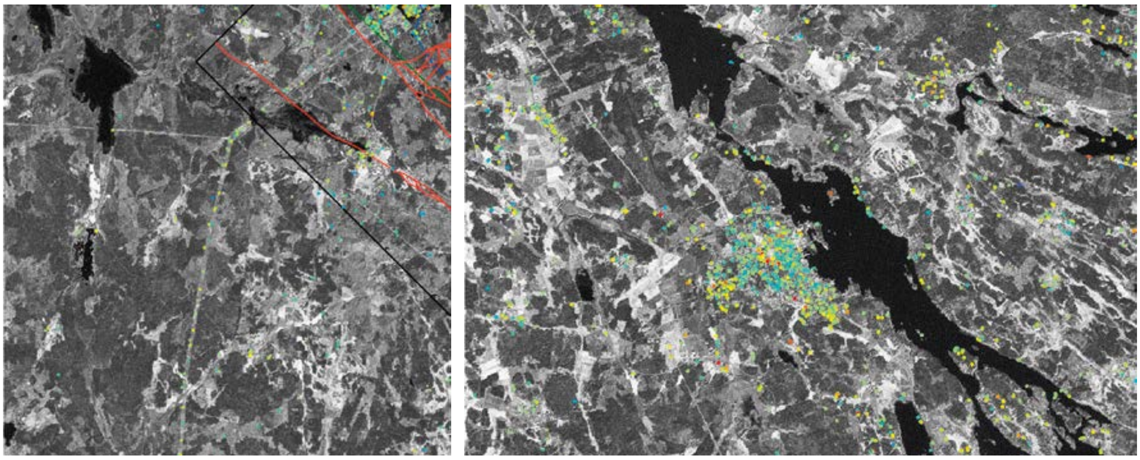

Figure 4-18. *Maps on which green colour indicates subsidence. Left: Note the number of data points along the power line. Vertical metal structures act as exceptionally good permanent scatterers (from Dehls 2006, Figure 3-4). Right: Town of Östhammar. Numerous buildings are affected (from Dehls 2006, Figure 3-5).*

Data confidence

Two main classes of objects act as PS in the Forsmark-Östhammar area: natural reflectors, such as rocks, and man-made reflectors, such as parts of buildings. The PS technique determines motion relative to an arbitrarily chosen PS. There are many reasons why one object may be moving relative to the others. An old building may be collapsing, or a building may be subsiding due to poor structural foundations. An area of sediments may be undergoing compaction due to surface loading, or due to lowering of pore pressure due to groundwater extraction. Regional causes may include crustal tilting due to isostatic uplift, or active tectonics. In addition, ground motion may be fictitious due to sources of error such as inaccuracy of satellite orbital information.

One of the most difficult challenges faced in this type of study is to distinguish and quantify the different contributions to the velocities measured. Indeed, there are no established quantitative techniques that can separate regional displacements, local displacements and point displacements.

Deterministic spatial interpolators, such as inverse distance weights, are highly affected by the strong spatial clustering typical of these data. Since the object of this investigation was to determine if any differential motion could be detected across faults in the Forsmark area, the dataset was divided into three groups for analysis. The division was based upon the location of regional lineaments provided by SKB, see Figure 4-19. Both statistical and geostatistical techniques were used.

Figure 4-20 shows the distribution of velocities for the entire population. Block 1 as here defined as the northernmost block, Block 2 as the central block and Block 3 as the southernmost block. Block 1 has a significantly higher number of scatterers because it includes most of the coastline. All of the frequency distributions have very long tails, with more outliers on the negative side than the positive side. This is expected, as most of the scatterers are expected to be fairly stable. Those with significant motion are more likely to be undergoing subsidence than uplift.

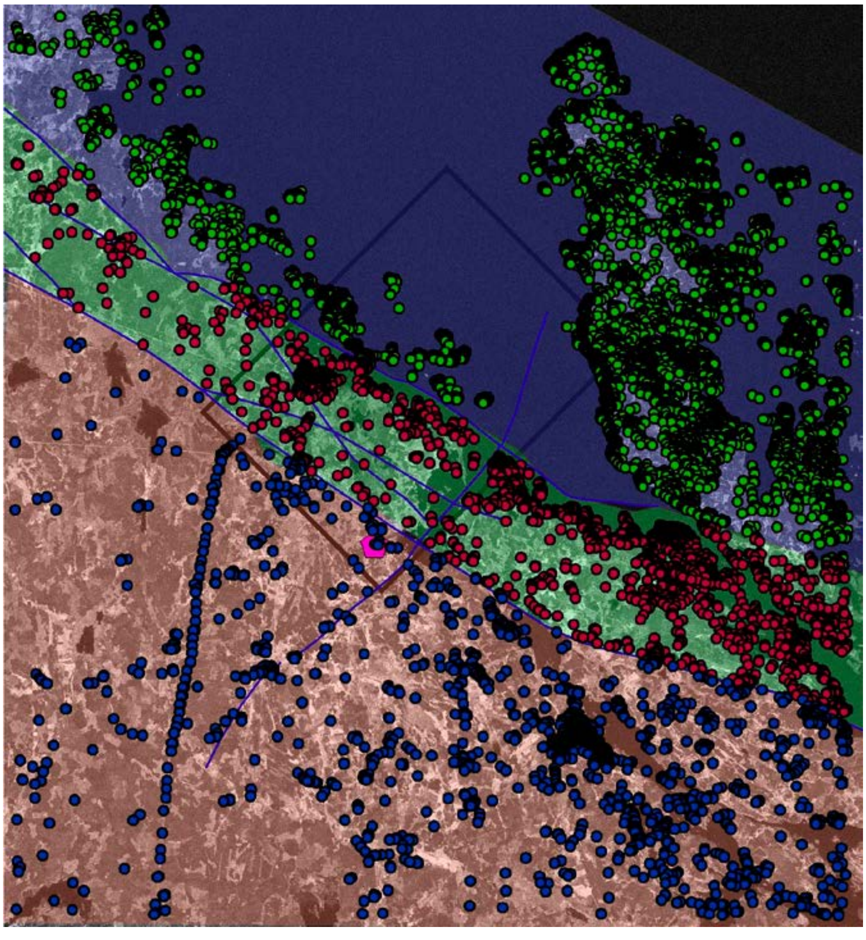

Figure 4-19. *Division of PS into three groups, based upon blocks defined by regional lineaments (from Dehls 2006, Figure 3-7).*

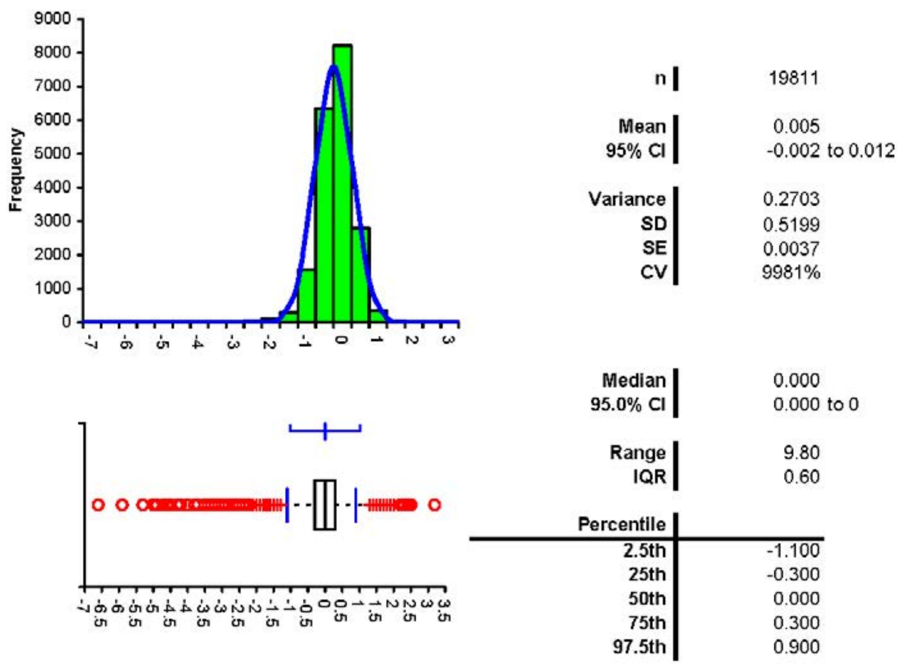

Figure 4-20. *Frequency distribution and summary statistics for all the PS in the study. The distribution is characterised by long tails, especially on the negative side. The mean and median are both effectively zero (from Dehls 2006, Figure 3-8).*

Outliers, who represent very local trends, are of no interest here, and therefore the median is a good estimate of the average velocity. The median velocity for Block 2 is zero. The median velocity for the northern block is 0.1 mm/yr, implying uplift relative to the centre block. The median velocity for the southernmost block is –0.1 mm/yr, implying subsidence relative to the centre block. The difference is, however, too small to be conclusive without looking at the spatial distribution of the velocities within each block.

In the Forsmark PSInSAR study almost 20 000 stable reflectors were identified, either natural or man-made. Satellite to ground line-of-site velocity was determined for each of these reflectors, with precision better than 1 mm/yr. Many local subsidence phenomena were identified, for example compaction in loose sediments. Analysis of motion trends across regional lineaments does not support the hypothesis of slow, aseismic vertical movement taking place along these features. However, horizontal movement cannot be ruled out (Dehls 2006). Recommendations for future radar measurements at Forsmark are given in Section 8.1.4.

4.3 Monitoring of earth electrical currents

4.3.1 Background

Earth electrical currents can cause corrosion in metallic structures in the ground. Forsmark is an area with several sources of earth electrical currents. As the monitoring system for the planned repositories in Forsmark includes a number of metal devices of substantial extent installed in boreholes drilled from the ground surface to about 1 000 m depth into the rock (see Figure 4-21), monitoring of earth currents is important. Elongated and/or insulated objects with small areas of damage to the covering insulating sheets are especially sensitive to the effects of such currents. In such a case, minor insulation damage to different parts of a device may result in a potential gradient between the exposed parts of the object, if earth currents are present. An electrical current will then be channelled through the object, and corrosion may arise where the current leaves the object and returns to the ground.

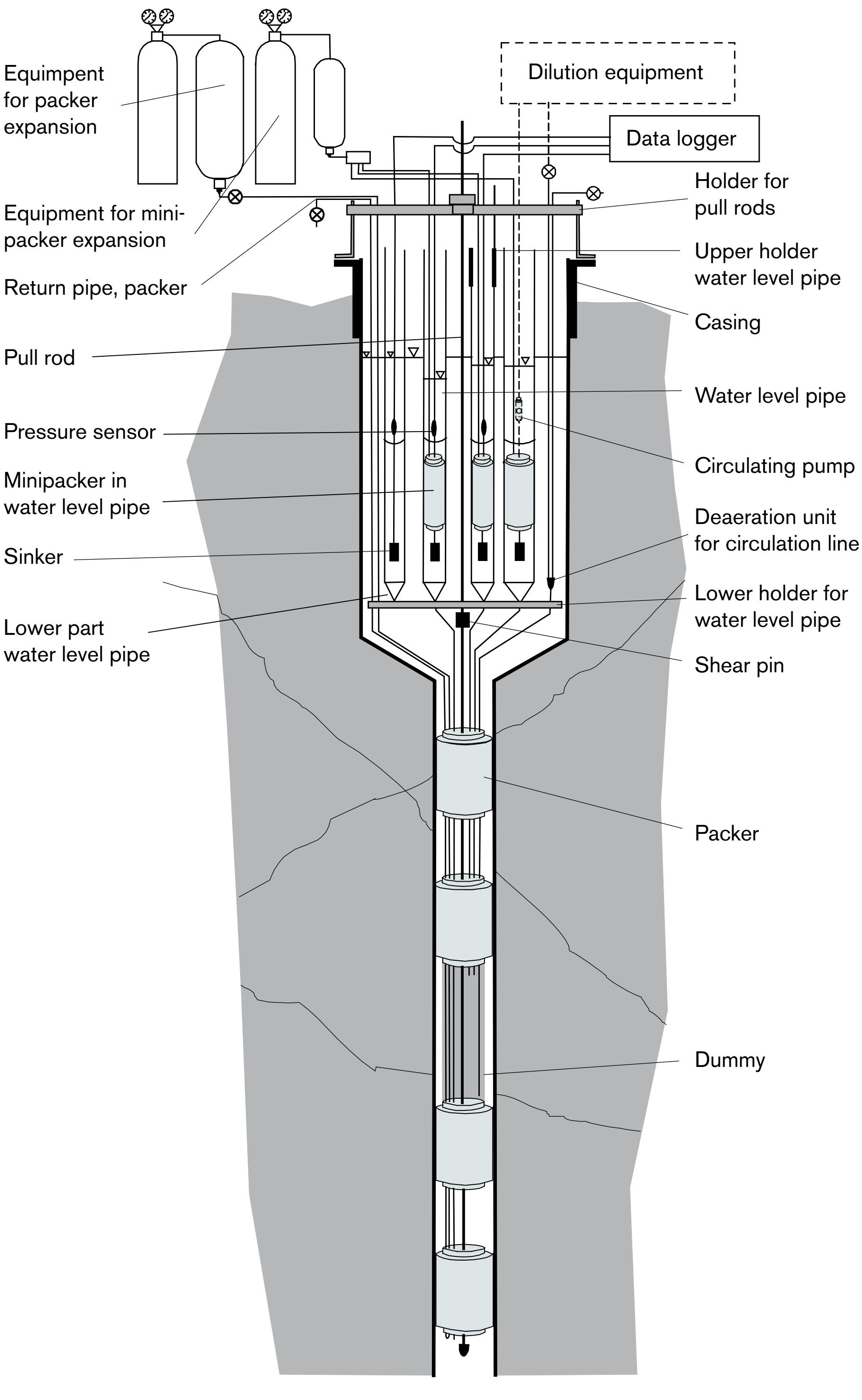

***Figure 4-21.** Schematic picture of a core-drilled so-called telescopic borehole at Forsmark supplied with hydraulic monitoring equipment.*

The Swedish and Finnish power grids are interconnected via the Fenno-Skan high-voltage direct current (HVDC) link. Power may be traded between Sweden and Finland via this link. The Fenno-Skan 1 (here abbreviated F1) and 2 (F2) HVDC power transmission link consists of two monopolar circuits. The direction of the current in each of the two cables is always the same, irrespective of whether electrical power is exported to or imported from Finland. The intention is that the two circuits normally are balanced with approximately the same effect, but with the opposite direction of the current in the two cables. But in Figure 4-22 we can see that this is only temporarily the case. Instead, F1 is usually quite steady with a power transmittal of about 450 MW, whereas F2 is used with the purpose of balancing the demand for electrical power in Sweden or Finland, and therefore the rate of power transmission varies considerably in this cable. If one of the cables is out of operation, the earth replaces one of the cables as the return loop, i.e. unbalanced current is returned through the ground between sea-located electrodes close to the Swedish and Finnish shores, respectively.

The link can be operated in monopolar mode if one of the cables is out of operation due to maintenance or repair. The Swedish electrode is located at Fågelsundet, around 25 km northwest of the Forsmark nuclear power plant (Figure 4-23). The Fågelsundet electrode will function as an anode (current directed from the electrode F1 > F2) or as a cathode (current directed into the electrode F2 > F1), depending on which of the two cables dominates at the time (Thunehed 2017).

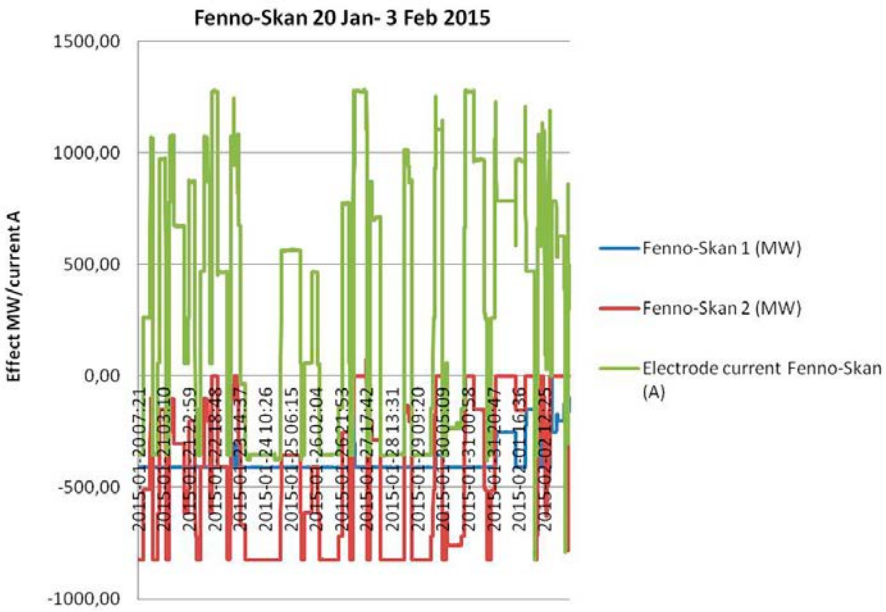

Figure 4-22. *Mean values of electrode current at Fågelsundet and direct currents in the Fenno-Skan cables during a period of one week, in this case January 20–February 3, 2015. The electrode current varies considerably.*

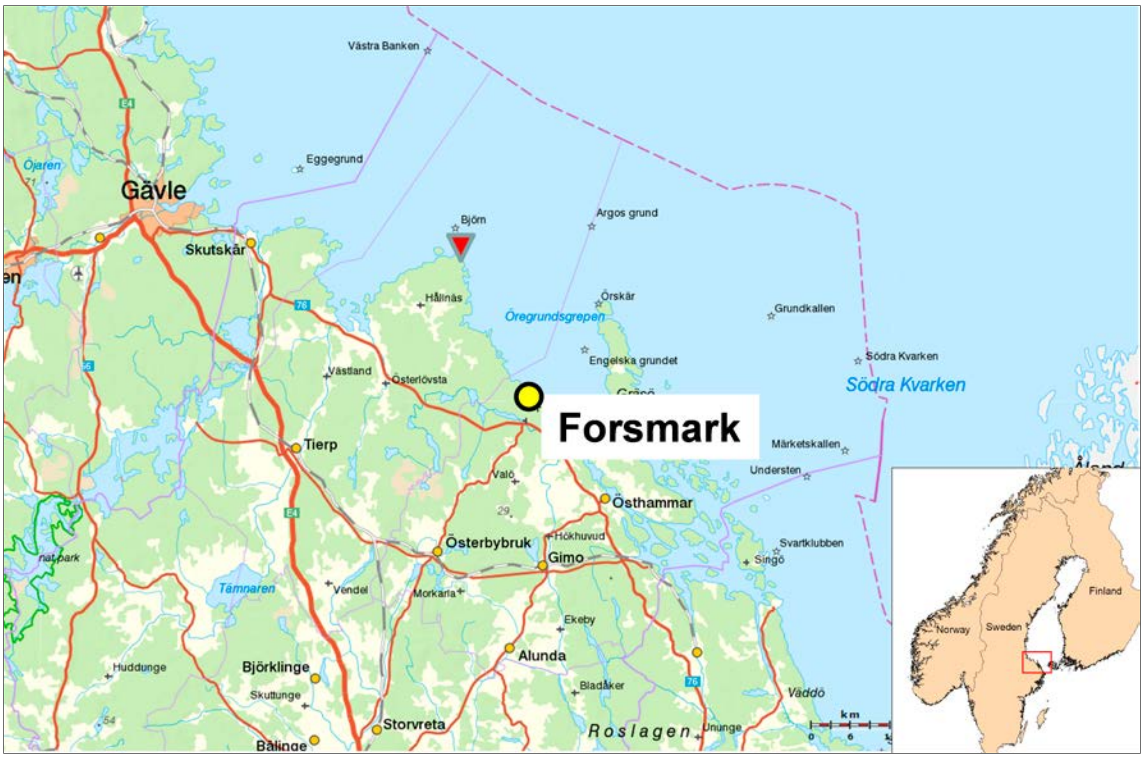

Figure 4-23. *Locations of the electrode at Fågelsundet (red triangle) and Forsmark.*

4.3.2 Earth currents and corrosion of monitoring equipment

Earth currents from the Fågelsundet electrode create an electric potential field that can be detected at Forsmark. Corrosion that is probably due to currents generated by this field has damaged components of hydraulic monitoring equipment in several deep boreholes at Forsmark; Figure 4-24 shows an example of a corroded component placed in the upper part of a borehole at about 40 m depth below the ground surface. Several investigations related to earth currents and corrosion problems have been carried out at Forsmark, e.g. Nissen et al. (2005), Pedersen et al. (2013) and Thunehed (2017). The details of the corrosion process are not fully understood, but earth currents generated at the Fågelsundet electrode are suspected as the primary driving force.

The AC power lines, the substation and the power plants are grounded at Forsmark. The groundings are either in direct galvanic contact, or through short routes via ground in contact with remote groundings of the AC power grid through power-line top and ground conductors. The grounding system at Forsmark is also expected to have a good current supply from ground due to the short distance to sea water. An elevated electric potential at Forsmark due to anodic operation of the Fågelsundet electrode will drive a current through the grounding system, via the top and ground conductors to remote groundings (and the opposite for cathodic operation of the electrode). The grounding system will thus act as a secondary cathode if the Fågelsundet electrode is operated as an anode. Such a process will create an electric field around Forsmark of larger magnitude than the primary electric field due to the electrode operation.

The different drill sites with monitored boreholes at Forsmark are provided with electrical power supply with a mutual grounding grid. The grid nodes (drill sites) will be set at different electric potential by the secondary effects described above. This will drive a DC current in the grid from drill sites at a high potential to the ones at a lower potential. Drill site grounds will thus act as tertiary anodes or cathodes due to electrode operation at Fågelsundet. Amperages are rather small, but may nevertheless create significant electric fields locally at the drill sites.

Figure 4-24. *Corroded monitoring equipment in drill hole KFM08B in 2012. This particular component had been installed in the borehole, after service, only two months earlier.*

Factors that are likely to determine whether metal monitoring equipment in boreholes will be damaged by earth currents are the following (Thunehed 2017):

- If equipment is insulated from the steel rod (i.e. the item labelled “Pull rod” in Figure 4-21),
- If equipment is grounded to earth via a cable with a shield.

The degree of influence is determined by factors such as:

- The size of the unbalance in the Fenno-Skan link.
- The level of the cathodic protection at each drill site.
- The distance to the high-voltage AC substation.
- Electrical conductivity of the groundwater inside the monitoring equipment.
- Resistance between equipment and earth.
- Inclination and direction of the borehole where the equipment is installed.

The kind of corrosion we discuss here, i.e. corrosion in terms of influence from earth currents, is restricted to the monitoring equipment installed in deep or semi-deep boreholes, and especially to components placed down to about 40 m below the ground surface. Possible corrosion due to earth currents of metal installations in the existing and planned repositories are discussed in other documents. According to these, most waste at SFR is deposited in such a way that corrosion is not an issue in the safety assessment. However, corrosion of deposited reactor tanks from future dismantled reactors might possibly lead to release of radionuclides. Corrosion caused by earth currents from monopolar operation of the Fenno-Skan link is estimated to be negligible compared to normal corrosion rates (Vahlund 2014). Monopolar operation of the Fenno-Skan link is also estimated to cause negligible corrosion on copper canisters in the future deep repository for spent nuclear fuel (Taxén et al. 2014).

4.3.3 Measurements of electric potentials

In Thunehed (2017), a regional resistivity model of the Fågelsundet-Forsmark area has been elaborated from available information. The electric potential due to an injected current (1 000 A) at the electrode installed at Fågelsundet was calculated with a finite-difference program. The modelling predicts an electric potential at Forsmark of around 5 V relative to a remote reference. The electric field was estimated to be around 700 mV/km horizontally, whereas the vertical component of the electric field was estimated to be around 2 000 mV/km at SFR. The reason behind the stronger vertical component is that low-resistive sea water tends to act as an extended part of the electrode, transmitting current down into the much more resistive earth.

Measurements of electrical fields related to earth currents have been carried out with a number of different methods and configurations at Forsmark. The methods include time-series monitoring between boreholes, borehole logging, surface profiling and DC (direct current) measurements in power-supply grounding grids. The measured electric fields show a strong correlation with the current magnitude through the Fågelsundet electrode. However, the direction and magnitude of the measured field is not consistent with the expected and modelled primary electric field from the Fågelsundet electrode, especially for measurements in the vicinity of the Forsmark power plant and the high-voltage AC sub-station.

Cable currents can follow different paths between the electrodes, not necessarily the shortest way through the sea water. The actual path depends on resistances in e.g. the earth, water, and buried pipes and other infrastructure. Low-resistance metal structures such as pipes and pumps will make an easy path for the current, which also may cause corrosion. This is a well-known problem in the neighbourhood of the electrodes where the current is high. In the surroundings of Forsmark, the voltage drop is believed to be around 300 mV/km with one cable.

Several studies of the potential gradients in Forsmark have been performed in 2005, 2009, 2010, and 2012–2014. The first study started during the site investigations for the spent fuel repository, at which time only one Fenno-Skan cable existed. In 2005, corrosion was observed on stainless-steel equipment installed in two of the Forsmark boreholes (KFM04A and KFM08A), SP (self-potential) measurements were conducted in these boreholes and also in borehole KFM07A. The measurements indicated correlation with the direct current in the F1 HVDC cable. However, the SP measurements did not show any correlation with magnetic data obtained from the Uppsala Magnetic Observatory (see also Section 4.4).

In summary, the following measurements were conducted during 2005:

- SP loggings in the 1 000-metre long borehole KFM04A at a borehole length of 225 to 240 m.
- SP measurements between drill sites DS4 and DS1.
- SP measurements around DS4.
- Measurements with a gradient probe in drill holes KFM04A, KFM07A and KFM08A.

The measurements were carried out in boreholes as well as on the ground between drill sites. Logging with a gradient probe in KFM04A showed a significant correlation between the power in the Fenno-Skan 1 HVDC cable and the measured voltage gradient in the borehole. This relation has also been proven in later measurements, and also with two Fenno-Skan cables in operation.

Due to the first observations of corrosion and measurements of earth currents, active protection against corrosion of the borehole equipment was installed in 2010 (active cathodic protection). Later that year, corrosion was also observed on the mini-packer installation (see Figure 4-21) in borehole KFM04A. In 2011, investigations were carried out due to failure of equipment, and it was observed that the corrosion problems had increased rapidly. In 2012, SvK (Svenska Kraftnät, Swedish operator of the HVDC cables) had severe problems with the Fenno-Skan 1 cable, and only Fenno-Skan 2 was in operation for a long time. Simultaneously, corrosion occurred also in other boreholes, and SKB called meetings with the operator to discuss the need for understanding the processes at a deeper level. Ever since, SKB has been receiving operational data from Fenno-Skan 1 and 2 on a weekly basis, to be able to follow up what may happen in the boreholes.

In 2013, Uppsala University measured electric potentials in six boreholes around Forsmark (Pedersen et al. 2013). Three of the boreholes are located in the vicinity of SFR and three within the footprint of the planned spent fuel repository. The aim of the study was to quantify the potential gradients in the Forsmark area under varying Fenno-Skan 1 and 2 loads. During the period 23rd September to 9th October, 2013, measurements of the time variations of the electrical potential gradients were conducted in two sets of boreholes, with three boreholes in each set (Figure 4-25 and Figure 4-26). In both these sets, electrical potential differences between boreholes were measured in two independent horizontal directions at a depth of approximately 90 m. In addition, the three magnetic field components were monitored at each of the measurement setups, in order to study the effect of natural magnetic variations on the electrical potential variations in the boreholes.

Generally, the results show a very clear correlation between the variations in the net current in the Fenno-Skan cables and the potential gradients (Figure 4-27). There were considerable differences in measured potential gradients between the two setups. Part of the variation is likely due to the direction from the injection point at the Fågelsundet current electrode to the measurement locations at Forsmark. Other parts are interpreted to depend on lateral variations in electrical conductivity in the Forsmark area, whereby large jumps in the electrical potential may arise if currents are directed parallel to the gradients of the electrical conductivity. Such gradient discontinuities can be caused by transition from salt-water dominated to freshwater-dominated regimes in the earth's crust, or be the result of fracture zones that may form a strong conductivity contrast to the surrounding rock. Despite these complications, the average sensitivity of the potential gradients to the Fågelsundet current electrode can be assessed to be in the order of the magnitude 1 mV/m per 1 000 A.

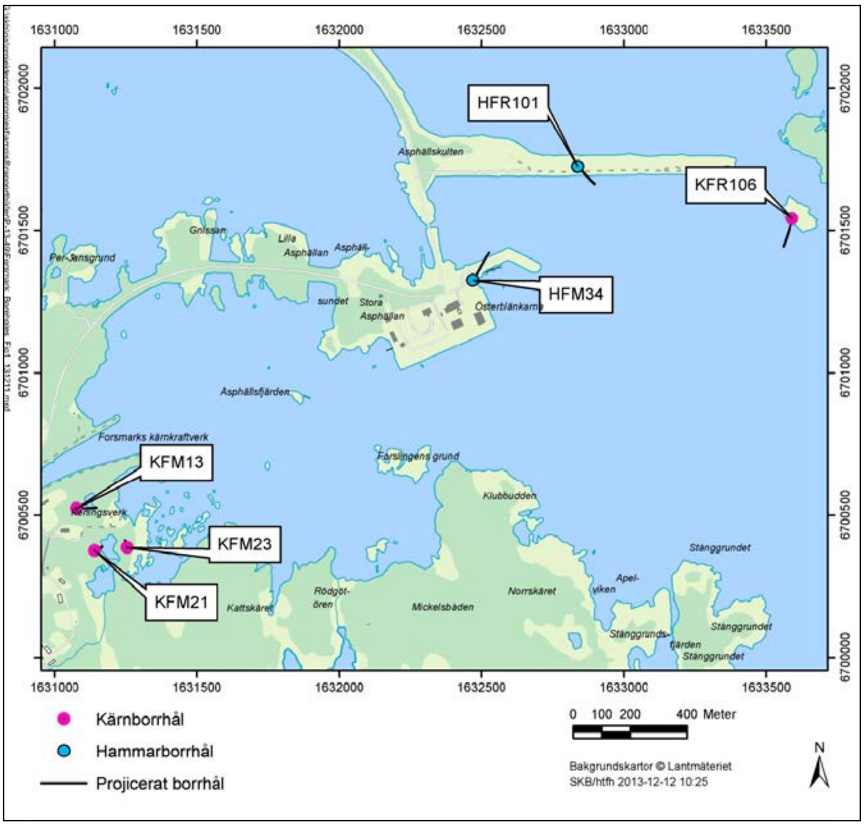

Figure 4-25. Positions of the two sets of boreholes used in the potential measurements. From Pedersen et al. (2013).

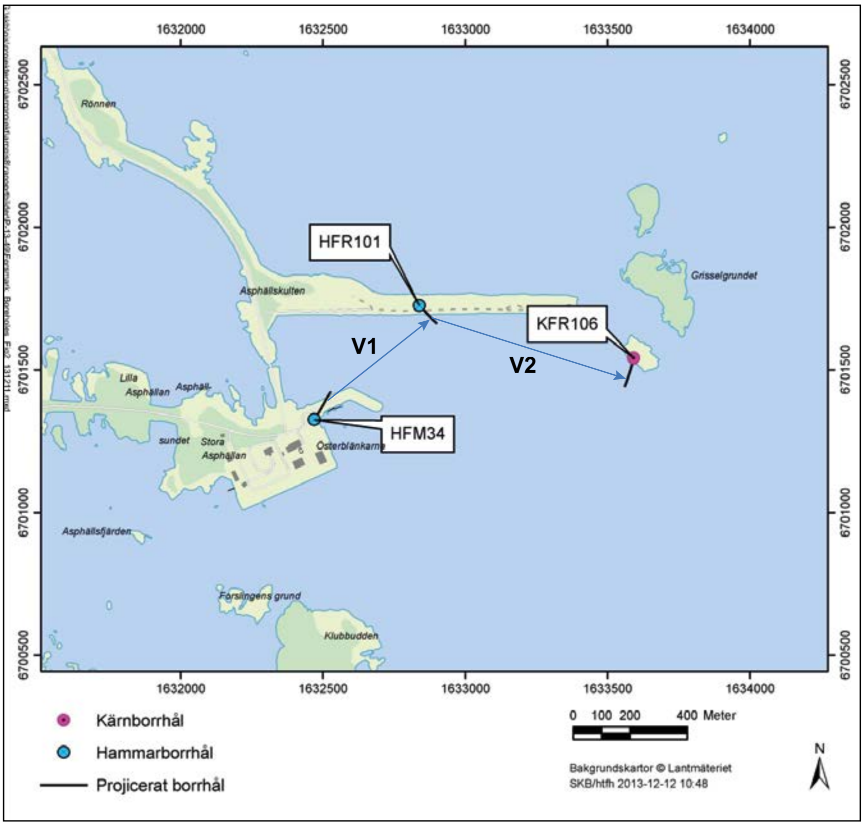

Figure 4-26. Boreholes at SFR with the boreholes HFR101, FHM34 and KFR106 marked together with the vectors V1 (left) and V2 (right). From Pedersen et al. (2013).

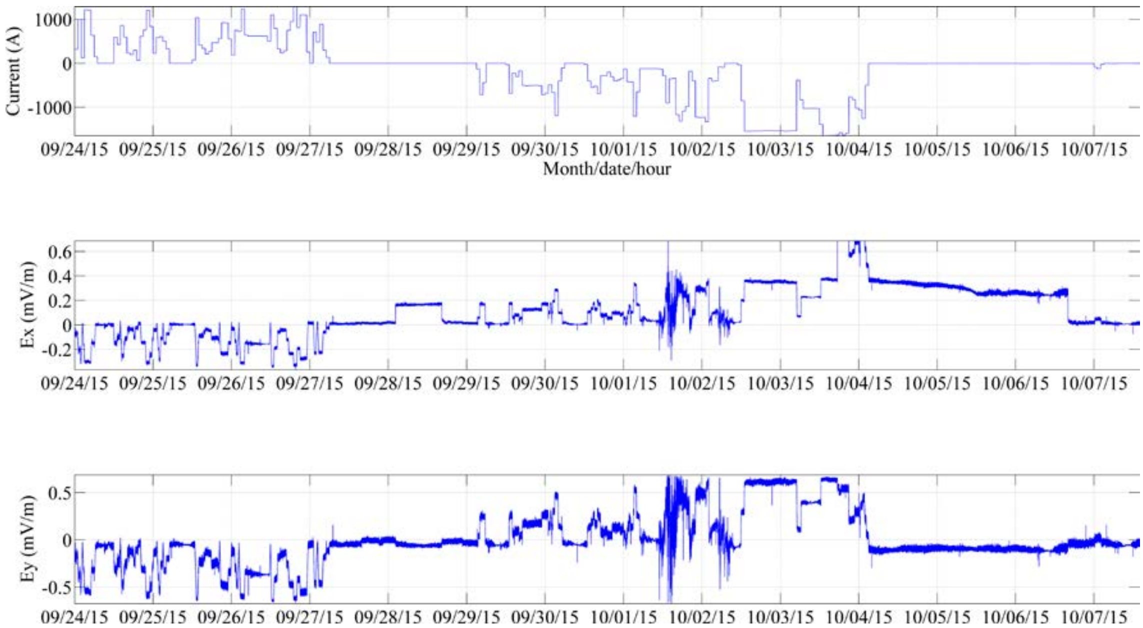

Figure 4-27. *Variation of the horizontal electric field at the SFR site, Forsmark (lower diagrams), and current injected at Fågelsundet (upper diagram). Ex corresponds to vector V1 and Ey to vector V2 (see Figure 4-26). From Pedersen et al. (2013).*

4.3.4 Present monitoring and plans for the future

Monitoring of earth electrical currents at Forsmark is considered to be of minor interest. The reasons for this judgement are that such monitoring technically is very complex and that it does not provide final, adequate answers. However, many studies of self-potentials in regolith and bedrock have been made, and some other types of monitoring activities are currently (2015) carried out. In borehole KFM04A, a zinc electrode is installed and monitored at a depth of 263 m (see Chapter 5). As mentioned above, SKB also receives operational data from SvK every week from the Fenno-Skan cables. Evaluations can thus be made and some conclusions about earth currents and their effects drawn, but it must be emphasised that this is a complex field, which requires years of experience to be properly evaluated.

During 2014, the cathodic protection was checked and adjusted to comply with two cables. However, it is not practically feasible to change the system settings every time the currents in the Fenno-Skan cables are changed. Hence, the primary goal is to protect the steel components (e.g. the line of steel rods used as equipment carrier) in the deep boreholes, see the item marked “Pull rod” in Figure 4-21. However, the cathodic protection is not functional for the measurement equipment in the upper part of the core-drilled boreholes. Therefore, alternative solutions for different boreholes have been continually tried out since 2014, and these tests will be evaluated starting in 2015.

Actions have also been taken against new corrosion of borehole equipment, insulating metal from metal with plastic insulation tubes and shrinking tubes. In borehole KFM08D, a new concept has been tested since 2014, according to which the traditional steel equipment and the mini packers are replaced by components made of PEEK (polyether ether ketone), see Figure 4-28 and Figure 4-29.

PEEK is a strong and stiff plastic material that is often used in applications where performance at elevated temperatures is required. PEEK has outstanding chemical resistance, as well as resistance to steam and hot water. Virgin PEEK is naturally abrasion resistant. Bearing-grade PEEK has enhanced bearing and wear properties. The only metal component left is the pressure transducer made of titanium, and this part has never been affected by corrosion even before these actions. The reason for this is a lesser sensitivity towards fluctuating potentials for titanium than for stainless steel.

***Figure 4-28.** PEEK installation in KFM08D. This specific part is lowered into the borehole and installed at a depth of about 40 metres.*

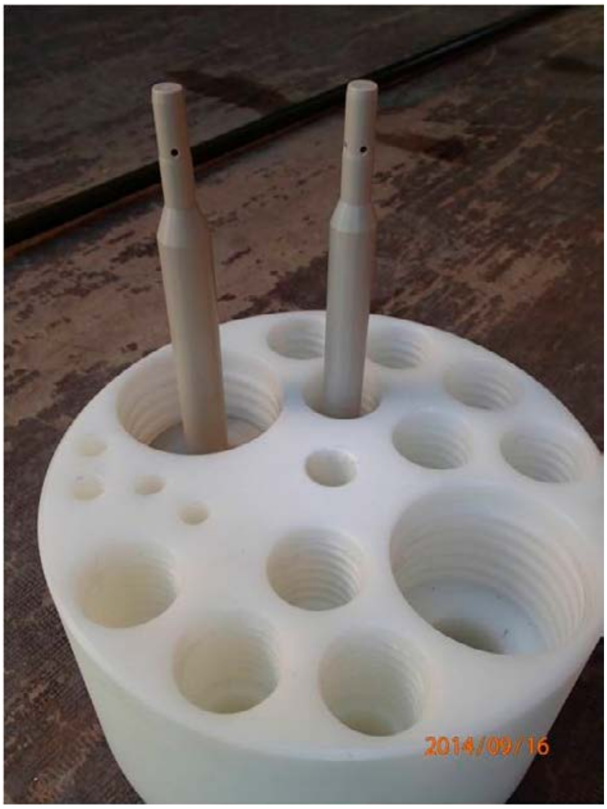

***Figure 4-29.** Details of the PEEK installation in borehole KFM08D. The white plate is where the plastic rods are attached and the beige parts are connected to the monitoring equipment inside the plastic rods. In all other boreholes these parts are made of stainless steel.*

4.4 Monitoring of the global magnetic field

4.4.1 Background

Borehole direction deviations can be measured with a combination of magnetic and accelerometer sensors. The azimuth of the borehole is estimated by comparing the direction of the borehole with magnetic north as sensed by the magnetic sensors during the time of surveying. The method relies on knowledge of the local declination of the magnetic field and assumes that this declination is stable over time. Investigations into the accuracy of borehole surveying have been presented by Nilsson and Nissen (2007), Sindle et al. (2006) and Munier and Stigsson (2007). However, in reality the magnetic field of the Earth varies with time. These variations can occur as slowly varying fields due to changes in the geomagnetic dynamo in the Earth´s interior, as daily variations due to the rotation of the Earth in the flow of charged particles from the Sun, or as more rapid variations due to sudden outbursts of charged particles from the Sun.

The normal magnetic field (excluding the contribution from man-made objects and local variations due to shallow geological sources) can be calculated with the help of models like the WMM (World Magnetic Model) or IGRF (International Geomagnetic Reference Field). The models take slowly varying temporal variations, so called secular variations, into account. The declination of the magnetic field is estimated to be 5.83° at Forsmark on the 26th of February 2015, with a change of 0.16°/year. The daily variations in the Earth’s magnetic field are usually fairly small and lead to variations in the declinations that are on the order of 0.1°. However, sudden outbursts of charged particles from the sun cause so-called magnetic storms. Such storms may give rise to variations in the magnetic field that are of considerable magnitude.

The occurrences of magnetic storms can be followed on several internet sites, such as TESIS (see TESIS n d). Figure 4-30 shows a generalised view of the magnetic activity during three days. According to this figure, minor magnetic storms have occurred during the 24th of February 2015. Predictions of magnetic activity can also be found on other internet sites, see example in Figure 4-31. However, the predictions can be somewhat uncertain, and it is quite possible that magnetic storms occur even if they have not been predicted.

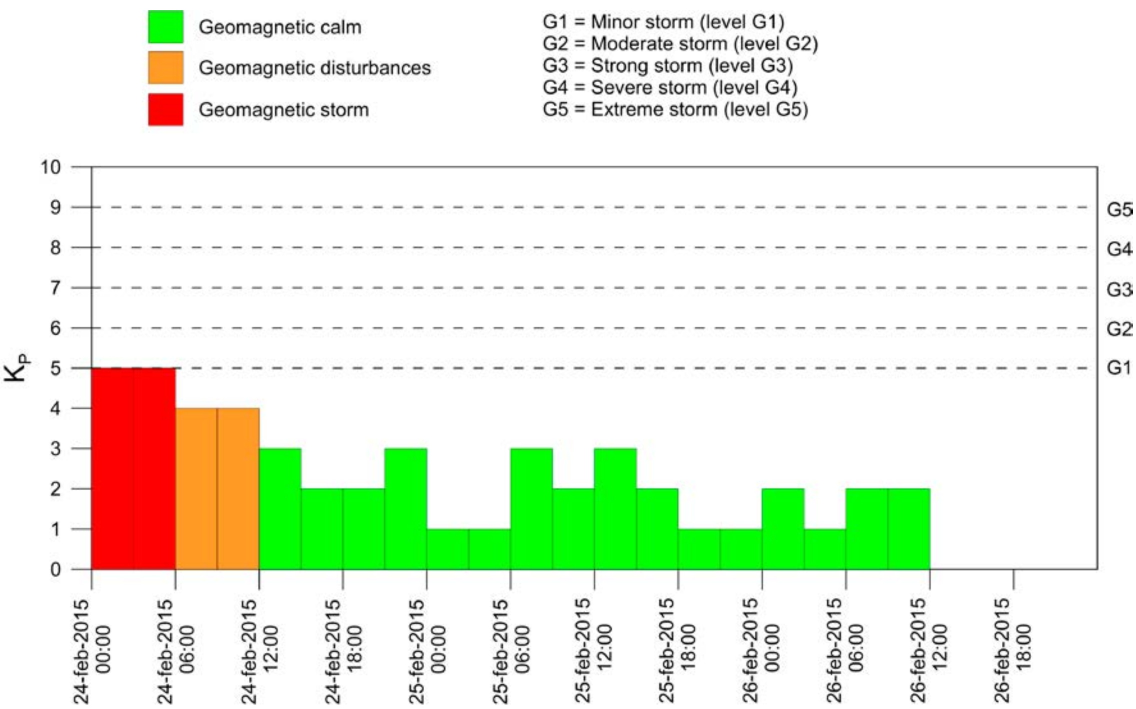

***Figure 4-30.** Magnetic Solar activity from the 24th to the 26th of February 2015 (TESIS n d).*

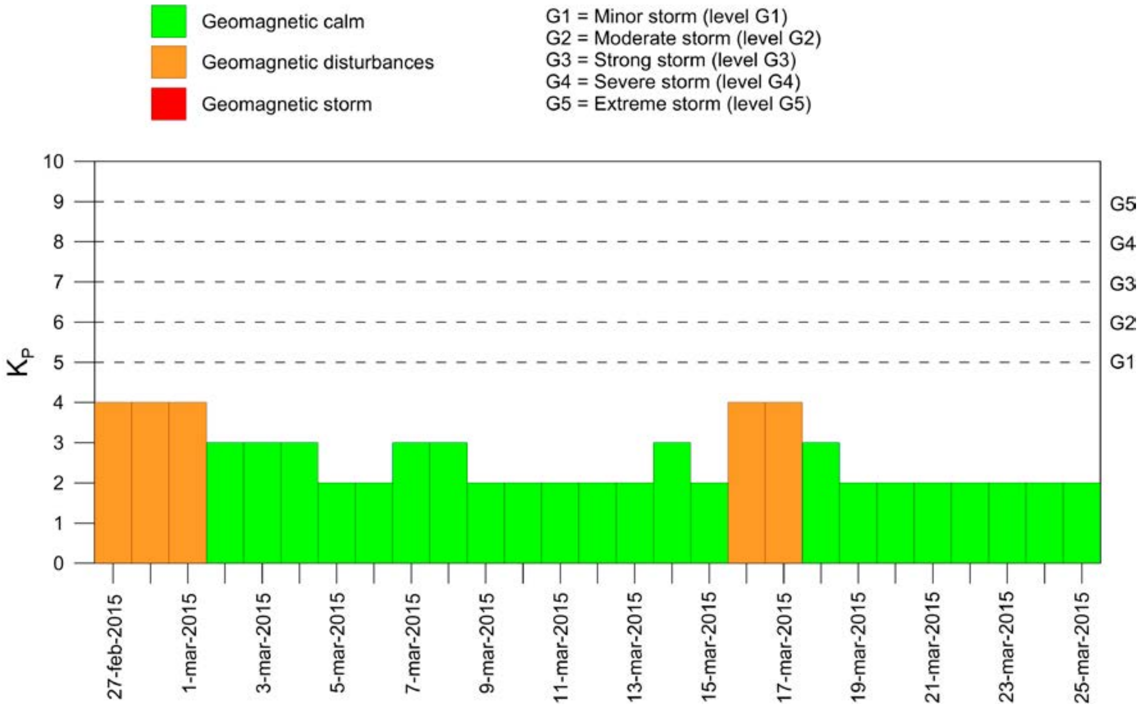

Figure 4-31. *Predicted magnetic Solar activity from the 27th of February to the 25th of March 2015 (TESIS n d).*

Variations in the magnetic field can also be due to HVDC power-lines or other DC or low-frequency sources. A long straight cable carrying 1000 A of current will create a magnetic field of 100 nT at a distance of 2 km. This corresponds to 0.2 % of the magnitude of Earth's magnetic field at Forsmark. The field from a long cable on the ground or at the seabed will also be predominantly vertical and will therefore not affect the declination of the magnetic field very much, unless the observation point is at a depth that is large compared to the horizontal distance to the cable.

It can be concluded that the Fenno-Skan HVDC cable will have quite small influence on deviation measurements based on magnetic tools unless the measurements are carried out, say, within one kilometre from the cable. Borehole surveying close to the HVDC cables should therefore be avoided when the cables are carrying strong currents, especially if the link is operated in monopolar mode. Information about transmitted power can be obtained from SvK (Swedish national grid), but on-line information can also be obtained by monitoring the total magnitude of the magnetic field at some location within around 2 or 3 km from the cables.

4.4.2 Magnetic observatories

Variations in the magnetic field are measured at different observatories. In Sweden, such observatories are located at Abisko, Lycksele and at Fiby outside Uppsala. There is also an observatory at Nurmijärvi in southern Finland. Magnetic data from the Fiby observatory for the day with magnetic storms according to Figure 4-30 can be seen in Figure 4-32. The declination is the most important parameter for borehole surveying. It can be seen in Figure 4-32 that the minor magnetic storm on the 24th of February caused declination variations of the order 0.3°. This is not very much by itself, but if surveying was carried out during this period the variations will add as an almost systematic error to other error sources and the monitoring results might not be up to standard.

Magnetic observatory data from Lycksele during the same day as in Figure 4-32 can be seen in Figure 4-33. One thing to notice is that the declination variations are much larger at the Lycksele observatory. The distance from Fiby to Forsmark is around 70 km. Declination variations are therefore expected to be fairly similar at the two locations during magnetically calm periods. However, the variations cannot be guaranteed to be below any specific limit during magnetically active periods.

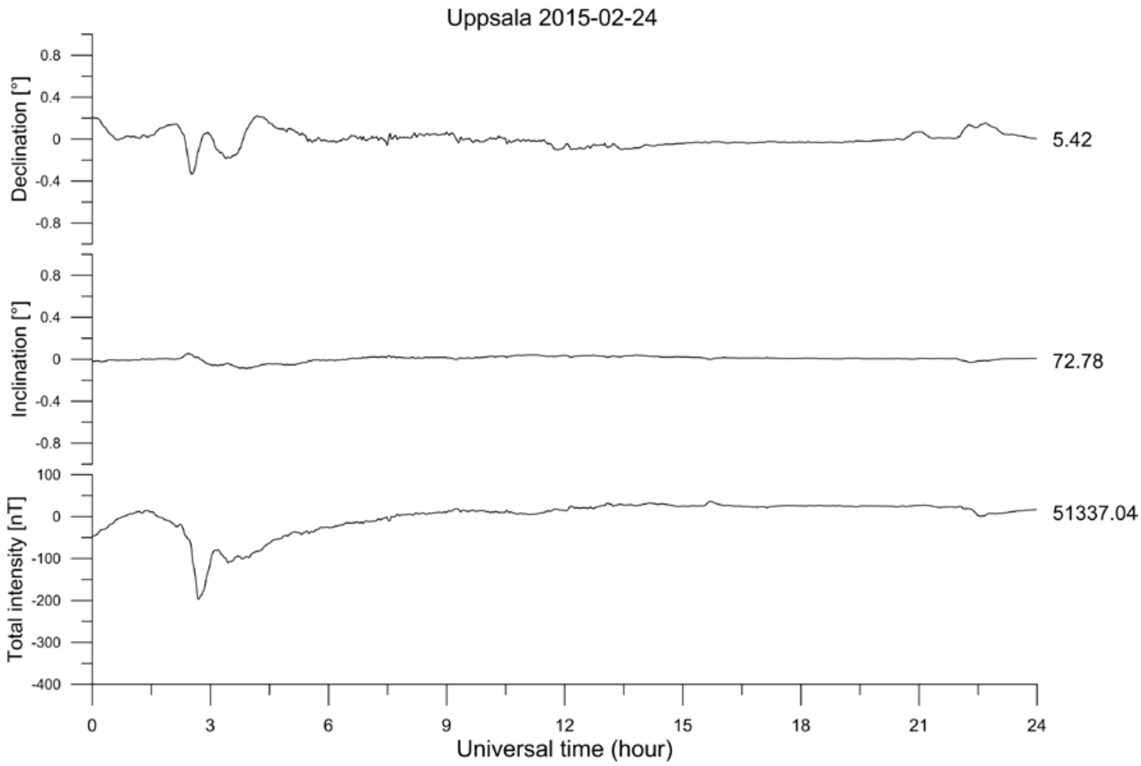

Figure 4-32. *Magnetic data from the Fiby observatory (INTERMAGNET n d). Note the declination variation around 03.00.*

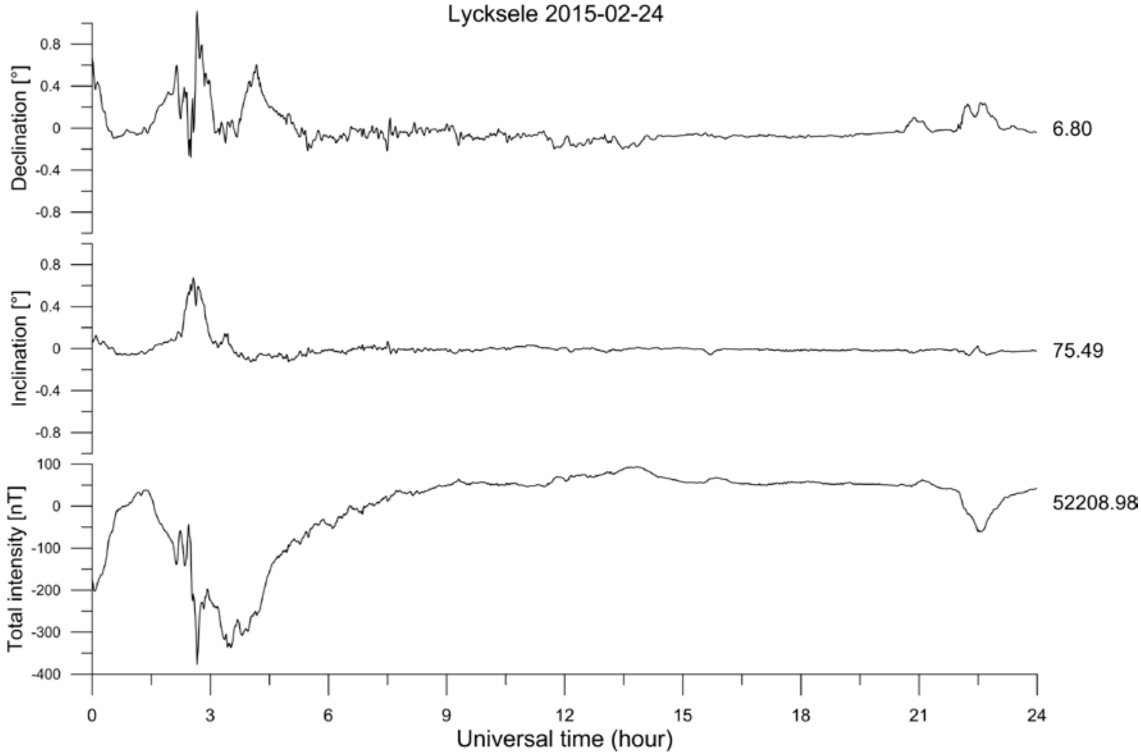

Figure 4-33. *Magnetic data from the Lycksele observatory (INTERMAGNET n d). Note the declination variation around 03.00, which is considerably larger than the corresponding Fiby variations (Figure 4-32).*

4.4.3 Borehole surveying

Boreholes will usually deviate from their intended directions to some extent. It is therefore important to measure the curvature of boreholes so that the positions and orientations of features detected and locations of monitoring conducted along a borehole can be accurately determined. The uncertainty in estimation of borehole orientation has been addressed in Munier and Stigsson (2007). They conclude that even small uncertainties in the measurements could under specific circumstances propagate to induce significant local effects on the computed orientation of mapped objects. In this context, magnetic deviation constitutes only one of several sources of uncertainty that may or may not interact.

Surveying methods rely on measurements of azimuth and inclination of the borehole at discrete intervals. Intermediate positions are calculated by interpolation, where different algorithms are available. The choice of interpolation method is obviously of less concern for a relatively straight borehole.

There are three different methods that dominate the commercial market for borehole surveying.

- **Optical tools.** These tools measure the relative displacement of three rings inside a tube that is bent by the curvature of the borehole. A digital camera is used to record the positions of the rings. Accelerometers may be incorporated into the tool for measurements of the dip. The azimuth at the collar of the hole has to be measured by an independent instrument and entered manually.
- **Magnetic tools.** These tools include a three-axis magnetometer and a three-axis accelerometer. The inclination at different lengths along the hole is estimated with the accelerometer and the azimuth is estimated from magnetic measurements. The tool-face (roll) of the probe is also measured with the help of the accelerometers. As described above, magnetic tools cannot be used in magnetically disturbed areas. Magnetic disturbance can be indicated by comparing the measured total magnitude and the inclination of the magnetic field against normal values.
- **Gyro tools.** Gyro tools have been used for a long time but the development of accurate gyros that are small enough for applications in slim boreholes has been very fast during the last 10–15 years. Some gyro tools only measure relative azimuth changes and the start azimuth at the borehole collar has to be measured separately. However, there are also north-seeking gyros available that estimate the absolute azimuth by measuring the Coriolis Effect on a gyro.

Both optical and magnetic tools were used during the site investigations for the spent fuel repository. It is not possible to say what methods will be used in future work and especially during the construction of a deep repository. It is likely that both magnetic and gyro tools will be used. Both operate with good accuracy under normal conditions and it can be anticipated that redundant measurements and quality checks will be made with different types of tools.

5 Meteorological and hydrological monitoring

5.1 Overview of the monitoring programme

As discussed in Sections 3.1 and 3.2, large amounts of meteorological and hydrological data have been collected at Forsmark, and continued monitoring contributes to the development of the site understanding and to address specific data needs in assessments of environmental and radiological consequences of nuclear waste disposal. This chapter contains a presentation and assessment of the ongoing monitoring at Forsmark, which is divided into sections as follows.

- Meteorology (Section 5.3), which includes continuous monitoring of a number of parameters in automatic meteorological stations in the Forsmark area, followed by data processing in the form of corrections (of precipitation data) and model calculations (to obtain time series data on potential evapotranspiration). The monitoring also includes observations of parameters describing snow and ice conditions in the winter. One automatic meteorological station is currently in full operation (i.e. it is active and delivers data to the Sicada database).
- Hydrology – streams (Section 5.4), which describes how data from discharge stations, primarily water levels in flumes, are measured and processed to yield surface water flow rates. In addition, water temperatures and electrical conductivities are measured in these stations. Four discharge stations are presently in operation in the Forsmark area.
- Hydrology – lakes, ponds and the sea (Section 5.5), including measurements of water levels in the sea, the larger lakes and a number of smaller ponds at the site. Whereas data on sea and lake water levels are central to the overall hydrological understanding of the site, the monitoring of the ponds, which in some cases also includes electrical conductivity, is motivated by their nature values and hence by their importance for the environmental impact assessment. Moreover, present ponds are also analogues for future biosphere objects of relevance for the assessment of long-term radiological safety.
- Near-surface hydrogeology (Section 5.6), which entails monitoring of groundwater levels in the regolith, mostly by means of automatic registration of water levels in groundwater monitoring wells. A majority of these monitoring wells are installed in till, which is the most common regolith type at Forsmark, but also other types of regolith are represented in the programme. The monitoring wells have been installed for different purposes and hence at different locations, such as near bedrock boreholes or lakes, or in the vicinity of objects with high nature values.
- Bedrock hydrogeology (Section 5.7), which considers the monitoring of groundwater levels in open or multi-section percussion- and core-drilled boreholes in the rock. Important aspects of this monitoring are what the data actually represent, given that density differences could be important, and that monitoring data sometimes are affected by disturbances due to, for instance, hydrochemical sampling.

5.2 Monitoring objectives, tasks and parameters

5.2.1 General

Overall key issues that need to be considered in the updated monitoring programme are described in Chapter 3. In that chapter, objectives and data users are divided into four groups, which here are aggregated into two groups:

- Site understanding, site-descriptive modelling, and assessment of long-term radiological safety.
- Assessment of environmental consequences of construction and operation, and repository design and construction.

Most of the meteorological and hydrological monitoring consists of automatic measurements that produce time series of high temporal resolution, which in some cases can be used directly and in other cases require corrections or other post-processing to give the parameters that users need.

This means that data management is important, including development of adequate routines and software systems for handling and checking data and the equipment that produces them.

The main uses of monitoring data produced within this discipline can be summarised as follows.

Direct data deliveries to site descriptions and others that use, for example, meteorological data with only relatively simple processing to provide general information about the site. This is to be able to answer questions such as "What is the annual precipitation at Forsmark?", or to have this type of information available when compiling reports about the site. Previously produced datasets with basic site data should be merged and continuously updated as new data are collected.

Input to conceptual modelling and site understanding**,** which means that data are collected, presented and then evaluated, as a basis for formulating conceptual models and to test various hypotheses regarding how the site works. For example, time series data on groundwater and surface water levels in different subsystems and at different locations are subject to joint interpretation in order to improve the understanding of how these subsystems interact and what implications this might have for the overall hydrological system.

Input to numerical modelling**,** which includes use of time series of meteorological parameters and sea- level data as boundary conditions in hydrological models, and applications of various time-series data for model calibration and validation. Numerical modelling is a basic component of the development of site understanding, and models representing present conditions also provide the starting point for the modelling of future conditions in connection with assessments of long-term radiological safety. In this context, time-series data from the site are often used as a basis for the formulation of calculation cases analysing possible future conditions.

Data for environmental impact assessment and development of monitoring programmes**,** including the important task of identifying the baseline against which monitoring data representing possibly disturbed future conditions are to be compared. This implies that the baseline also should be an important input to the formulation of the monitoring programmes that constitute important "final products" of the licensing processes. Monitoring data are also required for the design of water supply systems and other technical solutions that might be needed to mitigate effects of repository construction and operation on the environment.

Specific issues and monitoring-data needs, which form the basis for the evaluation of the present monitoring programme, are described further below.

5.2.2 Site understanding, site-descriptive modelling and long-term radiological safety

Table 5-1 lists specific objectives/monitoring targets of the meteorological and hydrological monitoring, in relation to the overall key issues listed in Section 3.4. It should be noted that some aspects require further studies, and they have therefore not been fully evaluated in the present report.

Table 5-1. Objectives/monitoring targets for the meteorological and hydrological monitoring, in relation to site understanding, site-descriptive modelling, and assessment of long-term radiological safety.

Site understanding and site-descriptive modelling		
Issue	**Comments**	**Objectives/monitoring targets**
Baseline (for the pre-construction period)	• Basis for conceptual models, process understanding and quantitative models (see below). • Basis for assessment of natural and anthropogenic trends and changes during the construction and operation period. • Various aspects of baseline datasets need to be evaluated well in time before initiation of the construction and operation period, e.g. data gaps, data quality (uncertainties/errors), and whether spatial and temporal distributions of datasets are relevant and representative.	• Description of short- and long-term variations, trends and changes. • Characterisation of influences from existing anthropogenic impacts. • Assessments of correlations (for replacement of missing data relating to reference objects to be used for the construction and operation period).

Site understanding and site-descriptive modelling		
Issue	**Comments**	**Objectives/monitoring targets**
Conceptual models and process understanding	• Description of abiotic subsystems and interactions between sub systems. • Interactions between abiotic and biotic systems. • Conceptual models and process understanding related to type areas and objects in the biosphere, i.e. areas/objects of importance for environmental impact assessment and/or analogues for future biosphere objects. • Assignment of basic parameters to be communicated across disciplines.	• Description of present hydrological subsystems (surface waters, wetlands and groundwater): Surface- and groundwater level time-series data. • Hydrological responses to meteorological periods/events (e.g. precipitation, freeze/thaw, snow melt, and evapotranspiration cycles): Meteorological time-series data, time-series data on groundwater levels and water saturation (unsaturated zone). • Hydraulic connections in rock: Repeated tracer or interference tests. • Characterisation of groundwater recharge and discharge areas: Groundwater-level time-series data from recharge and discharge areas, water-flow rates to/from the saturated zone (e.g. lysimeters). • Interactions between rock and regolith: Same-place monitoring of groundwater levels in rock and the regolith (e.g. areas where deformation zones outcrop, and outside such areas); requires conversions between different types of hydraulic heads. • Interactions between surface water and groundwater (including evaluation of possibly stagnant groundwater): Ground- and surface-water levels, and/or other parameters (e.g. temperature), in regolith, lakes, ponds and streams. • Interactions between lakes/ponds and wetlands (where present): Ground- and surface-water levels, and/or other parameters (e.g. temperature). • Interactions between present SFR and groundwater in present land areas: Groundwater levels in rock (see note on conversions above). • Interactions between the sea and near-coastal lakes: Surface-water levels, electrical conductivity. • Type areas and objects: See above (may also include areas/objects outside the Forsmark area). • Basic meteorological data: Meteorological time-series data (local and surrounding meteorological stations). • Water-balance data: Meteorological and stream-discharge time-series data, groundwater- and surface-water level time-series data (quantification of storage terms).
Quantitative models	• Assignment of initial and boundary conditions, input and calibration data	• Sea-level time-series data. • Meteorological time-series data (precipitation, air temperature, potential evapotranspiration, snow depth. • Groundwater- and surface-water levels (lakes/ponds). • Stream-discharge time-series data.
Assessment of long-term radiological safety		
Near zone	• Assessment of hydrogeological and chemical near-zone conditions, of importance for long-term radiological safety (e.g. canister and buffer integrity).	• See Section 5.7.
Geosphere	• Characterisation of groundwater flow paths in the rock, and chemical properties along flow paths. • Providing data for models of radionuclide transport and accumulation in the geosphere, including tests of alternative models and motivations for model simplifications.	• See Section 5.7.
Biosphere	• Characterisation of groundwater- and surface-water flow paths in the biosphere, and chemical properties along flow paths. • Providing data for models of radionuclide transport and accumulation in the geosphere, including tests of alternative models and motivations for model simplifications. • Providing data to support descriptions of landscape development.	• See Conceptual models and process understanding and Quantitative models above. • Characterisation of natural meteorological and hydrological changes and trends during the construction and operation period, and separation of such changes and trends from influences due to anthropogenic impacts. • Providing data for assignment of initial and boundary conditions for water-flow models for the post-operation period.

5.2.3 Assessment of environmental consequences, and repository design and construction

Table 5-2 provides a preliminary list of objectives/monitoring targets for meteorological and hydrological monitoring, in relation to the overall key issues listed in Section 3.4. From the table, it can be seen that drainage of subsurface facilities is the impact case that requires most of the meteorological and hydrological monitoring. It is also noted that even though monitoring of environmental impacts do not need to be initiated until the start of the construction period, evaluation of some impacts requires a baseline dataset gathered during the pre-construction period (see Section 5.2.2).

5.3 Meteorology

The meteorological monitoring comprises parameters measured at AMS (automatic meteorological stations) and measurements/observations of winter parameters (snow, ice and previously also ground frost). Meteorological monitoring data are used as boundary conditions and input to conceptual and numerical hydrological-hydrogeological models. The method description for meteorological measurements SKB MD 364.007 (SKBdoc 1230439, SKB internal document in Swedish) mainly refers to AMS standards set by WMO (World Meteorological Organization), including inaccuracies, quality control, control measurements and maintenance (WMO 1983). Measurements/observations of winter parameters are done according to standards set by Swedish Meteorological and Hydrological Institute, SMHI (SMHI 1979).

Table 5-2. Preliminary list of impact cases and associated meteorological and hydrological monitoring needs. N.A. = not applicable.

Impact case	Source monitoring	Pathway monitoring	Recipient monitoring
Construction of surface facilities			
Infilling of ponds	N.A.		
Upfilling of land areas	N.A.		
In- and upfilling of sea bay	N.A.		
Construction of bridge	N.A.		
Drainage for construction of building foundations and ramp access	• Groundwater level in and around construction sites.	N.A.	
Rock crushing	N.A.		
Road- and boat transport	N.A.		
Operation of surface facilities			
Rock-dump drainage	• Groundwater-level time-series data from rock dump.	Groundwater-level time series data from areas between the rock dump and drainage-water recipient (cooling-water canal).	• Water flow in cooling-water canal.
Handling of drainage from subsurface facilities	• Groundwater diversion time-series data.	N.A.	• Water flow in cooling-water canal.
Stormwater handling	N.A.		
Sewage-water handling	• Discharge rate	N.A.	• Water flow in cooling-water canal.
Rock crushing	N.A.		
Road- and boat transport	N.A.		
Drainage of subsurface facilities	• Groundwater diversion time-series data.	• Groundwater-level and hydrochemical time series data from the rock (supporting data for delineation of hydraulic influence areas in the rock).	• Delineation of hydraulic influence areas in the biosphere: Groundwater-level time series data from (predicted) influence areas, and from outside of such areas. • Ground- and surface-water levels from type areas and objects. • Stream-discharge time-series data. • Water-level and capacity data from private wells.
Management of wetlands, forests and agricultural areas	N.A.		• Ground- and surface-water level time-series data from managed and unmanaged areas/objects (including constructed ponds).

5.3.1 Present measurements

Figure 5-1 and Figure 5-2 show the locations of SKB's previous AMS (Högmasten and Storskäret) and surrounding meteorological stations operated by SMHI, respectively. Figure 5-2 also shows the new AMS PFM006281 (Labbomasten), which in June 2015 replaced Högmasten at the time when Högmasten was decommissioned. SKB's measurements comprise precipitation, air temperature, air pressure (measured at Högmasten, and at Labbomasten from May 2014), wind speed and wind direction, relative air humidity, and global radiation (only measured at Högmasten), see Table 5-3.

Moreover, PET (potential evapotranspiration) is a calculated parameter. Installations and other technical details are presented in Andersson (2011) and in AMS monitoring reports for the period June 2003–December 2015 (Table 5-4). Wind speed and wind direction are measured at 10 m above the ground surface, whereas all other parameters are measured at 2 m above the ground surface. As mentioned above, the controlling document for the AMS monitoring (Larsson-McCann et al. 2002) mainly refers to WMO standards. According to SKB's activity plans, function control and maintenance are to be performed by SMHI once a year or when needed. Simpler maintenance, such as emptying of precipitation gauges, is done by SKB.

Table 5-3. Equipment and registration intervals for SKB's AMS measurements. Note that PET is a calculated parameter.

Parameter	Equipment	Registration interval
Precipitation.	Geonor T-200 with pedestal and wind shield.	Acc. sum 30 min.
Air temperature.	Pentronic Pt100 with R.M. Young ventilated radiation shield.	Average of 1-sec. values over 30 min.
Barometric pressure (Högmasten and Labbomasten).	Vaisala PTB200.	Average of 1-sec. values over 30 min.
Wind speed and direction.	R.M. Young Wind Monitor.	Average of 1-sec. values over 10 min.
Rel. air humidity.	Rotronic HydroClip MP 100H.	Average of 1-sec. values over 30 min.
Global radiation (Högmasten and Labbomasten).	Kipp & Zonen CM21 with warming and fan.	Average of 1-sec. values over 30 min.
Potential evapotranspiration (PET, calculated for Högmasten and Labbomasten).	Calculated using the Penman equation.	Acc. sum 30 min.

Table 5-4. Summary of monitoring reports on AMS data. The reporting consists of (essentially) annual reports and, from 2011 and onwards, internal quarterly quality-control reports on the AMS data. Until 2010, the annual reports were published in the SKB P-report series. After that, they are internal reports identified by their SKBdoc numbers.

Period	Annual report	Internal QC reports
June 2003–July 2005	P-05-221 (Wern and Jones 2006)	
August 2005–September 2006	P-06-322 (Wern and Jones 2007a)	
October 2006–June 2007	P-07-175 (Wern and Jones 2007b)	
July–December 2007	P-08-100 (Wern and Jones 2008)	
January–December 2008	P-09-04 (Andersson and Jones 2009)	
January–December 2009	P-10-05 (Andersson and Jones 2010)	
January–December 2010	P-11-11 (Andersson and Jones 2011a)	
January–December 2011	SKBdoc (Andersson and Jones 2012b)	Andersson and Jones (2011b, c, d, 2012a)
January–December 2012	SKBdoc (Andersson and Jones 2013b)	Andersson and Jones (2012c, d, e, 2013a)
January–December 2013	SKBdoc (Andersson and Jones 2014b)	Andersson and Jones (2013c, d, e, 2014a)
January–December 2014	SKBdoc (Jones and Kindell 2015)	Andersson and Jones (2014c, d, e, 2015)
January–December 2015	SKBdoc (Jones and Kindell 2016)	Kindell and Jones (2015), Jones (2015a, b, 2016)

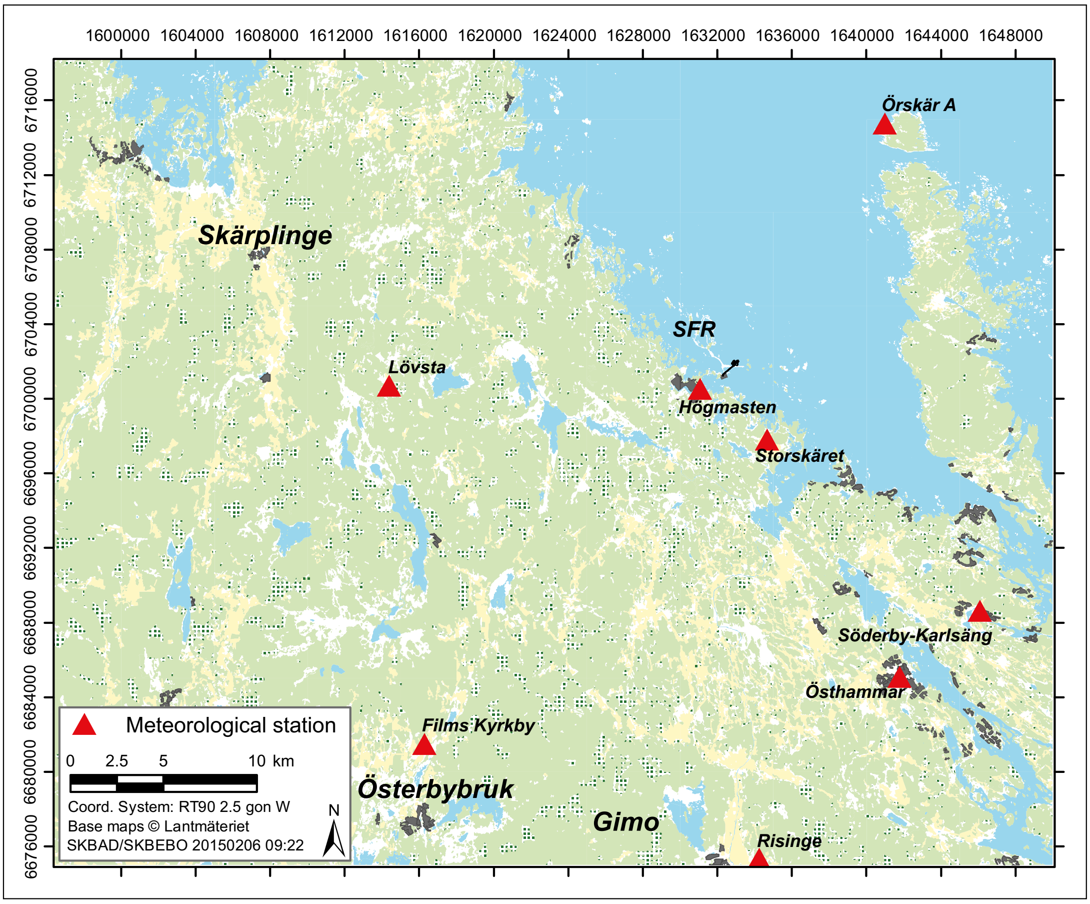

Figure 5-1. Locations of SKB's AMS Högmasten and Storskäret (decommissioned in 2015 and 2007, respectively), and surrounding meteorological stations operated by SMHI. The AMS Labbomasten (cf. Figure 5-2) replaced Högmasten when it was decommissioned.

Figure 5-2. Detailed map showing the locations of SKB's AMS.

Winter parameters, in the form of snow depth, snow weight per unit area (for calculation of the water content of the snow) and lake- and sea-bay ice coverage, are currently measured and observed at five locations (not all parameters at all locations), see Figure 5-3 and Figure 5-4. Ground-frost measurements started during the 2003/2004 winter season. Due to various technical problems, measurements were discontinued after the 2005/2006 winter season. As mentioned above, measurements/observations of winter parameters are done according to standards set by SMHI. Installations and other technical details are presented in winter-parameter monitoring reports for the winter seasons 2002/2003 through 2015/2016 (Table 5-5).

Table 5-5. Summary of monitoring reports on winter parameters.

Period	Annual report
Winter 2002/2003	P-03-117 (Aquilonius and Karlsson 2003)
Winter 2003/2004	P-04-137 (Heneryd 2004)
Winter 2004/2005	P-05-134 (Heneryd 2005)
Winter 2005/2006	P-06-97 (Heneryd 2006)
Winter 2006/2007	P-07-81 (Heneryd 2007)
Winter 2007/2008	P-08-92 (Nyberg and Wass 2008a)
Winter 2008/2009	P-09-70 (Nyberg and Wass 2009a)
Winter 2009/2010	P-10-45 (Nyberg and Wass 2010a)
Winter 2010/2011	P-11-13 (Wass 2011)
Winter 2011/2012	SKBdoc (Wass 2012b)
Winter 2012/2013	SKBdoc (Wass 2013c)
Winter 2013/2014	SKBdoc (Wass 2014c)
Winter 2014/2015	SKBdoc (Wass 2015g)
Winter 2015/2016	SKBdoc (Wass 2016c)

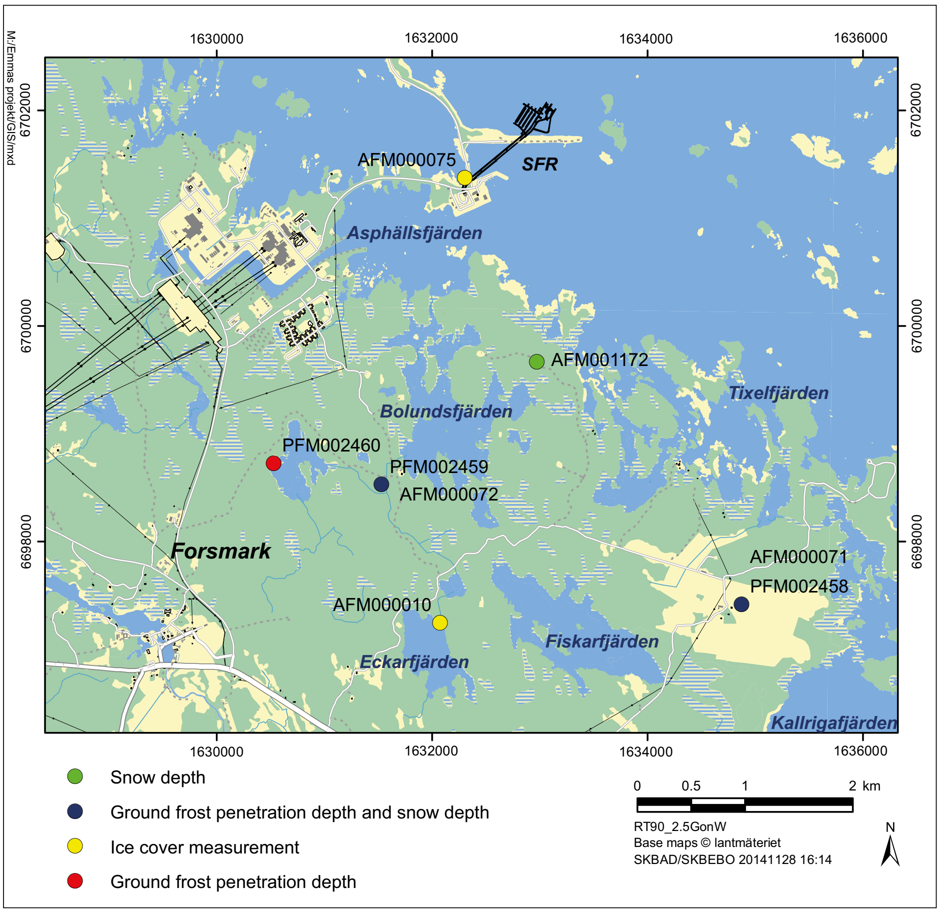

Figure 5-3. Locations of monitoring points for winter parameters. Ground-frost depth measurements were discontinued after the 2005/2006 winter season.

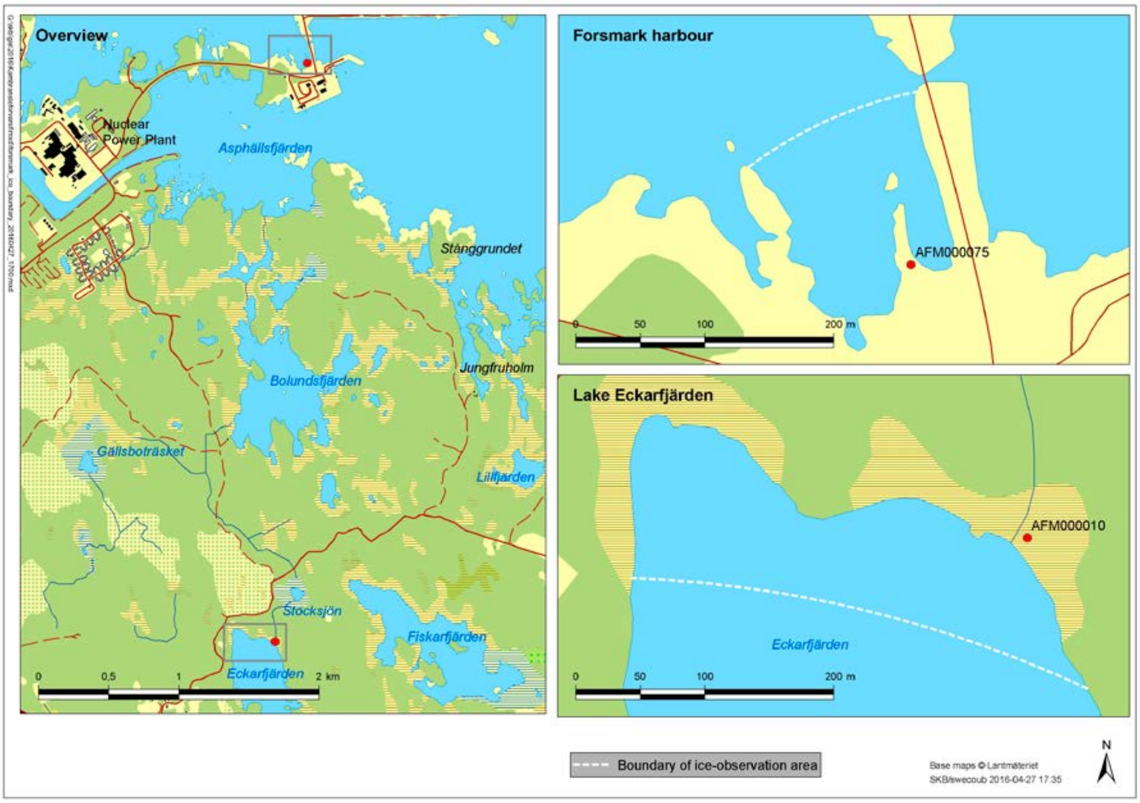

Figure 5-4. *The sea bay (left) and Lake Eckarfjärden (right) are considered to be ice covered when the areas inside the dashed lines have a permanent ice cover.*

5.3.2 Measurement history

Monitoring at the Högmasten (PFM010700) and Storskäret (PFM010701) stations was initiated on May 12, 2003. The Storskäret station was decommissioned on July 1, 2007 and Högmasten was decommissioned on June 10, 2015; the Högmasten AMS is located in the area of the planned surface facilities for the final repository for spent nuclear fuel. A new AMS, PFM006281 (Labbomasten), was established at drill site 1 (i.e. close to bedrock boreholes KFM01A and KFM01B) in 2012 and taken into operation in 2013. Hence, Högmasten/Storskäret and Högmasten/Labbomasten, respectively, have been in operation simultaneously during separate periods. The Labbomasten AMS formally replaced Högmasten at the time when Högmasten was decommissioned. Snow-depth measurements and ice-cover observations started in the winter season of 2002/2003, whereas snow-weight and ground-frost measurements started in the following winter season (2003/2004). Due to various technical problems, the ground-frost measurements were discontinued after the 2005/2006 winter season.

5.3.3 Experience from operation

SMHI's quarterly and annual reports (Table 5-4) show that sensors and other equipment at the AMS generally have worked well during more than 10 years of operation. Moreover, the annual winter-parameter reports (Table 5-5) do not report any nonconformities associated with measurements/observations. In summary, the following problems have been experienced during AMS operation.

- The type of precipitation gauge used at the AMS (Geonor T200) is highly sensitive, causing false registrations of small amounts of precipitation. Such false values are removed by a software filter integrated in the data logger (see further below).
- In 2003, there were some initial system malfunctions at both AMS (Högmasten and Storskäret), causing loss of some precipitation data. Moreover, by mistake the precipitation gauges were not emptied after the 2004/2005 winter season, causing overflow of both gauges during the following summer (Wern and Jones 2006). There have also been some precipitation-data losses in conjunction with gauge emptying (e.g. Wern and Jones 2007b), and also due to technical problems with both precipitation gauges in 2005 (Wern and Jones 2006) and the Högmasten gauge in 2012 (Andersson and Jones 2013b).

- There were temporary malfunctions of the relative-humidity sensors at Högmasten and Storskäret 2006–2007 (Wern and Jones 2007b), and in 2012 it was noted that the Högmasten sensor reported unusually high relative-humidity values during a period (Andersson and Jones 2013b).
- There was a temporary malfunction of the wind measurements (speed and direction) at Högmasten during 2012 (Andersson and Jones 2013b). Moreover, comparisons show that the wind speeds measured at both Högmasten and Storskäret are substantially lower than the wind speed obtained from the MESAN grid points (see further below). According to SMHI, this is due to the MESAN values (one of the grid points is actually located at sea) representing wind at 10 m elevation for a grid area with mixed vegetation, whereas the Högmasten and Storskäret AMS measured wind speed at 10 m above ground level in forest vegetation (e.g. Andersson and Jones 2014b).
- During summer days with clear skies, it is noted that there is a brief shadowing of the global-radiation sensor at Högmasten, hence influencing PET calculations (see further below). According to SMHI, the sensor was partly shadowed by buildings (e.g. Wern and Jones 2006) or possibly vegetation (Andersson and Jones 2014b).
- There was a loss of two weeks of data in September–October 2013 associated with malfunction and replacement of the Högmasten data logger (Andersson and Jones 2013e).
- The barometric-pressure sensor at Högmasten began to malfunction in February 2014 (Andersson and Jones 2014c). A new sensor was installed and became operational at the new Labbomasten AMS in May 2014 (Andersson and Jones 2014d), and there are hence no barometric-pressure data from the AMS during the period February–May 2014.

5.3.4 Present data handling

SMHI is responsible for installation and operation of all AMS equipment, quality control, data operation and data deliveries, whereas measurements and observations of winter parameters are performed by SKB. Every third hour, data are automatically transferred from the AMS data logger to the SMHI Airviro server (Airviro n d) by GSM telephony. Non quality-checked data are transferred daily by ftp to the SKB HMS (Hydro Monitoring System) server. Every week, SMHI checks in Airviro that the sensors are in operation, that the data logger is sending data, and that data seem reasonable. Every third month, SMHI performs a quality control and calculates the corrected precipitation and PET (potential evapotranspiration), see further below. The three-month quality-controlled dataset is delivered to SKB, approved by the activity leader and stored in Sicada. An SKB-internal quality-control report is also delivered, approved by the activity leader and stored in SKBdoc. The results of the meteorological monitoring are reported annually, up to 2010 in the SKB public P-report series and as SKB-internal reports (stored in the SKBdoc document database) from 2011 and onwards.

As part of the quality-control performed every third month, AMS data are compared with data from surrounding meteorological stations and data from MESAN grid points (see below). These comparisons are reported in the annual report. Specifically, monthly and annual sums of uncorrected and corrected precipitation are qualitatively compared with corresponding sums for the SMHI stations Films Kyrkby, Lövsta, Risinge, Östhammar, Söderby-Karlsäng and Örskär (Figure 5-1). Moreover, the annual total potential evapotranspiration is qualitatively compared with corresponding annual sums for the SMHI stations Örskär and Films Kyrkby.

Daily averages of air temperature, air pressure, wind speed and direction and relative humidity from the AMS are compared with corresponding interpolated values from the four nearest MESAN grid points. MESAN (MESoscale ANalysis) is a routine-operating mesoscale meteorological analysis system (Häggmark et al. 1997). Mesoscale meteorology is the study of weather systems on scales less than the synoptic scale (horizontally on the order of 1 000 km) but larger than the microscale (horizontally on the order of 1 km or smaller) and the scale of individual thunderstorms. Specifically, MESAN has the same temporal (4 hours) and spatial (11×11 km^2) resolution as routinely generated data from the HIRLAM (HIgh Resolution Limited Area Model) climate model (Undén et al. 2002). Daily averages of global radiation are compared to values calculated by the Strång system (Gueymard 1995, Landelius et al. 2001), which uses MESAN data as one of its inputs.

According to the annual reports, the Geonor T200 precipitation gauge is very sensitive and may register small amounts of false precipitation. The data logger (Campbell CR10X) is equipped with a software filter, which removes false values from the raw dataset (denoted "001" in the annual reports) and produces a corrected precipitation dataset (denoted "COR"). For instance, consider the following raw-data time series of accumulated precipitation: 50.0, 50.1, 50.0 and 50.2. The second value (50.1) is a false value, which is removed by the filter to produce the corrected time series 50.0, 50.0, 50.0, 50.2 (Frankenberg and Andersson 2010). Moreover, precipitation measurements are generally considered to be subject to three main types of measurement errors:

- Precipitation-catch errors caused by the wind, implying that some part of the precipitation that approaches a gauge from above does not reach the gauge. Although the Geonor T200 gauge is equipped with an Alter type of wind shield, it is subject to larger wind-loss errors compared to the traditional manual type of precipitation gauge (Alexandersson 2003).
- Measurement errors due to evaporation of water from the gauge. A thin oil film is used in the precipitation gauges to prevent evaporation losses. Hence, it can be assumed that there is no need to correct precipitation data for this type of loss (Alexandersson 2003).
- Losses due to adhesion of precipitation within the gauge. For the Geonor gauge, this type of error is corrected by a lumped "adhesion/evaporation" factor, taking into account errors due to evaporation of adhered precipitation (Alexandersson 2003). Specifically, it is assumed that the adhesion/evaporation loss is 0.1 mm/d for each day with precipitation.

Up to the middle of 2005, the precipitation was corrected using a relatively simple method (Wern and Jones 2006), here referred to as the "old" method. Specifically, the actual (corrected) accumulated precipitation (P_a) during each 30-minute period was estimated from the measured precipitation (P_m) as $P_a = P_m \times 1.10$ if the average air temperature during that time interval was less than +1 °C (precipitation in the form of snow), and as $P_a = P_m \times 1.06$ if the average air temperature was equal to or higher than +1 °C (precipitation in the form of rain). During 2005, a new correction method replaced the old method. The new method, which is commonly referred to as the "Alexandersson method", was also used to re-correct previously collected precipitation datasets. The new correction method was originally developed for correction of long-term precipitation time series and first applied to the current so-called reference normal period 1961–1990 (Alexandersson 2003).

Specifically, the Alexandersson method takes wind losses into account based on long-term air-temperature data providing typical monthly fractions of precipitation in the form of rain or snow (the method also uses +1 °C as the rain/snow air-temperature threshold). For purposes of precipitation corrections, in the Alexandersson method monthly average air temperatures are adjusted by subtracting 1 °C during July and adding 2 °C during January to mimic the fact that the air temperature usually drops in conjunction with rainfall in summer, and rises during snowfall in winter. Moreover, monthly wind-correction factors depend on the assigned "wind class" for the AMS (i.e. the degree of wind exposure). Both the Högmasten and Storskäret stations are assigned wind class 2, described as "well protected from wind in all directions, rather close to forest" (Wern and Jones 2006). For this wind class, $P_a = P_m \times 1.06$ during snow and $P_a = P_m \times 1.025$ during rain. In contrast to the old correction method, the Alexandersson method provides month-specific wind-correction factors, independent of the actual air temperature and hence whether precipitation occurs in the form of rain or snow.

The Alexandersson method also considers adhesion and evaporation of precipitation on/from the gauge, using the long-term average (1961–1990) number of precipitation days per month in Sweden to estimate monthly correction factors. For further details, see Wern and Jones (2006) and Werner et al. (2008). The resulting monthly precipitation correction factors (%) for the Högmasten and Storskäret AMS and surrounding SMHI stations are shown in Table 5-6 and Table 5-7, respectively. Hence, the precipitation monitoring produces three types of datasets (following the terminology of the annual reports): Raw data, not stored in HMS or Sicada (001), filtered raw data, stored in Sicada (COR), and calculated actual precipitation, i.e. precipitation corrected for various types of measurement losses, based on COR data and stored in Sicada (ALX).

Table 5-6. Monthly precipitation-correction factors (%) according to the Alexandersson method for the Högmasten and Storskäret AMS (Wern and Jones 2006).

AMS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Högmasten (PFM010700)	13	14	13	11	10	10	10	10	10	10	11	12
Storskäret (PFM010701)	13	14	13	11	10	10	10	10	10	10	11	12

Table 5-7. Monthly precipitation-correction factors (%) according to the Alexandersson method for SMHI meteorological stations surrounding Forsmark (Wern and Jones 2006). A denotes automatic measurements and D denotes manual measurements. Stations without letter have manual measurements.

AMS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Örskär A	19	22	23	15	15	13	13	15	14	15	17	20	16
Östhammar	9	13	10	9	9	12	8	9	8	7	8	10	9
Lövsta	10	9	12	10	11	12	8	8	8	8	9	9	9
Risinge	11	12	10	11	13	12	8	8	8	9	8	9	9
Films Kyrkby A	13	16	19	15	13	14	11	13	13	13	14	16	14
Films Kyrkby D	9	9	12	9	13	13	8	8	8	9	8	10	10
Söderby-Karlsäng	10	11	10	10	12	12	9	9	8	8	8	9	10

As noted above, PET (potential evapotranspiration) is calculated every third month by SMHI. The calculations are done using a modified form of the Penman equation (Penman 1948, Monteith 1965), taking into account heat flux into the ground. The equation requires data on temperature, relative humidity, wind speed and global radiation.

Every winter season, SKB performs measurements of snow depth and weight and observes ice formation and breakup. Specifically, snow depth and weight are measured once per week and registered using specific protocols. Moreover, ice observations in a sea bay are made every day during weekdays, whereas ice observations in Lake Eckarfjärden are done once per week. Ice-freeze and ice-breakup dates are noted in a specific protocol. Measurements and observations are approved by the activity leader after each winter season and stored in Sicada. Measurements and observations are reported annually, up to the end of the 2010/2011 winter season in the public P-report series and as SKB-internal reports thereafter (see Table 5-5).

5.3.5 Available datasets

The datasets from SKB's AMS available in Sicada in January 2015 are summarised in Table 5-8. Table 5-4 provides a list of corresponding monitoring reports, whereas Table 5-5 shows the winter-parameter monitoring reports. The AMS datasets include Högmasten (PFM010700) and Storskäret (PFM010701), both taken into operation on May 12, 2003. Note that air pressure measurements started on July 9, 2003 and that global radiation was measured at Högmasten only; this implies that calculated PET data also are available for Högmasten only. Measurements at the AMS Storskäret were discontinued on July 1, 2007. As mentioned above, the Högmasten AMS was decommissioned and formally replaced by the new Labbomasten AMS (PFM006281) in June 2015. In Table 5-8 it is noted that precipitation data corrected according to the old method are available up to the end of June 2006, but also for two subsequent time intervals (July 2009 and April–June 2011).

As shown in Table 5-9, meteorological data are also delivered annually to SKB for a number of surrounding SMHI stations, including Films Kyrkby (PFM010714), Lövsta (PFM010725), Risinge (PFM010811), Östhammar (PFM010815), Söderby-Karlsäng (PFM010818) and Örskär (PFM010832). These data are used in the annual reports for comparison with measurements at SKB's AMS (cf. above). Table 5-10 through Table 5-14 summarise the SMHI datasets presently available in Sicada. Most data for periods prior to 2003 were compiled as part of the pre-study by Larsson-McCann et al. (2002), including the year 1988 for which data with high temporal resolution were compiled.

In Table 5-10 to Table 5-14, it can be noted that for PFM010714 (Films Kyrkby), daily PET sums are missing for the period October 1, 2006–March 31, 2007 and for the year 2013, and that monthly PET sums are available only up to the end of 2008. Moreover, monthly average air-temperature data are missing for July 2007. For PFM010815 (Östhammar), it is noted that daily P (precipitation) sums are missing for the period August 1, 2011–December 31, 2013, and that monthly P sums are missing for the period July 1, 2011–December 31, 2012 (i.e. for this station, Sicada does not contain P data for the period August 1, 2011–December 31, 2012 and only monthly P sums for 2013). For PFM010832 (Örskär), daily PET sums are missing for the period October 1, 2006–March 31, 2007 and for the year 2013, whereas monthly PET sums are missing for June 2007 and such data are not available after 2008. Moreover, monthly average air-temperature data are missing for June 2007, and wind-direction data are missing for July 1–2, 2007.

For the Örskär station, the 2008 relative-humidity dataset is in Sicada erroneously marked as 2009. The relative-humidity dataset for this station is erroneously denoted to represent the period 1963–1990, whereas measurements started in 1969 according to Larsson-McCann et al. (2002). Larsson-McCann et al. (2002) also points out that the 1961–1990 global-radiation dataset for the Örskär station available in Sicada is based on calculations and not actual radiation measurements.

Table 5-8. Summary of data from SKB's AMS available in Sicada. Dates are given as YYYY-MM-DD.

Parameter	PFM010700 (Högmasten)	PFM010701 (Storskäret)
Precipitation (measured)	2003-05-12–	2003-05-12–2007-06-30
Precipitation (old correction method)	2003-05-12–2006-06-25, 2009-07-01–2009-08-01, 2011-04-01–2011-07-01	2003-05-12–2006-07-01
Precipitation (Alex. correction method)	2003-05-12–	2003-05-12–2007-06-30
PET	2003-05-12–	No data
Air temperature	2003-05-12–	2003-05-12–2007-06-30
Air pressure	2003-07-09–	No data
Global radiation	2003-05-12–	No data
Wind speed and -direction	2003-05-12–	2003-05-12–2007-06-30
Relative humidity	2003-05-12–	2003-05-12–2007-06-30

Table 5-9. Summary of data delivered annually from SMHI to Sicada. Text in italics indicates parameters that according to activity plans are to be included in the annual monitoring reports. "P" denotes precipitation and "A-corrected" the correction method of Alexandersson (2003).

SKB id	Location	Parameter	Temporal resolution
PFM010714	Films Kyrkby	P (measured and A-corrected)	Year, month
		Air temperature	*Year, month*, 3 hours
		PET	*Year, month*, day
		Snow depth	Day
PFM010725	Lövsta	P (measured and A-corrected)	*Year, month*, day
PFM010811	Risinge	P (measured and A-corrected)	Year, month
		Air temperature	Year, month
PFM010815	Östhammar	P (measured and A-corrected)	*Year, month*, day
PFM010818	Söderby-Karlsäng	P (measured and A-corrected)	Year, month, day
		Snow depth	Day
PFM010832	Örskär	P (measured and A-corrected)	*Year, month*, day
		Air temperature	*Year, month*, 3 hours
		Air pressure	3 hours (*day*)
		PET	*Year, month*, day
		Wind speed and -direction	3 hours (*day*)
		Relative humidity	3 hours (*day*)

Table 5-10. Summary of precipitation (P) data from surrounding SMHI stations available in Sicada. "Alex. method" denotes the correction method of Alexandersson (2003). Dates are given as YYYY-MM-DD.

Parameter	Temp. resol.	SKB id (PFM010xxx), cf. Table 5-9					
		-714	-725	-811	-815	-818	-832
Measured	12 hours	2005-08-01–2006-09-30	No data	No data	No data	No data	1994–
	Daily sums	No data	1994–	2005-08-01–2006-09-30	1994-01-01–2011-07-31	2003-12-01–	1994–
	Monthly sums	2003–2004, 2005-01-01–2005-07-31, 2006-10-01–	1961–	2001–	1994-01-01–2011-06-30, 2013–	2005-08-01–	1994–
Corrected (old method)	3 hours	No data	No data	No data	No data	No data	1988
	12 hours	2005-08-01–2006-09-30	No data	No data	No data	No data	1994-
	Daily sums	No data	1994-01-01–2005-07-31	2005-08-01–2006-09-30	1994–2011	2003-12-01–	1994-
	Monthly sums	2003	2003	2003	2001–2003	No data	2001–2003
Corrected (Alex. method)	12 hours	2005-08-01–2006-09-30	No data	No data	No data	No data	1994–
	Daily sums	No data	1994–	2005-08-01–2006-09-30	1994-01-01–2011-07-31	2003-12-01–	1994–
	Monthly sums	2003-01-01–2005-07-31, 2006-10-01–	1994–	2001–	1994-01-01–2011-06-30, 2013–	2005-08-01–	1994–

Table 5-11. Summary of air-temperature data from surrounding SMHI stations available in Sicada. Dates are given as YYYY-MM-DD. There are no air-temperature data from the stations at Lövsta, Östhammar and Söderby-Karlsäng.

Temporal resolution	SKB id (PFM010xxx)		
	-714	-811	-832
1 hour	2004-01-01–2005-07-31	No data	2004-01-01–2006-09-30
3 hours	1994–	No data	1988, 1994-01-01–2003-12-31, 2006-10-01– 2007-06-02, 2007-07-01–
Monthly average	2001-12-31–2005-06-30, 2005-08-01–	2001–2013	1961-01-01–2006-08-31, 2006-10-01–2007-05-31, 2007-07-01–

Table 5-12. Summary of PET data from surrounding SMHI stations available in Sicada. Dates are given as YYYY-MM-DD. There are no PET data from the stations at Lövsta, Risinge, Östhammar and Söderby-Karlsäng.

Temporal resolution	SKB id (PFM010xxx)	
	-714	-832
Daily sums	1999-01-01–2006-09-30, 2007-04-01–2012-12-31, 2014-01-01–	1999-01-01–2006-09-30, 2007-04-01–2012-12-31, 2014-01-01–
Monthly sums	1999–2008	1999-01-01–2007-05-31, 2007-07-01–2008-12-31

Table 5-13. Summary of snow-depth data from surrounding SMHI stations available in Sicada. Dates are given as YYYY-MM-DD. There are no snow-depth data from the stations at Lövsta, Risinge, Östhammar and Örskär.

Temporal resolution	SKB id (PFM010xxx)	
	-714	-818
Daily	1988, 1994-01-01–2005-07-31	2005-08-01–

Table 5-14. Summary of other meteorological data from surrounding SMHI stations available in Sicada. Dates are given as YYYY-MM-DD.

Parameter	Temporal resolution	SKB id (PFM010xxx)	
		-714	-832
Relative humidity	3 hours during daytime (1 AM–7 PM), average per month	1963–1990	1963-01-01–1990-12-31
	3 hours	No data	1988, 2002–
Global radiation	1 hour	No data	1988
	Monthly average (W/m^2)	No data	1961-01-01–1990-12-31
Wind rose	3 months	No data	1968-01-01–2000-01-01 (whole year, 6 wind classes, 8 direction classes)
			1968-01-01–2000-12-31 (wind in connecion to precipitation, as above)
			1968-01-01–1995-12-31 (wind in connecion to snow, as above)
Wind speed and direction	1 hour	No data	2004–2006
	3 hours	No data	1988, 2002–2003, 2007-04-01–2007-06-30, 2007-07-01–2013-12-31 (w speed), 2007-07-03–2013-12-31 (w direction)
	Daily average	No data	2008–
Air pressure	1 hour	No data	2004-01-01–2007-03-31
	3 hours	No data	2002–2003, 2007-04-01–
	Monthly average	No data	2008–

5.3.6 Evaluation

Aspects of relevance for the continued monitoring

Sensors and other equipment at the current Högmasten AMS seem to be in good condition, and the AMS have generally worked well during more than 10 years of operation. Moreover, the annual winter-parameter reports do not report any nonconformities associated with measurements/ observations. However, for important meteorological parameters such as precipitation, air temperature, global radiation (for calculation of potential evapotranspiration) and air pressure, it can be argued that redundancies (more than one sensor) would be justified to protect against failure and to facilitate detection of potential measurement errors.

To handle inevitable dataset inhomogeneities, it is recommended that SKB should compile and evaluate all AMS data to assess differences and correlations between different AMS locations and associated sensors (see further below). For instance, in contrast to Högmasten and Storskäret, the Labbomasten precipitation gauge is equipped with a heater.

A complete evaluation, which also should take into account sensor differences, cannot be performed until late 2016. Specifically, the non-heated Högmasten precipitation gauge has been moved to Labbomasten, where it will be in operation for at least one year in parallel with the heated gauge.

The data evaluation should take into account different types of potential errors and differences, including partial shadowing of global-radiation sensors and dubious wind-speed data.

Parameters and measurements

It is not required to include further parameters in the AMS monitoring. As part of long-term AMS monitoring, it is essential to continue with regular removal of trees, bushes and other maintenance of AMS to secure that the conditions for monitoring are not changed. However, it must also be kept in mind that the AMS monitoring is supposed to reflect land uses, coverage of different vegetation types and other site conditions, which may change with time. Such changes may influence the evapotranspiration and its temporal pattern, which in turn can affect groundwater levels and stream discharges. Influences of land-use and vegetation changes on site-specific meteorological parameters, and their relation to local AMS conditions, are therefore of importance for the continued AMS monitoring. This emphasises the importance of regularly updated land use and vegetation maps (Section 7.2.2.), and high quality hydrological monitoring (Sections 5.4 to 5.6). Moreover, the potential use of long-term ground-frost measurements should be evaluated, as these measurements are not included in the current meteorological monitoring programme. The design of the current snow-depth monitoring programme should also be evaluated, taking into account land uses (that may change with time) and problems to fit these measurements to a relatively simple degree-day model.

It is essential that datasets previously delivered from surrounding SMHI stations are as complete as possible, and that it is clarified and documented how daily average air temperatures and other delivered data are produced. In support of the continued, long-term monitoring, an overview is recommended concerning the relevance of parameters and associated temporal resolutions of the annually delivered SMHI datasets. It is also recommended to secure the access to technical and other types of support for long-term AMS monitoring. The relevance of SKB's current method description can also be questioned, as it mainly refers to standards. Specifically, the AMS monitoring and associated sensors, quality control, control measurements and maintenance follow standards set by WMO (1983), whereas measurements/observations of winter parameters are done according to standards set by SMHI (1979). For the continued, long-term monitoring, rather than repeated method-description updates it is essential with continuous access to technical and scientific support, and to integrate sensor and method developments in the meteorological monitoring when needed.

Testing and inspections of equipment

The recommendation given above regarding an evaluation of the organisation of the AMS monitoring is relevant also for the organisation of AMS testing and inspections.

Data handling and reporting

As part of the previously mentioned compilation and evaluation of AMS data (see above), it is recommended to also consider methods that can be used for quality control and to fill in potentially missing data for important meteorological parameters, such as precipitation, air temperature, potential evapotranspiration and air pressure. Therefore, the evaluation should, as far as possible, include all meteorological parameters, and it should also take into account MESAN data and data from surrounding SMHI stations (including long-term averages).

An evaluation is also required regarding important data-handling methods, such as corrections of precipitation measurements, and methods for calculation of potential evapotranspiration and associated parameters. For instance, the currently used Alexandersson method for correction of precipitation measurements provides month-specific correction factors for precipitation, independent of the actual air temperature and hence whether precipitation occurs in the form of rain or snow. Moreover, as the AMS are equipped with accumulating precipitation gauges, consideration should also be given to reporting accumulated precipitation data to Sicada, as this would facilitate data interpolation in the case of missing highly resolved precipitation data.

5.4 Hydrology – streams

Stream-discharge data are used for water-balance calculations and calibration of numerical hydrological-hydrogeological models. The hydrological monitoring of streams also includes EC (electrical conductivity) and temperature. EC data have mainly been used to demonstrate its generally inverse relation to stream discharge, and to investigate seawater intrusion into Lake Bolundsfjärden (Tröjbom et al. 2007, Johansson and Öhman 2008, Nilsson et al. 2010a). To the authors' knowledge, stream-temperature data have not been used. The method description for hydrological measurements SKB MD 364.008 (SKBdoc 1230440, SKB internal document in Swedish) states that the discharge monitoring has a maximum allowed inaccuracy of ± 5 % of the current discharge. Moreover, it is stated that water-level measurements have a maximum allowed inaccuracy of ± 0.01 m (see discussion in Section 5.4.6). The SKB method description was produced at an early stage, prior to commencement of the monitoring, and it neither provides specific information on discharge measurements using flumes (Figure 5-5), nor does it include EC and temperature measurements.

5.4.1 Present measurements

The current stream monitoring comprises discharge, EC and temperature. The monitoring takes place at four gauging stations (Figure 5-6) equipped with flumes. At each station, the water level at the upstream flume edge is measured automatically every 10 minutes in observation wells located alongside each flume. Moreover, sensors installed in screened tubes located in the streams measure EC and temperature every 10 minutes. Water levels are converted to water depths (i.e. water level minus flume-bottom level), which in turn are converted to stream discharge using flume-specific discharge equations and associated parameters (Table 5-15). The choice of discharge-monitoring equipment is motivated by the limitations set by the flat landscape, the need for accurate measurements, and the desire to avoid introduction of fish-migration obstacles (Johansson 2005). For further details on discharge measurements using flumes, see Clemmens et al. (2001).

Figure 5-5. The two flumes at the recently (2015) refurbished PFM002669 stream-gauging station.

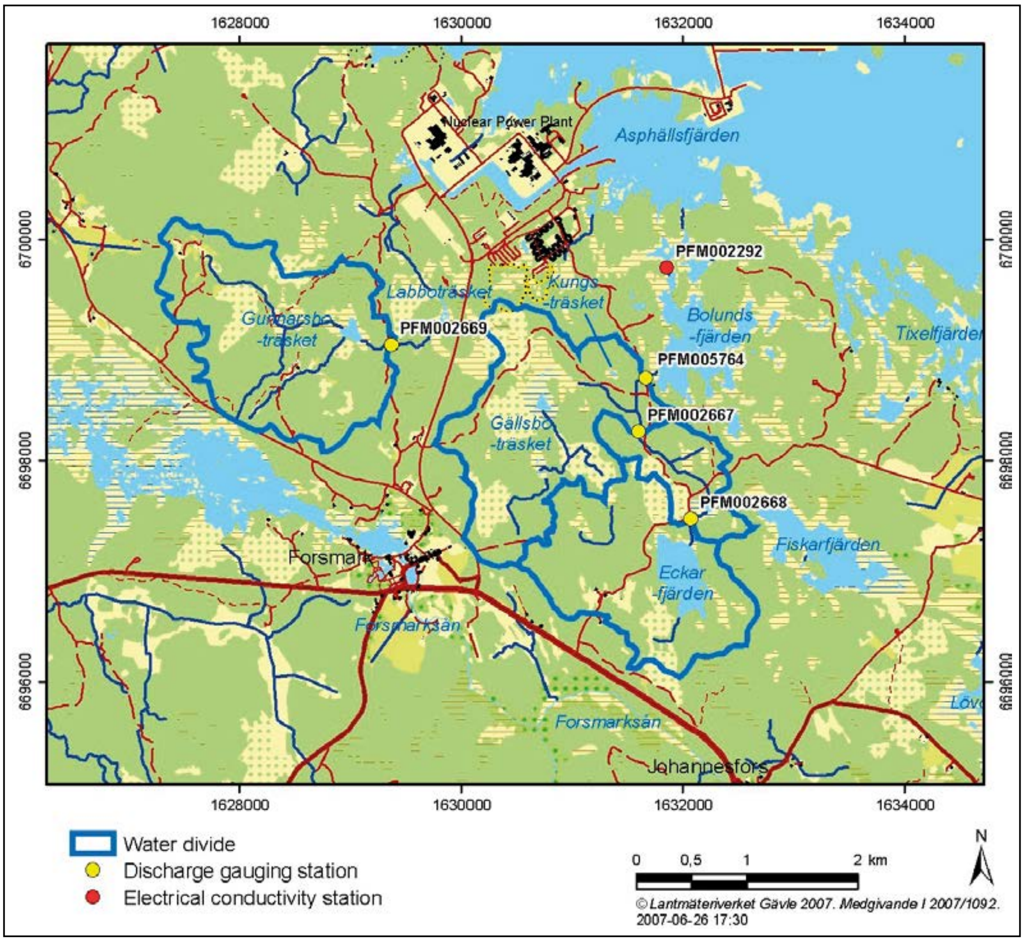

Figure 5-6. Locations of the four stream-discharge gauging stations, their associated catchment areas, and the decommissioned PFM002292 station for EC monitoring. Based on field inspections in 2006, the catchment-area boundaries were revised in December 2006.

Table 5-15. Flume-specific discharge equations Q = f(h) and recommended discharge ranges. Q = discharge (L/s), h = water depth (m).

Id	Discharge eq.	Rec. range (L/s)	dQ/dh
PFM005764			
Nov. 27, 2003–Oct. 1, 2004			
Small flume	$Q = 864.9 \times h^{2.576}$	0–20	$2227.9825 \times h^{1.576}$
Large flume)	$Q = 1175 \times h^{2.15}$	20–70	$2526.25 \times h^{1.15}$
PFM005764			
Oct. 5, 2004–			
Small flume	$Q = 864.9 \times h^{2.576}$	0–20	$2227.9825 \times h^{1.576}$
Large flume	$Q = 2298 \times (h + 0.03459)^{2.339}$	20–1400	$5375.022 \times (h + 0.03459)^{1.339}$
PFM002667			
Small flume)	$Q = 864.9 \times h^{2.576}$	0–20	$2227.9825 \times h^{1.576}$
Large flume	$Q = 2001.5 \times (h + 0.02660)^{2.561}$	20–500	$5125.8415 \times (h + 0.02660)^{1.561}$
PFM002668	$Q = 979.1 \times h^{2.574}$	0–250	$2520.2034 \times h^{1.574}$
PFM002669			
Small flume	$Q = 864.9 \times h^{2.576}$	0–20	$2227.9825 \times h^{1.576}$
Large flume	$Q = 1117.6 \times (h + 0.02727)^{2.604}$	20–920	$2910.2304 \times (h + 0.02727)^{1.604}$

Three of the gauging stations are equipped with two flumes (a small flume and a large flume) to obtain good accuracy over a wide range of discharge (PFM002668 has a single flume). Installations, flume designs and other technical details are presented in Johansson (2005) and in Appendix 1 of

Werner (2014a). The results of monitoring and discharge calculations are reported in Johansson and Juston (2007, 2009, 2011a, b) for the period April, 2004–December, 2010, and in Werner (2014a, b, 2016) for the period 2011–2014 (see Table 5-16). As stated above, the controlling document for the stream monitoring (SKBdoc 1230440, internal document) neither describes discharge measurements using flumes, nor does it include EC and temperature measurements. Moreover, the method description does not provide information on a number of important issues related to long-term monitoring, such as quality control, function controls, maintenance and control measurements. Field inspections are done by SKB, typically once a month (more often if needed), to check and maintain equipment.

Table 5-16. Monitoring reports on stream discharge, EC and temperature.

Period	Report	Reference	Comment
April 2004–March 2007	P-07-135	Johansson and Juston 2007	
April 2007–December 2008	P-09-68	Johansson and Juston 2009	
2009	P-10-44	Johansson and Juston 2011a	
2010	P-11-12	Johansson and Juston 2011b	
2011–2012	SKBdoc	Werner 2014a	Internal report
2013	SKBdoc	Werner 2014b	Internal report
2014	SKBdoc	Werner 2016	Internal report
2015	P-17-27	Werner 2017	

5.4.2 Measurement history

The PFM005764 gauging station was installed in November 2003, and measurements were initiated in March, 2004. Due to damming problems at high discharge, the station was reconstructed and the two flumes were reinstalled in October 2004 (Johansson 2005). The other stations (PFM002667, -2668 and -2669) were installed in October 2004, and measurements were initiated in December 2004. The small flume at the PFM002669 station was stolen in July 2007, and replaced in November the same year.

The PFM005764 station was refurbished in the summer of 2014, including construction of concrete foundations for the flumes and replacement of the small flume, as the previous flume had cracks and a strut that disturbed the inflow to the downstream large flume. Moreover, a pool was dug between the two flumes to reduce the approach flow velocity, and the EC and temperature sensors were moved to the grating located upstream of the station (the previous tube that hosted the sensors disturbed the inflow to the large flume). In addition, a permanent electric supply was installed, which enabled switching the logger to a temperature-insensitive type (see further below).

In December 2004, automatic EC monitoring was initiated at station PFM002292 (Figure 5-6) in the channel between Lake Norra Bassängen and Lake Bolundsfjärden, primarily to identify occasions of seawater intrusion. In the quality control of the 2010 dataset, no PFM002292 EC data were approved due to the poor agreement with manual measurements (Johansson and Juston 2011b). The automatic monitoring at PFM002292 was terminated in the spring of 2012 and replaced by regular (10–12 times per year) manual EC measurements. As a result of extended quality control of EC and temperature measurements in spring 2012, EC and temperature sensors at the stream-gauging stations were moved and attached on the outside of the tubes (Werner 2014a).

5.4.3 Experience from operation

The main practical experience of the functioning of the gauging stations, based on 10 years of operation and inspections by flume experts, can be summarised as follows (Werner 2014a, b).

- The LPG (liquefied petroleum gas) heating systems installed in gravel beds below flumes are not efficient. This implies that regular snow and ice removal is required during winter, even when the heating systems are in operation. Another winter-time issue is freezing of pipes connecting flumes to observation wells, as these pipes are not heated.

- The small flumes are regularly submerged, in particular the small flumes at the stations PFM005764 and PFM002667, leading to erosion damage of the gravel beds that form their foundation.
- The PFM002667 station only works well for discharges up to approximately 55 L/s, when the downstream wetland is filled up. In the rising phase of a discharge peak, when the downstream wetland is not filled up, the station most probably works satisfactorily at considerably higher discharge.
- The plastic cloths that are installed to prevent leakage around the large flumes yield vortices at the flume inlets, which reduces the quality of water-level measurements. Moreover, prior to the 2014 refurbishment of the station PFM005764, the small flume could cause vortices at the inlet to the large flume.
- There is erosion damage downstream of the large flumes, which reduce the stability of the flumes.
- Manual water-depth measurements in flumes are done using a folding rule, which requires that the person making the measurements is walking on the slopes of the flumes. This inevitably leads to erosion damage that need to be repaired.

In order to check the validity of flume-specific discharge equations and associated parameters (cf. Table 5-15), independent discharge measurements were conducted on a number of occasions during the period 2004–2006 (Johansson 2005). Measurements were done using Doppler based area-velocity instruments (discharge = flow area times flow velocity) in flumes and upstream road culverts, and sonar transducers (discharge calculated based on water-depth measurements) in flumes. The general conclusion from these measurements was that flume-specific discharge equations and associated parameters likely are applicable. However, the possibilities to draw any firm conclusions were limited by various types of measurement uncertainties. Due to this incomplete knowledge, it was recommended to perform further area-velocity measurements, including the small flumes at low discharge (Werner 2014a). It was also recommended to clean road culverts from sediments and debris prior to further measurements.

In 2012, vegetation was removed along the stream furrow up- and downstream from gauging station PFM002667, and road culverts up- and downstream from all gauging stations were cleaned from sediments and debris. The overall status of the flumes was checked by flume experts and independent discharge measurements were done in May (Bergqvist 2014) and December 2013 (Bergqvist 2013). The discharge measurements only provided useful results for PFM002668. Specifically, for this gauging station, the independently measured discharge was 95–98 % of the discharge calculated using the flume-specific discharge equation and its associated parameters.

According to the experience described above, sonar-transducer measurements provide useful water-depth data, for comparison with water depths (water levels minus flume-bottom levels) measured by pressure sensors in observation wells. Area-velocity measurements seem less useful for regular checks of the validity of discharge equations and associated parameters, and it was recommended to consider alternative methods for independent discharge measurements, such as the salt-dilution method (Moore 2005, Werner 2014b). Such measurements were performed at all gauging stations in December 2014. It is planned to repeat these measurements, in combination with current-meter measurements, before the applicability of alternative methods is evaluated.

5.4.4 Present data handling

Data from the stream-gauging stations are regularly and automatically transferred from the data loggers to HMS using GSM telephony. Weekly checks are done in HMS that loggers are sending data and that pressure, EC and temperature sensors are in operation. In conjunction with the monthly field inspections, water depths are measured manually at the upstream edge of flumes using a ruler, and a hand-held instrument is used to measure the EC and temperature of the stream water, in the vicinity of the tube that hosts the EC and temperature transducers. Data from the manual measurements are stored in the "Lodis" database (database for manual measurements and field notes), but not in Sicada.

In HMS, pressure data are automatically transformed to water levels (m elevation). Specifically, HMS contains raw-value channels that store logger data (e.g. mA, mV or %), measurement channels (raw values converted to engineering units, e.g. m elevation) and calculation channels. In HMS, the water level in each flume (m elevation) is calculated in two steps. In the first step, raw values are converted to measured values using an expression of the following general form: measured value = $C_0 + C_1 \times$ raw value, where C_0 is the offset and C_1 is the amplification. In the next step, the water level (m) in the flume is calculated by subtracting the air pressure: calculated value = measured value – air pressure. In separate calculation channels, water depths are calculated as water level minus flume-bottom level, and discharge is calculated based on water depth and flume-specific discharge equations and associated parameters (Table 5-15).

Quality control of water-level data stored in HMS is done every third month. Obviously erroneous data are removed from HMS, supported by field notes stored in Lodis from the field inspections. Moreover, manually measured water depths are transformed to water levels and compared to automatically measured water levels. The offset C_0 (see above) is adjusted in case of mismatch (a few mm or more) between the manually measured water level (flume-bottom level + water depth) and the automatically measured water level. In practice, the offset is adjusted if at least two consecutive manual measurements show a mismatch. As part of the quality control, an SKB-internal data report is also delivered, approved by the activity leader and stored in SKBdoc.

Water-level data are not approved and stored in Sicada as part of the quarterly quality control, but a supplementary quality control of such data is done as part of the annual reporting of calculated discharges and EC and temperature measurements (see below), which results in a list of water-level data to be removed from HMS prior to data approval and storage in Sicada. Highly resolved, screened water-level data are used for calculation of hourly average water levels and associated average water depths, as input to calculations of hourly average discharges for approval and storage in Sicada. This process includes choices of which flume to use to represent the discharge at stations equipped with two flumes, based on their recommended discharge ranges (Table 5-15). Transitions between small and large flumes may lead to short-term, artificial discharge fluctuations in situations when the calculated discharge fluctuates around 20 L/s, i.e. around the upper limit of the discharge range covered by the small flume and the lower limit of the range of the large flume. An annual SKB-internal data report is also delivered, approved by SKB and stored in SKBdoc.

EC and temperature data are quality controlled as part of the annual reporting, supported by field notes and manual EC and temperature measurements stored in Lodis. This quality control results in a list of EC and temperature data to be removed from HMS prior to approval and delivery to Sicada. Removed EC data typically concern unreasonably high/low and/or fluctuating values due to ice disturbances or low water level. Moreover, the quality controls show that there is a systematic difference between manually and automatically measured water temperatures at gauging station PFM002668. The monitoring of stream discharge, EC and temperature is reported annually, up to 2010 in the SKB public P-report series and as SKB-internal reports in SKBdoc from 2011 and onwards (Table 5-16).

The stream-discharge gauging stations, and also many surface-water level gauges and groundwater monitoring wells, are equipped with Mitec data loggers. It has been shown that water-level data from these loggers need to be compensated due to their sensitivity to the logger temperature (Geosigma 2005, Johansson 2006). The compensated surface-water level is below the uncompensated surface-water level at high logger temperatures and the opposite at low logger temperatures. The compensation reduces artificial water-level oscillations due to diurnal temperature variations, especially during summer. The compensation is done automatically and stored in specific channels in HMS.

5.4.5 Available datasets

Table 5-17 summarises the stream-gauging station datasets currently available in Sicada, whereas Table 5-16 provides a list of monitoring reports on stream discharge, EC and temperature. At the PFM005764 station (upstream of Lake Bolundsfjärden), EC and temperature monitoring started toward the end of 2003, whereas the discharge monitoring was commenced in April 2004. Monitoring at the other stations started at the end of 2004. As mentioned above, the PFM005764 station was initially taken into operation in November 2003. Due to damming problems, it was considered that the large flume only provided reliable discharge measurements up to about 70 L/s. During the period up to the reinstallation of the flumes, at the beginning of October 2004, the discharge never exceeded 70 L/s (Johansson and Juston 2007). The automatic EC monitoring at PFM002292 was terminated in the spring of 2012 and replaced by regular (10–12 times per year) manual EC measurements.

Table 5-17. Datasets available in Sicada (YYYY-MM-DD) from stream-gauging stations.

Station id	Parameter		
	Stream discharge (hourly averages)	EC (10-minute intervals)	Temperature (10-minute intervals)
PFM005794 (QFM1)	2004-04-15–	2003-12-01–	2003-12-01–
PFM002667 (QFM2)	2004-12-08–	2004-12-08–	2004-12-08–
PFM002668 (QFM3)	2004-12-08–	2004-12-08–	2004-12-08–
PFM002669 (QFM4)	2004-12-08–	2004-12-08–	2004-12-08–
PFM002292 (EC only)	No data	2004-12-09–2009-12-31	No data

The discharge calculation methodology was slightly revised in 2009. Accordingly, a revised stream-discharge dataset, including all data from initiation of measurements up to the end of 2008, was delivered to the Sicada database at the beginning of 2010 (Johansson and Juston 2009). The revised methodology only had minor effects on calculated discharges, affecting annual average discharges by 2 % or less compared to previously reported values. The revised data period includes that of Johansson and Öhman (2008), who analysed data up to the end of March 2007. Due to a handling error, Sicada contains both unrevised and revised data up to the end of March 2007. Moreover, up to the end of 2010 missing hourly discharge values have been estimated and delivered to Sicada. It is also noted that in March 2012, EC sensors were moved to the outside of the tubes that host the sensors.

As the data loggers at the stream-gauging stations are temperature sensitive, the measured water level must be compensated for temperature. Uncompensated water levels have erroneously been used in discharge calculations up to the end of 2010 (Johansson and Juston 2007, 2009, 2011a, b). No systematic analysis has yet been performed on the difference in calculated discharge using temperature-compensated or uncompensated water levels.

New levellings show that flumes and observation tubes have moved since they were installed. It has been shown (Werner 2014a, b) that manual water-depth measurements are important to compensate for such flume movements in discharge calculations. Experience from the independent discharge measurements shows that sonar-transducer measurements provide useful water-depth data, for comparison with water depths (water levels minus flume-bottom levels) measured by pressure sensors in observation wells. However, area-velocity measurements seem to be less useful for regular checks of the validity of discharge equations and associated parameters.

If the hourly average water level is at or below so called zero-discharge levels for the small flumes, the discharge is set to zero (Johansson 2005). Specifically, these levels represent the levels of the connections between pipes and observation wells, which due to installation errors are above the bottom of the upstream edge of three of the four small flumes. This issue has been resolved at the small flume of gauging station PFM005764, where the observation well was reinstalled at a larger depth in September 2006 (the station was also refurbished in 2014). Experience from quality controls shows that EC and temperature monitoring data from streams periodically are heavily fluctuating or are unreasonably high or low.

According to activity plans for the meteorological monitoring, annual, monthly and daily average stream discharges measured at the SMHI discharge-gauging station at Vattholma (SMHI id 50110) are to be delivered from SMHI to SKB once per year. The Sicada database contains a continuous stream-discharge dataset from Vattholma (SKB id PFM102244) from January 1, 1994 and onwards. However, Sicada does not contain any data for the period 1917–1993 reported in Larsson-McCann et al. (2002).

5.4.6 Evaluation

Aspects of relevance for the continued monitoring

Sensors and other equipment at the stream-gauging stations have been exposed to flowing water, snow, ice and debris during many years, causing deterioration that may reduce the quality of discharge data. Experience of about 10 years of operation and checks by flume experts show that refurbishments are required to make gauging stations suitable for long-term monitoring. As mentioned previously, the PFM005764 station was refurbished in the summer of 2014. A building has also been placed above the gauging station. Among other advantages, the building reduces the needs for winter maintenance and provide protection for EC and temperature sensors.

As a basis for refurbishments also of other stations, it is recommended to evaluate the effects of the PFM005764 refurbishment after some time of operation. This evaluation should take into account the electricity based heating system and the new logger (enabled by a permanent electric supply), the concrete foundation, the hydraulic conditions (including the pool between the two flumes), and EC and temperature data from the moved sensors.

Parameters and measurements

It is not required to include further parameters in the hydrological monitoring of streams. Rather, it is recommended to perform an overview regarding the necessity of EC and temperature data in long-term monitoring. EC data, which periodically are widely fluctuating or unreasonably high or low, require time-consuming quality control but have mainly been used to demonstrate the generally inverse relation between EC and stream discharge. Moreover, to the authors' knowledge, the available stream-temperature data have not been used.

It is essential that datasets that are delivered from the SMHI discharge-gauging station Vattholma are as complete as possible, and that it is clarified and documented in detail how the delivered data are produced. In support of the continued, long-term monitoring, an overview is recommended concerning the relevance of parameters and associated temporal resolutions of the annually delivered datasets from the Vattholma discharge-gauging station operated by SMHI. It should also be investigated whether discharge data from Forsmarksån could be obtained, as such data potentially could be used as reference for the data collected at SKB:s stream-gauging stations.

The relevance of SKB's current method description can be questioned. It neither takes into account discharge measurements using flumes, nor EC and temperature measurements. Moreover, the method description does not provide information on a number of important issues related to long-term monitoring, such as quality control, function controls, maintenance and control measurements.

The locations of the stream-gauging stations are relevant, and it is not required to install additional stream-gauging stations. The stations PFM005764 and PFM002669 are considered to be most important, and they were refurbished in 2014 and 2015, respectively. Specifically, PFM005764 has a large catchment area that includes a large part of the area above the planned repository for spent nuclear fuel, whereas the catchment area of PFM002669 is located outside of the predicted hydraulic influence area.

PFM002668 currently seems to be in good condition, and this station requires relatively small refurbishment efforts and construction of a building to reduce maintenance needs. In contrast, it is known that the PFM002667 station does not work well for large discharges (above 55 L/s). At this station, consideration should be given to replacing the current two flumes with a single flume, with a narrower recommended discharge range, and to accept that the PFM002667 station cannot be used to monitor high-discharge periods.

As mentioned above, experience shows that EC and temperature monitoring data from streams periodically fluctuate widely or are unreasonable high or low. If judged necessary to include these parameters in the continued, long-term monitoring, there is a need for improved methods that produce reliable EC and temperature data from streams. As for water-level monitoring, it is required to produce instructions on how errors, natural phenomena (e.g. ice or summer-time ingrowth) or otherwise disturbed EC or temperature data should be detected and deleted as part of the regular quality control.

Testing and inspection of equipment

Instructions should be developed and documented regarding the needs for regular function controls, maintenance, control measurements and levelling of stream-discharge gauging stations. Area-velocity measurements seem less useful for regular checks of the validity of discharge equations and associated parameters. It is therefore required to test and evaluate at least one alternative method that can be used for regular, independent discharge measurements. So called salt-dilution measurements were performed at all gauging stations in 2014. These measurements were repeated and combined with current-meter measurements in 2015, as a basis for evaluation of alternative methods for independent discharge measurements.

It is recommended that further knowledge is gained regarding the influences of, for instance, flume and observation-well movements and altered inflow conditions on calculated stream discharges. It is also recommended that alternative control-measurement methods are investigated. For instance, since 2013 manual measurements are done both of water depths in flumes and depth-to-water level in observation tubes.

Data handling and reporting

It is required to produce instructions on how errors, natural phenomena (dry or dammed flumes) or otherwise disturbed water-level data should be detected and deleted as part of the regular quality control. For water-balance calculations and model-calibration purposes, it is essential to fill in missing stream-discharge data. Up to 2010, such data filling was performed using undocumented methods as part of the monitoring, and it has also been performed using partly documented methods as part of SDM-Site and PSU. It is recommended that data from manual measurements, now only available in the "Lodis" database, are stored in Sicada. It is also recommended that a systematic analysis is done on the difference in calculated discharge using temperature-compensated or uncompensated water levels, and that estimated discharge data stored in Sicada are labelled as such. In addition, it is recommended that a method is developed and documented on how missing discharge data shall be estimated as a basis for water-balance calculations and model calibrations.

As mentioned previously, the SKB method description (SKBdoc 1230440, internal document) states that the discharge monitoring has a maximum allowed inaccuracy of ± 5 % of the current discharge. Moreover, it is stated that water-level measurements have a maximum allowed inaccuracy of ± 0.01 m. As the discharge is calculated based on measured water levels, it is of interest to investigate the practical implications of the inaccuracy limits given by the method description. Table 5-15 presents flume-specific discharge equations (Q = f(h)), associated parameters and recommended discharge ranges. Moreover, the table shows the derivative of each discharge equation (dQ/dh), enabling analyses of absolute and relative discharge errors as function of water depth (h) and water-depth error (dh). In the present analysis, the water-depth error is set equal to the maximum allowed inaccuracy of water-level measurements (dh = 0.01 m).

The analysis shows that in order to attain a maximum discharge accuracy of 5 %, it is required that water-level measurements have a maximum allowed inaccuracy less than the presently required ± 0.01 m. The latter accuracy demand is based on the demand for groundwater-level monitoring using pressure sensors and manual depth sounding (Section 5.6). In order to attain higher accuracy in the stream-discharge monitoring, it is recommended to consider other methods than pressure sensors to measure water levels in flumes.

5.5 Hydrology – lakes, ponds and the sea

Surface-water level data from inland waters (lakes and ponds, i.e. small, shallow lakes) are used as input to conceptual models and, depending on modelling approach, as input to, or for calibration of, numerical hydrological-hydrogeological models. Moreover, sea-level data are used as a boundary condition in such models. In order to assess the suitability of ponds recently constructed as pool-frog habitats, the hydrological monitoring has also included surface-water temperatures in such ponds.

However, the temperature monitoring has not provided reliable data, and the monitoring has been decommissioned until reliable methods are available. A brief overview of methods for surface-water level monitoring is given in SKB MD 364.008. Given the similarities in monitoring methods, the method description for groundwater monitoring SKB MD 360.002 (SKBdoc 1230438, SKB internal document in Swedish) is applied also for surface-water level monitoring. The method description states a maximum allowed level inaccuracy of ± 0.01 m.

5.5.1 Present measurements

The current surface-water level monitoring comprises six lakes, 11 ponds (of which six are constructed) and one sea-level gauge, see Figure 5-7. All gauges in lakes and ponds are made of partially perforated steel pipes, installed from ice cover using a top-hammer drill or a hand-held drill (Johansson 2003, Werner and Lundholm 2004, Werner et al. 2009). Note that there are no installation reports for gauges SFM000128–131 and SFM000136–137, installed in recently constructed ponds. Surface-water levels are measured automatically every 2 hours. The sea-level gauge PFM010038 (Figure 5-8) consists of a pressure sensor lowered through a hole in the concrete floor of a small building in the SFR harbour. As stated above, the controlling document for surface-water level monitoring is, in practice, the SKB method description SKB MD 360.002. Neither this method description nor SKB MD 364.008 provide information on a number of important issues related to long-term monitoring, such as quality control, function controls, maintenance and control measurements.

The results of the surface-water level monitoring are reported as described in Table 5-18 for the period June 2003–May 2014. The controlling document for the surface-water level monitoring is the SKB method description SKB MD 360.002. However, as stated above, it does not provide information on a number of important issues related to long-term monitoring, such as quality control, control measurements, maintenance or function controls. Field inspections are done by SKB, typically once a month, to check and maintain equipment.

Figure 5-7. Locations of surface-water level gauges.

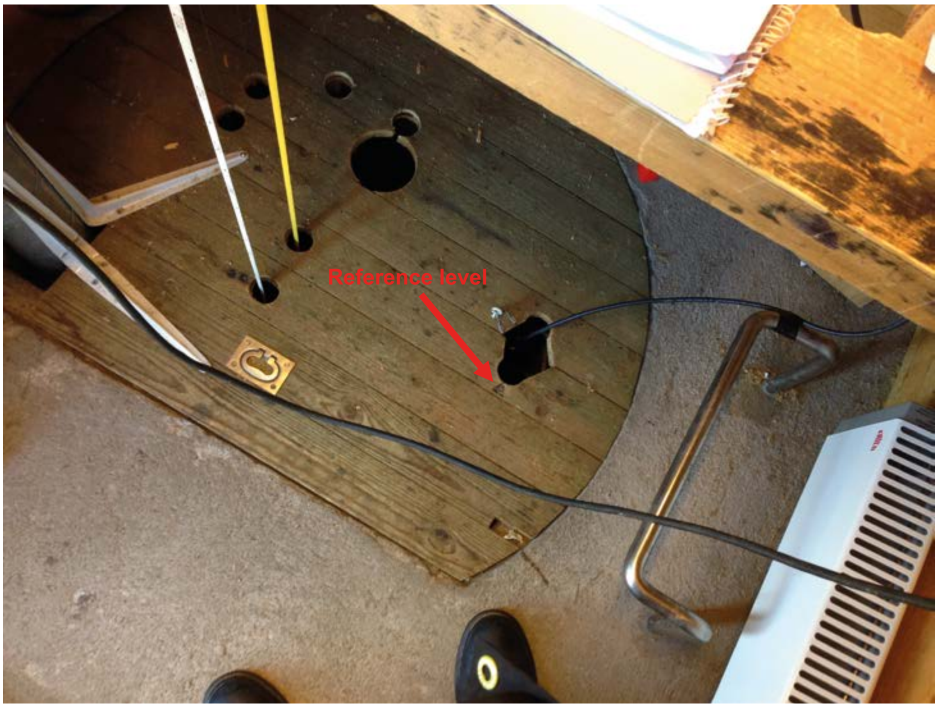

Figure 5-8. The sea-level gauge PFM010038, consisting of a pressure sensor lowered through a hole in the concrete floor of a small building in the SFR harbour. Approximately once per month, the depth to the sea-water level is measured manually using a water-level meter. The reference level for these measurements is the small triangle (marked with a red arrow in the picture) on the near side of the hole in the wooden lid. The SMHI gauge (SMHI station id 2179) is seen to the left of the SKB gauge.

Table 5-18. Monitoring reports on surface-water levels and groundwater levels (presented in the same reports). The reporting consists of annual reports presenting the dataset and internal quarterly quality-control reports. Annual reports until April 2009 are in the open SKB P-report series. After that, they are internal reports identified by their SKBdoc numbers.

Period	Annual report	Internal QC reports
June 2002–July 2004	P-04-313 (Nyberg et al. 2004a)	Nyberg et al. (2004b, c)
August 2004–July 2005	P-05-245 (Nyberg and Wass 2005a)	Nyberg and Wass (2004, 2005b, c, d)
August 2005–September 2006	P-06-263 (Nyberg and Wass 2006a)	Nyberg and Wass (2005d, e, 2006b, c, d, e)
October 2006–March 2007	P-07-113 (Nyberg and Wass 2007a)	Nyberg and Wass (2006e, 2007b, c)
April 2007–April 2008	P-08-72 (Nyberg and Wass 2008b)	Nyberg and Wass (2007c, d, e, 2008c, d)
May 2008–April 2009	P-09-42 (Nyberg and Wass 2009b)	Nyberg and Wass (2008d, e, 2009c) Wass and Nyberg (2010a)
May 2009–May 2010	SKBdoc (Nyberg and Wass 2010b)	Wass and Nyberg (2010a, b, c), Nyberg and Wass (2010b)
June 2010–May 2011	SKBdoc (Wass 2013a)	Wass and Nyberg (2010c, 2011), Wass and Thur (2011b, 2013a)
June 2011–May 2012	SKBdoc (Wass 2015b)	Wass and Thur (2013b, c), Wass et al. (2013)
June 2012–May 2013	SKBdoc (Wass 2014a)	Wass and Ragvald (2013), Ragvald and Wass (2013a, b)
June 2013–May 2014	SKBdoc (Wass 2015c)	Geosigma (2013), Ragvald and Wass (2014b)
June 2014–December 2015	Not available	Wass (2015e, f), Geosigma (2016a, b)

5.5.2 Measurement history

The gauges SFM0038 (sea-level gauge, later renamed to PFM010038), -39 (Lake Norra Bassängen), -40 (Lake Bolundsfjärden), -41 (Lake Eckarfjärden) and -43 (sea bay Kallrigafjärden) were installed in February–April 2003 (Johansson 2003). Moreover, the gauges SFM0042 (Lake Fiskarfjärden),

-64 (Lake Gällsboträsket) and -66 (Lake Lillsjön) were installed in February–March 2004 (Werner and Lundholm 2004). In February 2009, gauges were installed in four ponds (SFM000111, -113, -115, and -117) and in Lake Tjärnpussen (SFM000119) (Werner et al. 2009). The sea-level gauge SFM0043 and the lake-level gauge SFM0066 were permanently destroyed by ice in November 2005 and December 2006, respectively. In March 2011, the lake-level gauge SFM0041 in Lake Eckarfjärden was replaced by a new gauge (SFM000127), and gauges were installed in recently constructed ponds in March 2012 (SFM000128–131) and in March 2014 (SFM000136–137).

5.5.3 Experience from operation

According to the quarterly and annual reports (Table 5-18), missing data periods are mainly due to failures in mechanical or electronic equipment. Monitoring of groundwater-discharge areas, such as lakes and ponds, requires stable monitoring installations. In particular, the ToC (top of casing) of surface-water level gauges is the reference point for manual depth soundings, which are used to check, and, if required, adjust conversions of pressure data to surface-water levels (m, in the Swedish elevation system RHB 70).

The results of original and new ToC levellings (see principle in Figure 5-9) show that the ToC of all gauges are displaced in between levelling campaigns, likely due to winter-time ice shear in lakes and ponds. The total effects of repeated ice-shear periods are upward displacements that vary between 0.003–0.051 m for recently installed gauges (SFM000127–131), 0.0042–0.156 m for the oldest gauges (SFM0039, -40, -42 and -64) and 0.018–0.208 m for gauges installed in 2009 (SFM000111, -113, -115, -117 and -119). Sparse levellings do not provide any information on when actual displacements occurred, which is a serious uncertainty on issues such as actual hydraulic gradients between groundwater and surface water when gradients are small.

As an example, Figure 5-10 shows the results of original and new levellings of the reference level of the sea-level gauge PFM010038 (cf. Figure 5-7 and Figure 5-8). As mentioned previously, the reference level is located in the SFR harbour in a small building with a concrete foundation. The small level differences between the levelling campaigns (+0.007 and –0.002 m) are of the same order as the stated levelling inaccuracies (± 0.009 and ± 0.002 m, respectively), whereas ongoing subsidence (e.g. Dehls 2006) is also a possible explanation for the observed differences.

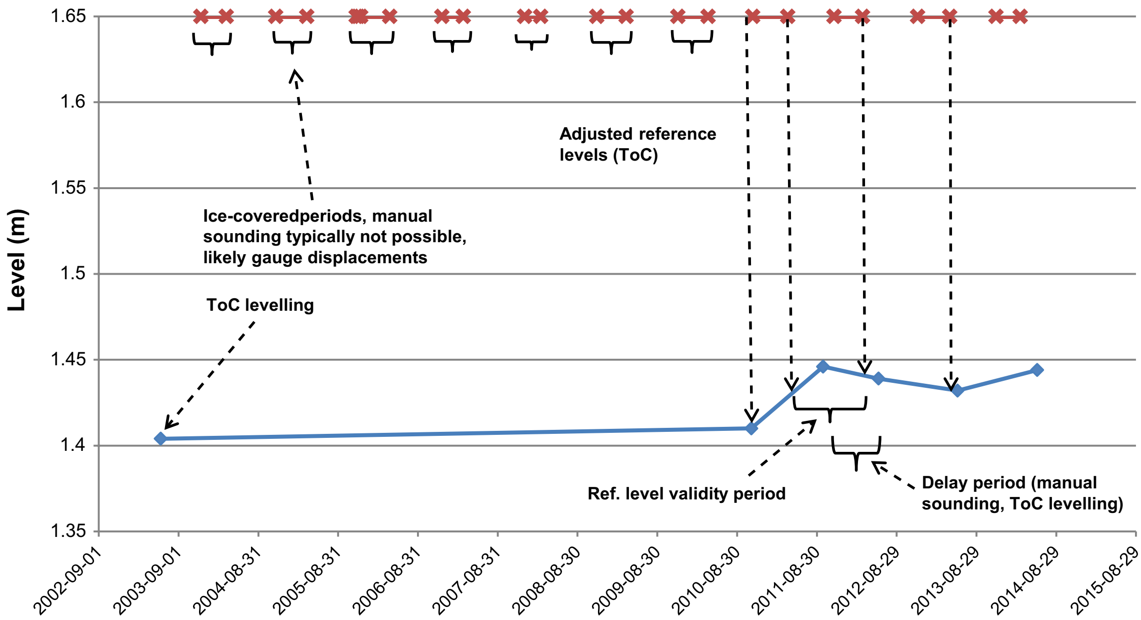

Figure 5-9. *Illustration of the use of annual ToC (top of casing) levellings (blue dots) in the quality control of surface-water level data (lake-level gauge SFM0039). Ice-covered periods (red lines) prevent manual depth soundings and are likely associated with ice-shear gauge displacements. The delay period is typically from ice freeze-up at the beginning of the winter until the subsequent summer-time levelling campaign.*

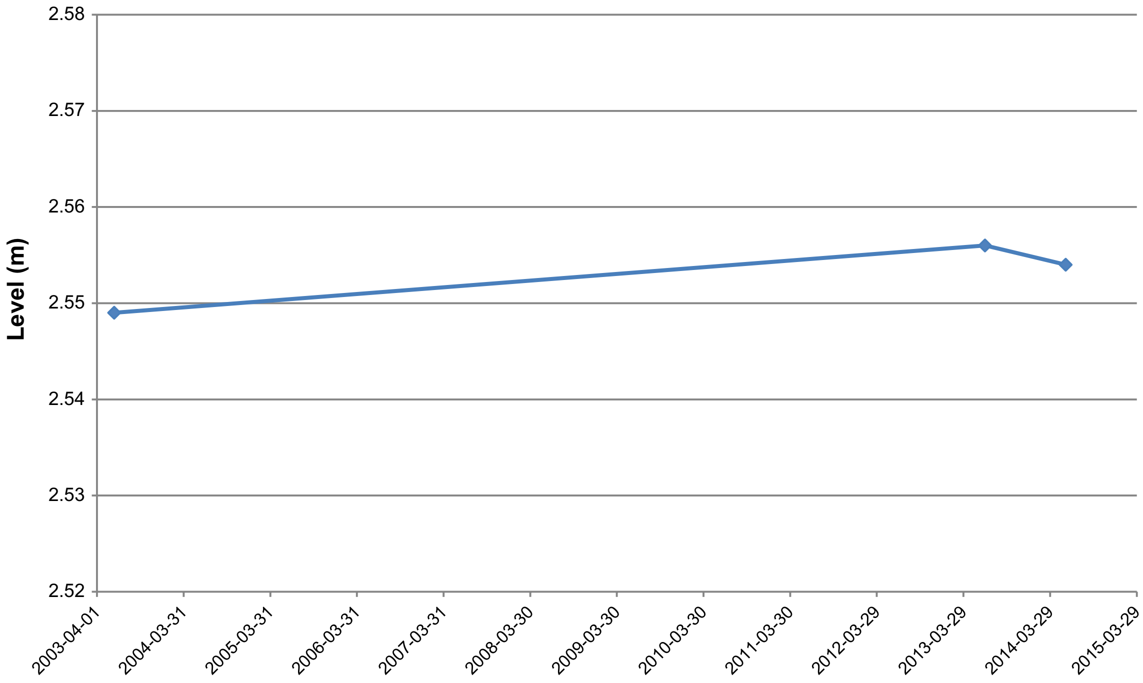

***Figure 5-10.** Results of original and new levellings of the reference level of sea-level gauge PFM010038.*

5.5.4 Present data handling

Data from the surface-level gauges are regularly transferred from the data loggers to HMS, either automatically by GSM telephony or manually, depending on data-logger type. Weekly checks are done in HMS that loggers are sending data and that pressure transducers are in operation. Field inspections are done typically once per month to check and maintain equipment. At these field inspections, surface-water levels are measured manually using a water-level meter. Data from the manual measurements are stored in the "Lodis" database, but not in Sicada.

For a description of the transformation of raw values to calculated values (surface-water level, m elevation), see Section 5.4.4. In the transformation, the offset constant C_0 is adjusted in the case of a poor fit between the manually measured surface-water level (ToC minus depth to water level) and the automatically measured water level.

Quality control of surface-water level data is done every third month, along with groundwater-level data (Section 5.6) and water-level data from stream-gauging stations (Section 5.4). The quarterly quality-controlled dataset is approved by the activity leader and stored in Sicada. As part of the quality control and data delivery, an SKB-internal data report is also delivered, approved by SKB and stored in SKBdoc (cf. Sections 5.4 and 5.6). Moreover, surface-water level data, along with groundwater-level data, are reported annually, up to 2009 in the SKB public P-report series and as SKB-internal reports in SKBdoc from 2011 onwards (Table 5-18).

5.5.5 Available datasets

Table 5-19 summarises the presently available datasets in Sicada, whereas Table 5-18 provides a list of surface-water level monitoring reports. As can be seen in Table 5-19, SKB's sea-level monitoring started in the end of May 2003, whereas hourly sea-level data from the SMHI gauge (SMHI station id 2179, see Figure 5-8) are delivered annually to SKB, approved by the activity leader and stored in Sicada. Moreover, the dataset contains surface-water levels from six lakes at Forsmark (Norra Bassängen, Bolundsfjärden, Eckarfjärden, Gällsboträsket, Fiskarfjärden and Tjärnpussen) and 11 ponds, including six recently constructed ponds. Monitoring of surface-water temperatures in recently constructed ponds (SFM000128–131 and SFM136–137) has not provided reliable data, and the monitoring has been decommissioned until reliable methods are available.

Table 5-19. Summary of surface-water level data available in Sicada. Dates are given as YYYY-MM-DD.

Gauge id	Comment	Start date	Stop date
PFM010038 (previous id SFM0038)	Sea level (gauge oper. by SKB)	2003-05-22	
PFM010039	Sea level (gauge oper. by SMHI)	2003-01-01	
SFM0039	Lake Norra Bassängen	2003-04-30	
SFM0040	Lake Bolundsfjärden	2003-05-16	
SFM0041	Lake Eckarfjärden, mon. terminated (replaced by the new gauge SFM000127)	2003-04-29	2011-02-28
SFM0042	Lake Fiskarfjärden	2004-02-05	
SFM0043	Sea-water level (Kallrigafjärden), mon. terminated	2003-04-28	2005-11-07
SFM0064	Lake Gällsboträsket	2004-04-21	
SFM0066	Lake Lillfjärden, mon. terminated	2004-05-06	2006-12-04
SFM000111	Pond in wetland object 7, see Werner et al. (2009)	2009-04-28	
SFM000113	Pond in wetland object 14 (Norra Labbofjärden), see Werner et al. (2009)	2009-04-28	
SFM000115	Pond in wetland object 16, see Werner et al. (2009)	2009-04-28	
SFM000117	Pond in wetland object 18 (Kungsträsket), see Werner et al. (2009)	2009-04-30	
SFM000119	Lake Tjärnpussen	2009-05-07	
SFM000127	Lake Eckarfjärden, replacement for SFM0041	2011-03-03	
SFM000128	Constructed pond	2012-06-29	
SFM000129	Constructed pond	2012-06-29	
SFM000130	Constructed pond	2012-06-29	
SFM000131	Constructed pond	2012-06-29	
SFM000136	Constructed pond	2014-05-20	
SFM000137	Constructed pond	2014-05-20	
PFM004513	Ephemeral pond in wetland object 23 (gauging scale on gw.-mon. well SFM000118), see Werner et al. (2009)	No data in Sicada	

5.5.6 Evaluation

Aspects of relevance for the continued monitoring

The ToC (top of casing), which is the reference point for manual depth soundings of surface-water gauges, is displaced in between levelling campaigns, likely due to winter-time ice shear in lakes and ponds. Together with the lack of winter-time depth soundings, this phenomenon causes serious uncertainty on issues such as actual hydraulic gradients between groundwater and surface water, and also causes "delay periods" until the subsequent summer-time levelling campaign. There is hence a need to improve gauge installations to make them more stable, to develop simpler methods for regular checks of gauge displacements, and/or other methods for surface-water level monitoring.

Moreover, new levellings of the reference level of the sea-level gauge PFM010038 show small level differences between levelling campaigns. It is recommended to include the sea-level gauge in continued annual levelling campaigns, and to investigate likely causes of the level differences. At some stage, it will be necessary to decide whether the reference level should be changed and, if so, from what point in time. It is necessary to supplement SKB's method description on issues of relevance for continued, long-term monitoring, such as quality control, function controls, maintenance and control measurements.

Parameters and measurements

The locations of the current surface-water level gauges are relevant. However, it is recommended to install a gauge (or some other surface-water level monitoring equipment) in Lake Puttan, as this lake has a small catchment area and may be sensitive to natural or anthropogenic hydrological changes.

In addition, wherever possible, it is recommended to change Mitec data loggers to temperature-insensitive loggers.

Temperature monitoring of recently constructed ponds has not provided reliable data. In order to assess their suitability as pool-frog habitats, it is required to develop methods for long-term monitoring of water temperatures in ponds. It is also required to produce instructions on how errors or otherwise disturbed temperature data should be detected and deleted as part of the regular quality control.

Testing and inspection of equipment

Instructions should be developed and documented regarding the needs for regular function controls, maintenance, and control measurements of surface-water level gauges.

Data handling and reporting

It is recommended that previous, not yet reported, and forthcoming data and monitoring installations are reported in one of SKB's public report series. It is also required to produce instructions on how errors, natural phenomena or otherwise disturbed surface-water level data should be detected and deleted as part of the regular quality control. Moreover, it is recommended that data from manual measurements, now only available in the "Lodis" database, are stored in Sicada. There is a need for a systematic analysis of the differences in temperature-compensated or uncompensated surface-water levels. In addition, it is recommended that a method is developed and documented on how missing sea-level data shall be estimated, including use of the SMHI sea-level gauge, to provide continuous boundary conditions for numerical hydrological-hydrogeological models.

5.6 Near-surface hydrogeology

Monitoring of groundwater levels in regolith and upper rock is important for conceptual modelling and calibration of numerical hydrological-hydrogeological models. As mentioned in Section 5.5, the method description for groundwater-level monitoring SKB MD 360.002 states a maximum allowed level inaccuracy of ± 0.01 m. The present section relates to monitoring of groundwater levels in regolith, whereas monitoring of groundwater levels in rock is described in Section 5.7.

5.6.1 Present measurements

In total, 98 groundwater-monitoring wells and 19 BAT-type filter tips (Torstensson 1984) have been installed in the regolith (Figure 5-11). Of these 98 wells, five are installed to enable interference pumping tests (i.e. they are large-diameter "pumping wells"). Of the total of 117 groundwater-monitoring points (wells and BAT-type filter tips), 99 are installed on land and 18 are installed below surface water (lakes, ponds or the sea). Seven of the 19 BAT-type filter tips are installed for pore-pressure measurements in low-permeable regolith (e.g. clay and gyttja), three are installed for hydraulic conductivity measurements, and nine are installed for chemical water sampling. The pore-pressure and hydraulic-conductivity measurements in the BAT-type filter tips have been terminated (Section 5.6.5). 55 of the totally 117 installed groundwater-monitoring points are not used in the current monitoring.

The well and BAT-type filter tip installations are reported in Claesson and Nilsson (2003a, b, c, 2004a, b, c, 2006, 2007), Johansson (2003, 2004), Werner and Lundholm (2004), and Werner et al. (2004, 2006, 2009, 2014). As described further below, there are as yet no installation reports for some of the wells installed during the period 2011–2014. Groundwater levels are measured automatically every 2 hours. The controlling document for the groundwater-level monitoring is the SKB method description SKB MD 360.002. However, the method description neither describes pore-pressure measurements using BAT-type filter tips, nor does it provide information on a number of important issues related to long-term monitoring, such as quality control, function controls, maintenance and control measurements. The results of the groundwater-level monitoring are reported in the same series of reports as the surface-water level monitoring (see Table 5-18 in Section 5.5), except SFR000001-3 on the SFR pier that are reported in a separate Forsmark-SFR report series (cf. Section 5.7.5). However, pore-pressure measurements in BAT-type filter tips have not yet been reported or evaluated.

Figure 5-11. Locations of groundwater-monitoring wells in regolith.

5.6.2 Measurement history

The first groundwater-monitoring wells were installed in May 2002 (SFM0001–3, Claesson and Nilsson 2003a), December 2002 (SFM0004–5, Claesson and Nilsson 2003b) and January–February 2003 (SFM0006–8, Claesson and Nilsson 2003c). Subsequent installation campaigns comprise those in February–March 2003 (Johansson 2003), April 2003 (Johansson 2004), September 2003 (Claesson and Nilsson 2004a), November 2003 (Claesson and Nilsson 2004b,Werner et al. 2004), February–March 2004 (Werner and Lundholm 2004), June 2004 (Claesson and Nilsson 2004c), June 2005 and January–March 2006 (Werner et al. 2006), November 2005 (Claesson and Nilsson 2006), August 2006 (Claesson and Nilsson 2007), February 2009 (Werner et al. 2009) and September 2012 (Werner et al. 2014). The installations of SFM000121–125 (April 2011), SFR000001–3 (January 2012), SFM000126 (replacement for SFM0015, March 2011) and SFM000138–142 (June 2014) are not yet reported.

5.6.3 Experience from operation

According to the quarterly and annual reports (Table 5-18), missing data periods are mainly due to failures in mechanical or electronic equipment. As mentioned previously, monitoring of groundwater-discharge areas, such as lakes and ponds, requires stable monitoring installations. Similarly to surface-water level gauges (Section 5.5.3) the ToC of monitoring wells is the reference point for manual depth soundings, which are used to check, and, if required, adjust conversions of pressure data to groundwater levels.

The results of original and new levellings show that the ToC heights of all wells are displaced in between levelling campaigns, likely due to winter-time ice shear in lakes and ponds (cf. Section 5.5). The total effects of repeated ice-shear periods are upward displacements that vary between 0.010 m (SFM0081) and 0.213 m (SFM0022). In comparison, displacements for wells installed on land are relatively small (e.g. 0.006–0.011 m for wells SFM000132–135, installed in 2012 and thereafter levelled annually). In the same way as for the surface-water level gauges, sparse levellings cause serious uncertainties on issues such as actual hydraulic gradients between groundwater and surface water.

5.6.4 Present data handling

The data-handling procedures for groundwater-level monitoring data are the same as those described for surface-water level data (Section 5.5.4), including control measurements, quality control and reporting intervals.

5.6.5 Available datasets

Table 5-20 summarises the presently available datasets in Sicada, whereas Table 5-18 in Section 5.5 provides a list of monitoring reports. As can be seen in Table 5-20, the groundwater level monitoring was initiated in wells SFM0001–3 and SFM0004–5 in September 2002 and February 2003, respectively. The monitoring in wells up to well id SFM0057 commenced during 2003, whereas wells SFM0058–65 and SFM0076–107 came into operation during 2004 and 2005–2006, respectively. Some years later, monitoring started in batches of wells installed below ponds and in the vicinity of and within fen areas (2009, 2012 and 2014), in the planned industrial area for the repository for spent nuclear fuel (2011) and in the SFR pier (2012). It can be noted that 55 of the totally 117 installed groundwater-monitoring points are not used in the current monitoring; some of these installations could be used in future monitoring, if needed (after testing).

Table 5-20. Summary of groundwater level data from regolith available in Sicada. Dates are given as YYYY-MM-DD.

Well ID	Comment	Start date	Stop date
SFM0001		2002-09-20	
SFM0002	Mon. terminated	2002-09-20	2006-05-03
SFM0003		2002-09-20	
SFM0004		2003-02-12	
SFM0005		2003-02-12	
SFM0006		2003-12-10	
SFM0007	No mon. data (the well is dry)		
SFM0008		2003-08-21	
SFM0009	Mon. terminated	2003-04-30	2006-01-12
SFM0010		2003-05-14	
SFM0011		2003-04-29	
SFM0012	Below Lake Gällsboträsket	2003-05-09	
SFM0013		2003-04-29	
SFM0014		2003-04-29	
SFM0015	Below Lake Eckarfjärden, mon. terminated (replaced by the new well SFM000126)	2003-04-29	2011-03-01
SFM0016	Mon. terminated	2003-04-29	2006-02-12
SFM0017	Mon. terminated	2003-04-29	2008-09-18
SFM0018	Mon. terminated	2003-04-29	2006-02-12
SFM0019		2003-04-30	
SFM0020	Mon. terminated	2003-04-30	2006-05-03
SFM0021		2003-04-30	
SFM0022	Below Lake Fiskarfjärden	2004-09-16	
SFM0023	Below Lake Bolundsfjärden	2003-05-16	
SFM0024	Below sea bay (Stånggrundsfjärden), mon. terminated	2003-05-25	2003-12-02
SFM0025	Below sea bottom (Kallrigafjärden), mon. terminated	2003-04-28	2008-11-05
SFM0026		2003-08-18	
SFM0027	No mon. data (only manual measurements)		
SFM0028		2003-04-30	
SFM0029	No mon. data		
SFM0030		2003-04-29	
SFM0031	No mon. data		
SFM0032	No mon. data		
SFM0033		2003-05-23	
SFM0034		2003-04-30	

Well ID	Comment	Start date	Stop date
SFM0035	No mon. data		
SFM0036		2003-04-30	
SFM0037	No mon. data		
SFM0049		2003-05-13	
SFM0050	BAT filter tip (only perm. test)		
SFM0051	BAT filter tip (only chem. sampling)		
SFM0052	BAT filter tip (only perm. test)		
SFM0053	BAT filter tip (only chem. sampling)		
SFM0054	BAT filter tip (only perm. test)		
SFM0056	BAT filter tip (only chem. sampling)		
SFM0057		2003-12-12	
SFM0058		2004-05-27	
SFM0059	Mon. terminated	2004-02-16	2006-05-02
SFM0060	No mon. data		
SFM0061		2004-02-16	
SFM0062	Below Lake Bolundsfjärden	2004-06-05	
SFM0063	Below Lake Bolundsfjärden, no mon. data		
SFM0065	Below Lake Lillfjärden, mon. terminated	2004-04-28	2005-11-07
SFM0067	No mon. data (only manual measurements)		
SFM0068	No mon. data (only manual measurements)		
SFM0069	No mon. data (only manual measurements)		
SFM0070	No mon. data (only manual measurements)		
SFM0071	No mon. data (only manual measurements)		
SFM0072	No mon. data (only manual measurements)		
SFM0073	No mon. data (only manual measurements)		
SFM0074	No mon. data (only manual measurements)		
SFM0075	No mon. data (only manual measurements)		
SFM0076	Mon. terminated	2005-01-10	2005-01-29
SFM0077		2005-10-18	
SFM0078		2005-10-18	
SFM0079		2005-10-18	
SFM0080		2006-10-02	
SFM0081	Below Lake Bolundsfjärden (well removed 2013-11-15)	2006-09-19	2013-11-04
SFM0082	BAT filter tip (pore-press. meas., terminated, well removed 2013-11-15)	2006-10-11	2009-01-08
SFM0083	BAT filter tip (only chem. sampling)		
SFM0084		2006-06-19	
SFM0085	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-12
SFM0086	BAT filter tip (only chem. sampling)		
SFM0087		2006-06-19	
SFM0088	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-12
SFM0089	BAT filter tip (only chem. sampling)		
SFM0090	No mon. data		
SFM0091		2006-06-08	
SFM0092	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-08
SFM0093	BAT filter tip (only chem. sampling)		
SFM0094	No mon. data		
SFM0095		2006-05-29	
SFM0096	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-07
SFM0097	BAT filter tip (only chem. sampling)		
SFM0099	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-07
SFM0100	BAT filter tip (only chem. sampling)		
SFM0101	BAT filter tip (pore-press. meas., terminated)	2006-10-10	2009-01-07
SFM0102	BAT filter tip (only chem. sampling)		
SFM0103	No mon. data		
SFM0104		2006-06-19	
SFM0105		2006-06-19	

Well ID	Comment	Start date	Stop date
SFM0106		2006-06-19	
SFM0107		2006-06-20	
SFM0108	No monitoring data		
SFM0109	No monitoring data		
SFM000110	Below pond (wetland object 7, Werner et al. (2009))	2009-04-28	
SFM000112	Below pond (wetland object 14, Werner et al. (2009))	2009-04-28	
SFM000114	Below pond (wetland object 16, Werner et al. (2009))	2009-04-28	
SFM000116	Below pond (wetland object 18, Werner et al. (2009))	2009-04-30	
SFM000118	Below wetland (wetland object 23, Werner et al. (2009))	2009-05-06	
SFM000121	Planned industrial area for the final repository for spent nuclear fuel	2011-05-12	
SFM000122	Planned industrial area for the final repository for spent nuclear fuel	2011-05-12	
SFM000123	Planned industrial area for the final repository for spent nuclear fuel	2011-05-12	
SFM000124	Planned industrial area for the final repository for spent nuclear fuel	2011-05-12	
SFM000125	Planned industrial area for the final repository for spent nuclear fuel	2011-05-12	
SFR000001	SFR pier	2012-02-01	
SFR000002	SFR pier	2012-02-01	
SFR000003	SFR pier	2012-02-01	
SFM000126	Replacement for SFM0015	2011-10-01	
SFM000132	Monitoring of hydraulic test at wetland object 16	2012-10-25	2014-02-05
SFM000133	Monitoring of hydraulic test at wetland object 16	2012-10-25	2014-02-05
SFM000134	Monitoring of hydraulic test at wetland object 16	2012-10-25	2014-02-05
SFM000135	Monitoring of hydraulic test at wetland object 16	2012-10-25	2014-02-05
SFM000138	Fen area, no monitoring during wintertime	2015-06-03	
SFM000139	Fen area, no monitoring during wintertime	2014-07-03	
SFM000140	Fen area, no monitoring during wintertime	2014-07-03	
SFM000141	Fen area, no monitoring during wintertime	2014-07-03	
SFM000142	Fen area, no monitoring during wintertime	2014-07-03	

5.6.6 Evaluation

Aspects of relevance for the continued monitoring

The ToC (top of casing) of groundwater-monitoring wells installed below surface water is displaced in between levelling campaigns, likely due to winter-time ice shear in lakes and ponds (cf. Section 5.5). There is hence a need to improve these well installations to make them more stable, and to develop simpler methods for regular checks of well displacements.

It is recommended to investigate the functioning of some of the current groundwater-monitoring wells to evaluate the maintenance needs, and to perform regular function controls as part of long-term monitoring. It is also recommended to supplement SKB's current method description on issues of relevance for continued, long-term monitoring in terms of quality control, function controls, maintenance and control measurements. Given the specific demands and problems associated with monitoring of near-surface groundwater, it is recommended that a separate method description be produced for monitoring of groundwater levels in the regolith.

Parameters and measurements

Wherever possible, it is recommended to change Mitec data loggers to temperature-insensitive loggers. It is recommended to evaluate different methods for monitoring of near-surface groundwater level and/or discharge in the upper part of the soil profile in fen areas, in which wells are likely to be prone to vertical displacements. This evaluation should include the previously measured BAT-type filter tips, for which pore-pressure data have not yet been reported or evaluated, and recently installed groundwater-monitoring wells in fen areas (SFM000138–142).

The evaluation of methods for monitoring of near-surface groundwater in the upper part of the soil profile in fen areas should include alternative methods such as DTS (distributed temperature sensing), or indirect methods for water-saturation measurements such as TDR (time-domain reflectometry).

Testing and inspection of equipment

Instructions should be developed and documented regarding regular function controls, maintenance, and control measurements of groundwater-monitoring wells.

Data handling and reporting

It is recommended that previous, not yet reported, and forthcoming installations are reported in one of SKB's public report series. It is also necessary to produce instructions on how errors, natural phenomena or otherwise disturbed groundwater- level data should be detected and deleted as part of the regular quality control. It is also recommended that data from manual measurements, now only available in the "Lodis" database, are stored in Sicada. Moreover, there is a need for a systematic analysis of the difference between temperature-compensated and uncompensated groundwater levels.

5.7 Bedrock hydrogeology

Time series of hydrological data in bedrock are acquired in boreholes. The hydrological monitoring is conducted in two areas, the Forsmark-SFR area and the Forsmark-Lens area. The Forsmark-Lens area is roughly defined by the eight insets A–H, shown in Figure 5-12, which together encompass the extent of the repository area for spent fuel. The current borehole monitoring in the Forsmark-Lens area only includes boreholes drilled from the surface, as the subsurface operations have not yet started. The Forsmark-SFR area coincides with inset I in Figure 5-12, and covers the submarine facility for short-lived low and intermediate level radioactive waste (SFR). About half of the monitored boreholes in the Forsmark-SFR area are subsurface boreholes, i.e. they are drilled from the underground SFR facility.

The hydrological monitoring in bedrock is conducted in two types of boreholes, core-drilled and percussion-drilled boreholes. The core-drilled boreholes are slimmer than the percussion-drilled and generally drilled to greater depths. Further, the boreholes in the Forsmark-SFR area are not as deep at the boreholes drilled in the Forsmark-Lens area. Apart from these differences, the collection of hydrological data is conducted in more or less the same way as explained below.

The hydrological monitoring in different places and at different depths is a means to distinguish the effects of natural meteorological-hydrological variations occurring at the ground surface from the effects of forthcoming anthropogenic hydrological disturbances associated with subsurface investigations and the execution of underground excavations. Time series of hydrological data from the bedrock are also used as input to conceptual and numerical hydrological-hydrogeological models, which in turn are used as input to safety assessment and environmental impact assessment.

5.7.1 Present measurements

The hydrological monitoring comprises two quantities:

- Groundwater level (m).
- Groundwater flow (m^3s^{-1}).

The method description for monitoring of groundwater levels and groundwater flow is SKB MD 360.002 (SKBdoc 1230438, internal document in Swedish). The 2012–2014 activity plan for monitoring of groundwater levels is AP SFK-10-042 (SKBdoc 1353113, SKB-internal document) and the 2015–2017 activity plan for monitoring groundwater levels is AP SFK-10-083 (SKBdoc 1464444, SKB-internal document). A major difference between the 2012–2014 and 2015–2017 activity plans is that the latter includes all monitored boreholes in both areas, whereas the 2012–2014 plan only considers monitoring of boreholes in the Forsmark-Lens area.

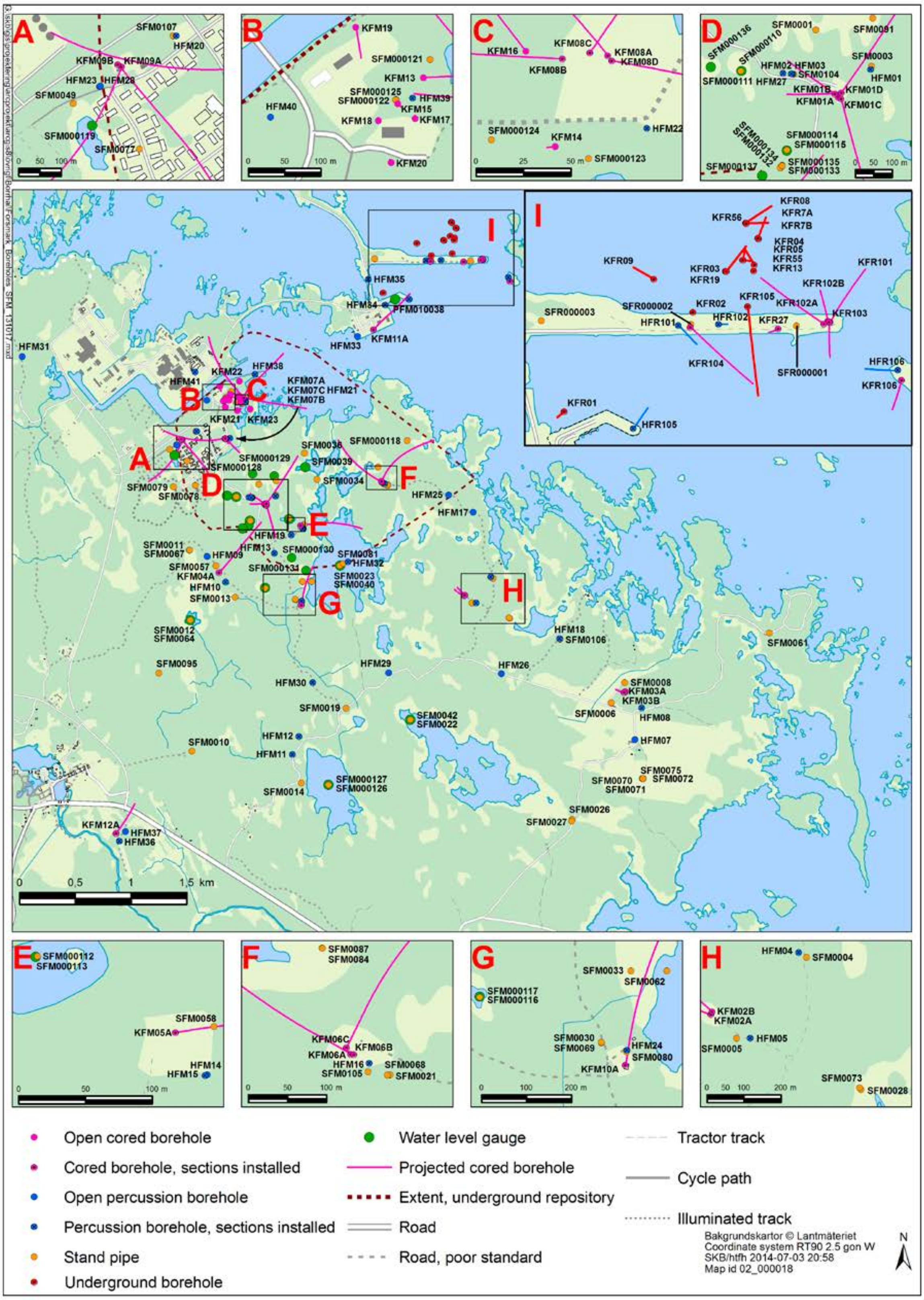

Figure 5-12. The hydrological monitoring in the bedrock in Forsmark is conducted in two areas, the Forsmark-Lens area (roughly defined by the insets A–H) and the Forsmark-SFR area (defined by the area of inset I). Hydrological data from the bedrock are acquired in two types of boreholes, core-drilled and percussion-drilled. A large number of boreholes have several monitoring sections which are separated by inflatable packers.

Groundwater flow is not monitored in the Forsmark-SFR area. The activity plan for monitoring groundwater flow in the Forsmark-Lens area in 2012 is AP SFK-10-050 (SKBdoc 1369718, SKB-internal document) and the activity plan for the 2014–2015 monitoring of groundwater flow is AP SFK-10-080 (SKBdoc 1443878, SKB-internal document). A major difference between the two activity plans is that in the plan for 2014–2015, the monitoring of groundwater flow in the Forsmark-Lens area is significantly reduced, from thirty to six borehole sections.

5.7.2 Measurement history

The hydrological monitoring in the Forsmark-SFR area started in the early 1980s in conjunction with the construction of the SFR 1 facility and has been extended in recent years during the site investigations for the extension of SFR. Bedrock drilling campaigns and boreholes in the Forsmark-SFR area can be summarised as follows.

- 59 core-drilled boreholes (KFR01–06, 07A–C, 08–14, 19–25, 27, 31–38, 51–57, 61–72, 80, 83–89) were drilled in the Forsmark-SFR area during the 1980s.
- During 2008–2009, seven additional core-drilled boreholes (KFR101, 102A–B, 103–106) and four percussion-drilled boreholes (HFR101–102, 105–106) were drilled as a part of the site investigations for extension of SFR. In addition, the existing borehole KFR27 was extended. Equipment for automatic pressure measurements was installed in new boreholes and a subset of the boreholes from the 1980s.
- In 2014, again for the SFR extension project, an additional ten core-drilled boreholes were drilled (KFR107-116) and supplied with equipment for automatic pressure measurements.

In the Forsmark-SFR area, measurements are currently conducted in the 31 core-drilled boreholes and the four percussion-drilled holes listed below (see Section 5.7.5 and the current activity plan). Data from twelve of the core-drilled boreholes are included in the monitoring programme reported annually to SSM (see Sections 3.3.3 and 5.7.5 and Harrström 2016).

- Core-drilled: KFR01–05, 7A–B, 08–09, 13, 19, 27, 55–56) and KFR101, 102A–B, 103–116).
- Percussion-drilled: HFR101–102, 105–106.

Of the core-drilled boreholes in the monitoring programme, seven are surface boreholes, i.e. are drilled from the ground surface, whereas 24 are drilled from the SFR tunnels. All four percussion-drilled boreholes are surface boreholes.

The site investigation for the spent fuel repository in the Forsmark-Lens area began in 2002, and the hydrological monitoring started in 2003.

- 25 core-drilled boreholes (KFM01A–12A, 1B–3B, 6B–9B, 1C, 6C–8C, 1D, 8D) and 38 percussion-drilled boreholes (HFM01–38) were drilled in the Forsmark-Lens area during 2002–2007. During 2011–2012, eleven additional core-drilled boreholes (KFM13–23) and three percussion-drilled boreholes (HFM39–41) were drilled as part of the preparatory investigations for the spent fuel repository.
- Measurements are currently conducted in 33 core-drilled and 36 percussion-drilled boreholes. The monitored core-drilled boreholes are KFM01A–12A, 1B–3B, 6B–9B, 1C, 6C–8C, 1D, 8D) and KFM16–23, whereas the monitored percussion-drilled boreholes comprise HFM01–05, 07–27, and 29–38.

Surface boreholes are either fully open (one monitoring section) or have two or more monitoring sections, see Figure 5-13. The sections are separated by 1-m long inflatable packers. Boreholes with two or more monitoring sections have at least one stand pipe that reaches the “top of casing” of the borehole, where the measurements are made. Some tests require two stand pipes, see below. Subsurface boreholes are never open, i.e., they have always at least one packer placed at the “well head” (“top of casing”), see Figure 5-14. Table 5-21 shows the number of current boreholes and monitoring sections in each area.

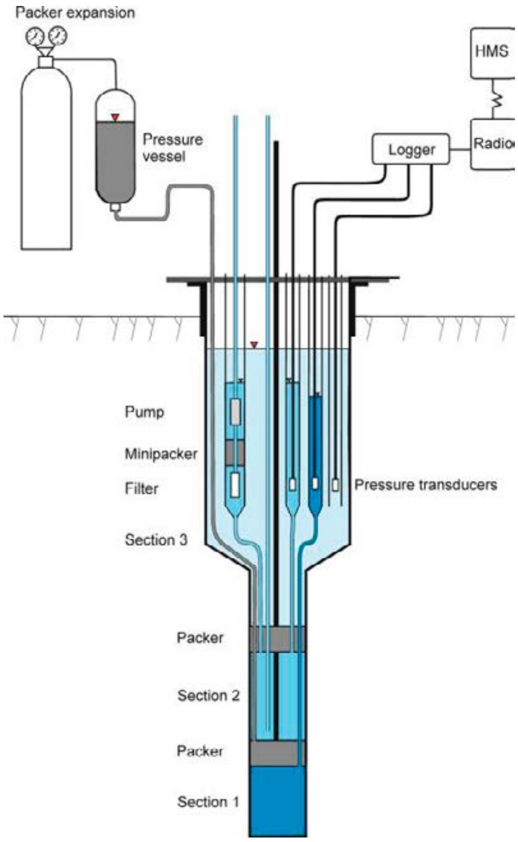

Figure 5-13. *Simplified outline of equipment for pressure, groundwater composition, and groundwater flow monitoring in a telescopic borehole drilled from the ground surface. (Telescopic means that the uppermost part of the borehole has a much larger diameter than the rest of the borehole.) The sampling equipment (from the top: pump, mini packer and filter) is placed in a stand pipe, which connected to the section of interest (section 2 in this figure). A maximum of ten stand pipes/pressure sections can be installed in a telescopic borehole, of which generally two are equipped for water sampling and circulation of tracers during groundwater flow measurements (e.g. section 2 in this figure). (Groundwater flow measurements require two stand pipes.) The other sections are equipped solely for pressure measurements and connect to one narrow stand pipe each (e.g. section 1).*

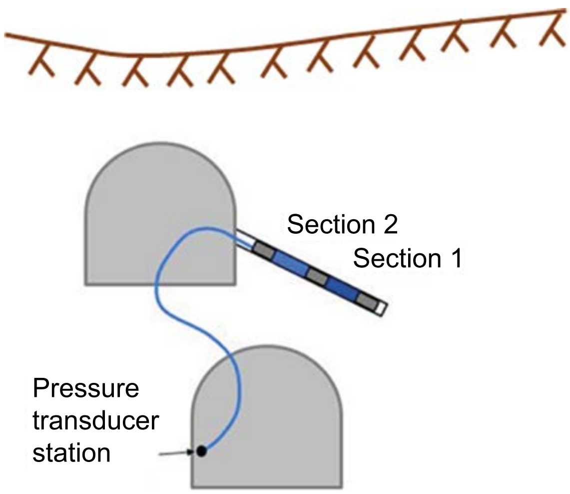

Figure 5-14. *Simplified outline of equipment for pressure monitoring in a borehole drilled from the subsurface. Pressure is measured by means of a hose from the section of interest (section 2 in this figure) that connects to a pressure transducer station at another level.*

Table 5-21. Number of monitored boreholes and borehole sections in the Forsmark-SFR and Forsmark-Lens areas. Values in parentheses refer to the monitoring programme reported annually to SSM.

Monitoring	Forsmark-SFR	Forsmark-Lens
Number of boreholes with one monitoring section	1 (1)	20
Number of boreholes with two or more monitoring sections	21 (11)	28
Number of monitoring sections, groundwater level	77 (38)	228
Number of monitoring sections, groundwater flow and level	0 (0)	34
Number of unmonitored (”blind”) sections	4 (4)	4

5.7.3 Experiences from operation

The method description for groundwater monitoring in the Forsmark-Lens area requires that the density of the water in the stand pipe should be the same as the density of the groundwater in the bedrock where the monitoring section is located. This implies that monitored groundwater levels are point-water hydraulic heads h_p (m):

$$h_p(z) = \frac{p(z)}{\rho(z)\, g} + z \qquad \text{(Eq 5-1)}$$

where $p(z)$ (Pa) is the gauge pressure in the stand pipe at the point of measurement, z (m) is the elevation of the point of measurement relative to a geodetic datum, $\rho(z)$ (kg/m^3) is the vertical groundwater-density profile in the bedrock (as measured in the monitoring sections), and g is the acceleration of gravity (m/s^2). In the Forsmark-SFR area, however, it has since the measurements started in the early 1980's been common practice to express all pressure measurements conducted in the subsurface boreholes as fresh-water hydraulic heads:

$$h_f(z) = \frac{p(z)}{\rho_f\, g} + z \qquad \text{(Eq 5-2)}$$

where ρ_f as a rule is set to 1 000 kg/m^3. The reason for using freshwater hydraulic head in the Forsmark-SFR area is that potential buoyancy effects in the groundwater in the uppermost part of the bedrock are considered small, as the salinity of the brackish seawater is very low. However, it is noteworthy that the density of the groundwater is measured neither in the monitoring sections nor in the hoses (cf. Figure 5-14).

Figure 5-15 shows how the content of total dissolved solids in groundwater, TDS (mg/L), and groundwater temperature varied with depth in a number of deep core-drilled boreholes in the Forsmark-Lens area at the time of the site investigation. The buoyancy forces that arise due to the associated density variations affect the flow field differently at different depths, and hence flow interpretations based on point-water hydraulic heads at different depths must be made with caution. In theory, water pressures measured in variable-density groundwater systems need to be expressed as fresh-water hydraulic heads for the estimation of horizontal hydraulic gradients and as environmental-water hydraulic heads for the estimation of vertical hydraulic gradients (Lusczynski 1961). The environmental head h_e (m) is determined from the measured water density profile in the bedrock $\rho(z)$:

$$h_e(z) = h_p(z) - \left(\frac{\rho(z) - \rho_a}{\rho(z)} \right)(z - z_r) \qquad \text{(Eq 5-3)}$$

where z_r (m) is the elevation of the geodetic datum and ρ_a (kg/m^3) is the average water density between z (m) and z_r:

$$\rho_a = \frac{1}{z_r - z} \int_z^{z_r} \rho(z)\, dz \qquad \text{(Eq 5-4)}$$

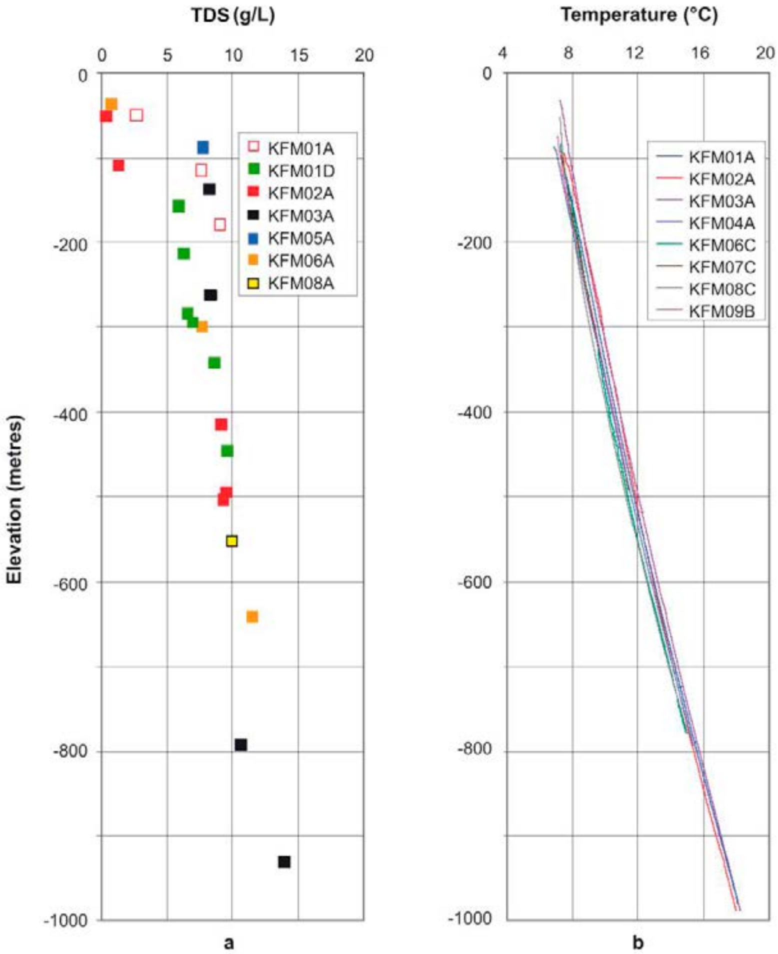

Figure 5-15. *Total dissolved solids (TDS) and temperature for seven (a) and eight (b) core-drilled boreholes in the Forsmark-Lens area (modified after Figure 4-9 in Follin 2008).*

Figure 5-15 suggests that the groundwater density increases with depth as the content of total dissolved solids (TDS) increases with depth. The increase in temperature has a significantly lesser effect and cannot mitigate the effect of the increasing content of TDS. The net effect of the TDS and the temperature profiles shown in Figure 5-15 on $\rho(z)$ and ρ_a is shown in Figure 5-16 (left graph). The effect on h_p, h_f and h_e relative to a hydrostatic head profile based on $\rho(z)$ is also shown in Figure 5-16 (right graph). Down to approximately –100 m elevation the head differences are small (< 0.5 m) regardless of which of the hydraulic heads is considered. This implies that freshwater hydraulic heads measured in the Forsmark-SFR are could be an acceptable proxy depending on the application. However, at lower elevations (larger depths) the differences become considerable. The calculated environmental hydraulic head profile suggests a head difference of about 1 m at –200 m elevation and about 2 m at –500 m elevation. The point-water and fresh-water hydraulic head profiles are both misleading in this regard.

Groundwater flow Q (m^3/s) is calculated from dilution measurements using a tracer, cf. Figure 5-13. The calculation of groundwater flow is based on the following equation:

$$Q = -V \ln(C / C_0) / t \qquad \text{(Eq 5-5)}$$

where V (m^3) is the volume of water in the monitored section, C is the concentration of the tracer at time t (s) and C_0 is the initial tracer concentration. The time needed to carry out a dilution test depends largely on the lumped transmissivity of the fractures intersecting the monitoring section. Also in other aspects, dilution measurements are significantly more complex to manage in comparison with pressure measurements.

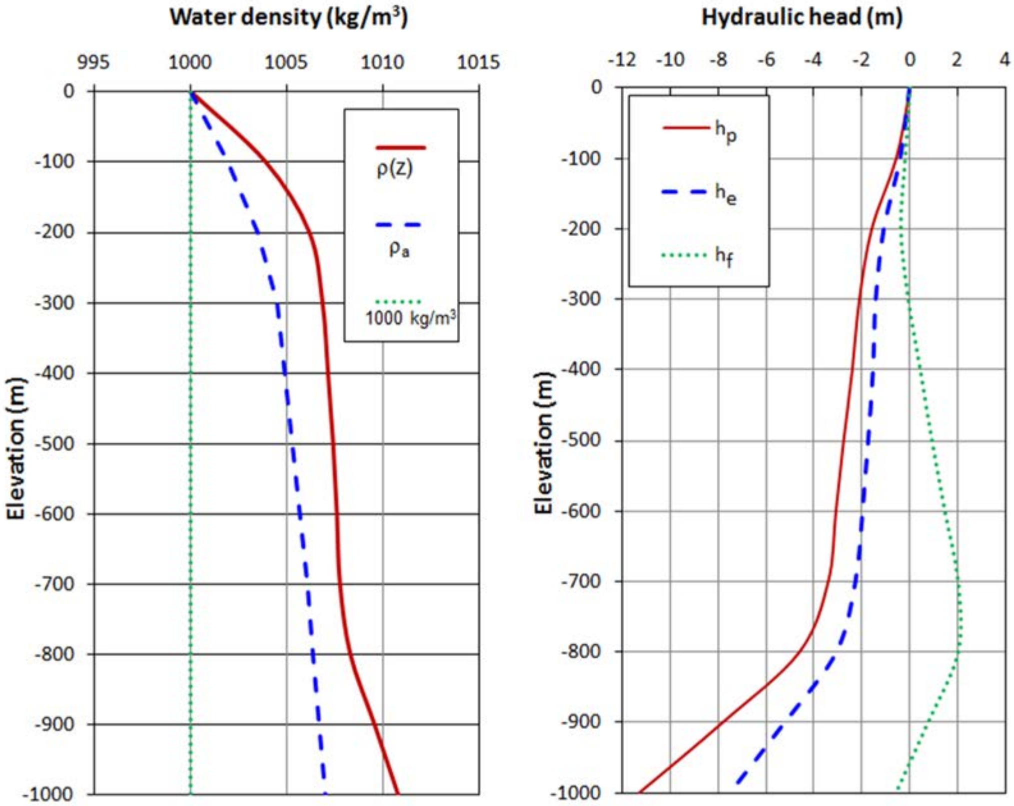

Figure 5-16. Left: Calculated water density profile ρ(z) and average water density ρ_a profile using the temperature and TDS data shown in Figure 5-15 as input. Right: Calculated hydraulic head profiles h_p, h_f and h_e relative to a hydrostatic head profile based on ρ(z).

Groundwater flow measurements in the Forsmark-Lens area have been made in available monitoring sections once a year since the measurements started in 2005. Each measurement campaign typically lasts between four to seven days per borehole section. However, due to strong variations in the calculated flows, the measurement programme for 2014–2015 was revised. Groundwater flow measurements are currently carried out in six borehole sections only. The purpose of this change is to improve the understanding of the diurnal variations in flow by means of continuous measurements during the period September 2014 to July 2015. It is expected that continuous measurements will provide a better picture of how the flows are affected by meteorological events such as rainfall or snow melt, so that these effects can later be distinguished from the effects of repository construction. The measurement times for the six monitoring sections studied during 2014–2015 vary between 10 and 300 days.

Groundwater flow measurements are not possible in the Forsmark-SFR area as none of the monitoring sections has double stand pipes installed. However, the discharge from the submerged SFR 1 facility has been measured at two pump pits since 1988, see Figure 5-17. The pumping demonstrates the importance of groundwater flow measurements for site understanding during construction and operation. The total discharge from the SFR 1 facility in 1988 was about 720 L/min. Since then there has been a relatively steady decreasing trend during the last 15 years, despite the constant head boundary condition above the submerged facility. The total discharge has decreased to about 285 L/min (average value for 2010), which corresponds to a 61 % decrease compared with the 1988 value. As no grouting has occurred since the completion of the existing SFR facility, the decreasing discharge trend is due to other mechanisms. Gustafson (2009) suggests three processes as plausible explanations for the decreasing trend: increasing effective normal stress, two-phase flow, and chemical precipitation.

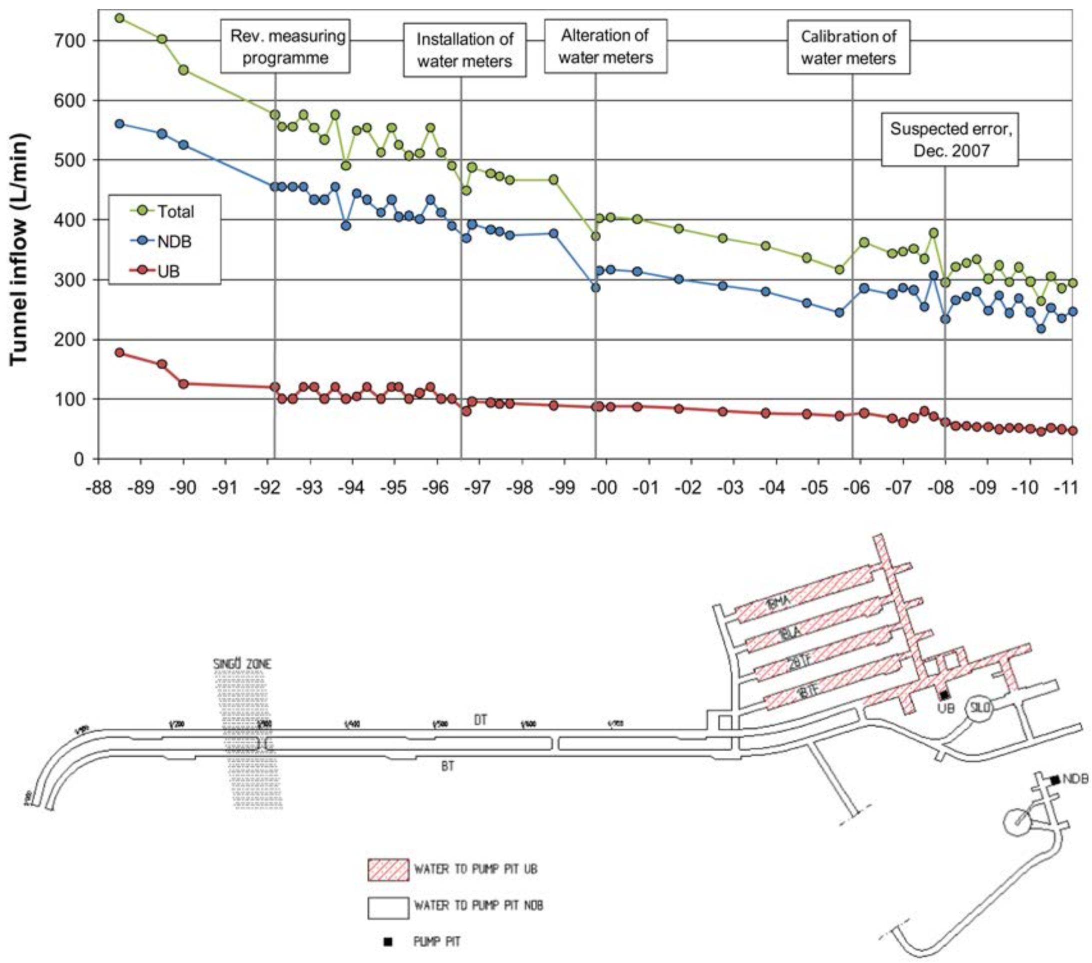

Figure 5-17. Plot of discharge groundwater from the existing facility in the Forsmark-SFR area, SFR 1, between 1988 and 2011. The curves show the discharge from the two pumping pits UB and NDB that are located in the operational area and in the lower construction tunnel, respectively, see the location map below the plot (from SKB 2013b).

Today, the entire head field is more or less affected by the ongoing drainage, but the drawdowns (changes in groundwater level) indicate quite heterogeneous hydraulic conditions. There are in total 12 boreholes and 38 borehole sections in the Forsmark-SFR area that are monitored (cf. Table 5-21 and Figure 5-18). In general, the groundwater levels dropped rapidly during the construction period and at the first time of measurement thereafter. However, the head stabilised quickly in the largest zones, ZFMWNW0001 (Singö deformation zone, SDZ) and ZFMNW0805A/B (splay to SDZ). In the bedrock sandwiched between these two boundaries there has been a slow, relatively constant decreasing head trend in most borehole sections since 1987–1988; an example is shown in Figure 5-19.

In summary, the long-term monitoring of groundwater levels in the bedrock in the Forsmark-SFR area (and discharge from the pumping pits) is a pertinent example of the advantages, and importance, of installing and maintaining a robust measurement system for hydrological monitoring. The experience gained from the construction and operational phases of the SFR 1 facility are essential for the planning and construction of the expansion nearby, SFR 3, see Figure 1-5, but they are also of great interest for the planning and construction of the deep repository for spent fuel in the Forsmark-Lens area. An example of how the acquired geological, hydrogeological, rock mechanics and hydrogeochemical monitoring data during the last 25 years can be used for site understanding and safety assessment modelling is found in Odén et al. (2014).

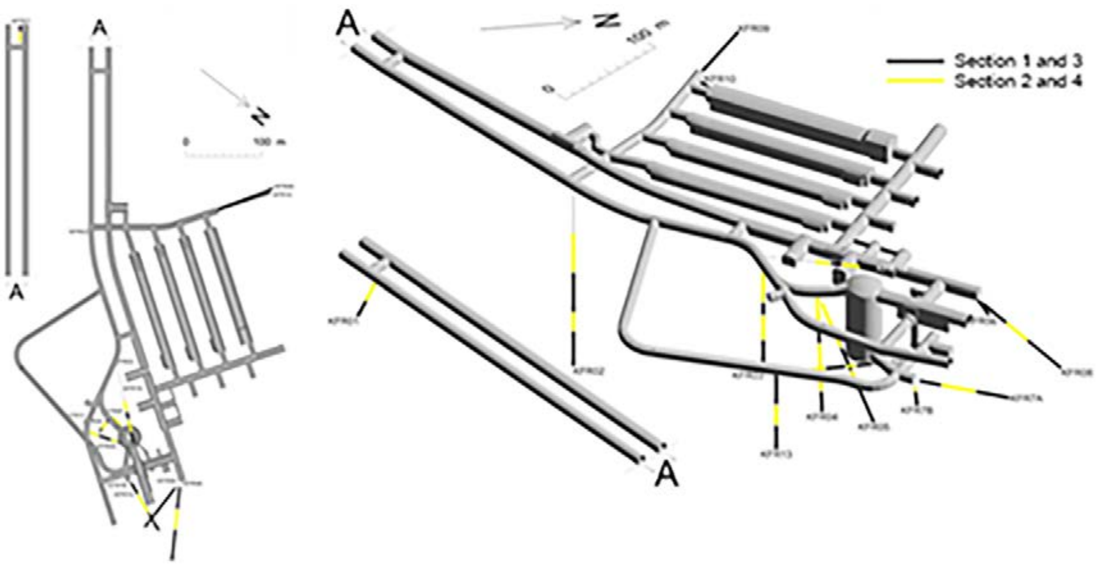

Figure 5-18. *Two views showing the existing SFR 1 facility and the monitored twelve boreholes and 38 borehole sections (cf. Table 5-21).*

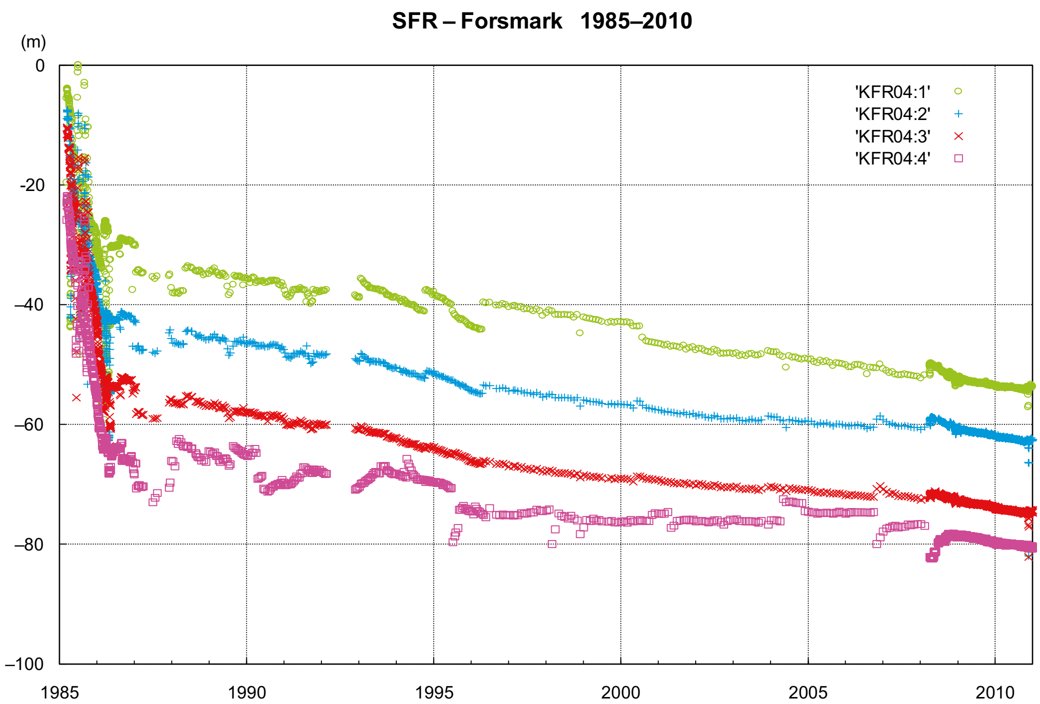

Figure 5-19. *Example of a time-series plot showing the trend in hydraulic head in borehole KFR04. The four monitoring sections in KFR04 are located at different distances (16–42 m) from the SFR 1 facility (from SKB 2013b).*

Groundwater level data from the Forsmark-Lens area are also reported annually for all monitored boreholes/borehole sections. However, none of these reports provide any hydrological evaluation or further analysis of the acquired data. Pertinent examples of how to use, evaluate and model hydrological monitoring data acquired in the Forsmark-Lens are provided in Follin et al. (2007, 2008), Johansson (2008), and Bosson et al. (2008). Figure 5-20 shows an example from Appendix J in Follin et al. (2007); the plot shows 14 months of hydrological data from a monitoring section in a core-drilled borehole at approximately 400 m depth (KFM02A:5), four monitoring sections in a 200-m long percussion-drilled borehole (HFM32:1-4), and one 10-m long monitoring well in regolith below Lake Bolundsfjärden (SFM0023). The six time series of environmental heads are plotted together with time series of water-level data from Lake Bolundsfjärden and the Baltic Sea.

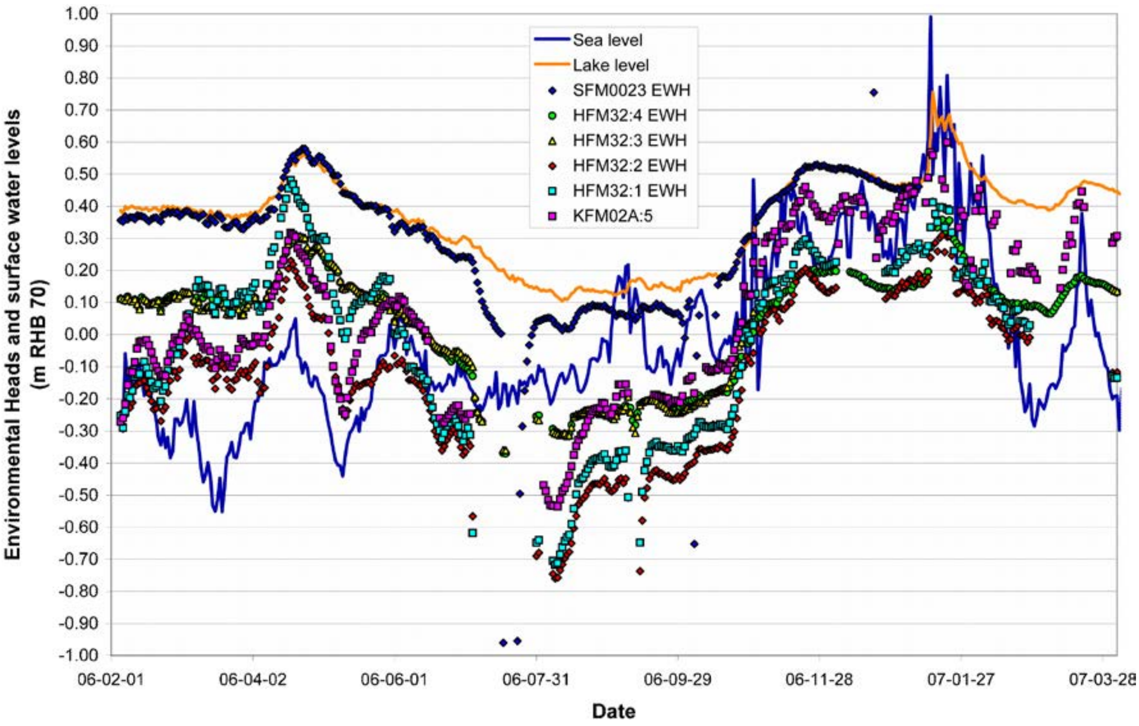

Figure 5-20. *Fourteen months of time-series data showing surface-water levels and environmental heads in the regolith and in the bedrock down to 400 m depth, see Appendix J in Follin et al. (2007) for a detailed time-series analysis.*

Figure 5-20 shows how the seasonal and diurnal variations of near-surface hydrological conditions affect the hydraulic heads in the selected boreholes. By analysing different time-series of data in a systematic manner it is possible to delineate important interactions, e.g., deformation zones with good hydraulic contact to the near-surface hydrological conditions, which is indicative of which surface areas may be affected by the flow to the repository during construction and operation. It is noteworthy that plots like Figure 5-20 have not been produced from data acquired in the Forsmark-Lens area since 2008.

5.7.4 Present data handling

The procedures for processing pressure measurements in bedrock boreholes and calculation of groundwater levels in the Forsmark-Lens area are the same as those described for surface-water and near-surface groundwater level data, e.g. HMS (Section 5.5.4), including control measurements, quality control and reporting intervals. The procedures for processing pressure measurements in bedrock boreholes and calculation of groundwater levels in the Forsmark-SFR area are described in the annual reports described below.

As dilution measurements are more complex and take longer to perform than pressure measurements, they are not carried out on a regular basis. Acquired field data are processed and interpreted manually and thereafter reported to Sicada. The evaluation of the measurements is described in the method description SKB MD 368.010 (SKBdoc 1328059, SKB-internal document in Swedish) and the data handling in a document in the SKB company management system (SDBP-508) and associated instructions and routines referred to therein. As mentioned above, dilution measurements are not conducted in the Forsmark-SFR area.

5.7.5 Available datasets

Groundwater levels in the Forsmark-SFR area have been recorded since 1985, and quality-assured data are stored in Sicada. Annual reports are sent to SSM, as a part of the official SFR monitoring programme. The groundwater level monitoring reports are issued as documents in SKBdoc (e.g. 2010: Jönsson (2011), 2011: Jönsson (2012), 2012: Jönsson (2013), 2013: Jönsson (2014), 2014: Harrström (2015), 2015: Harrström (2016)).

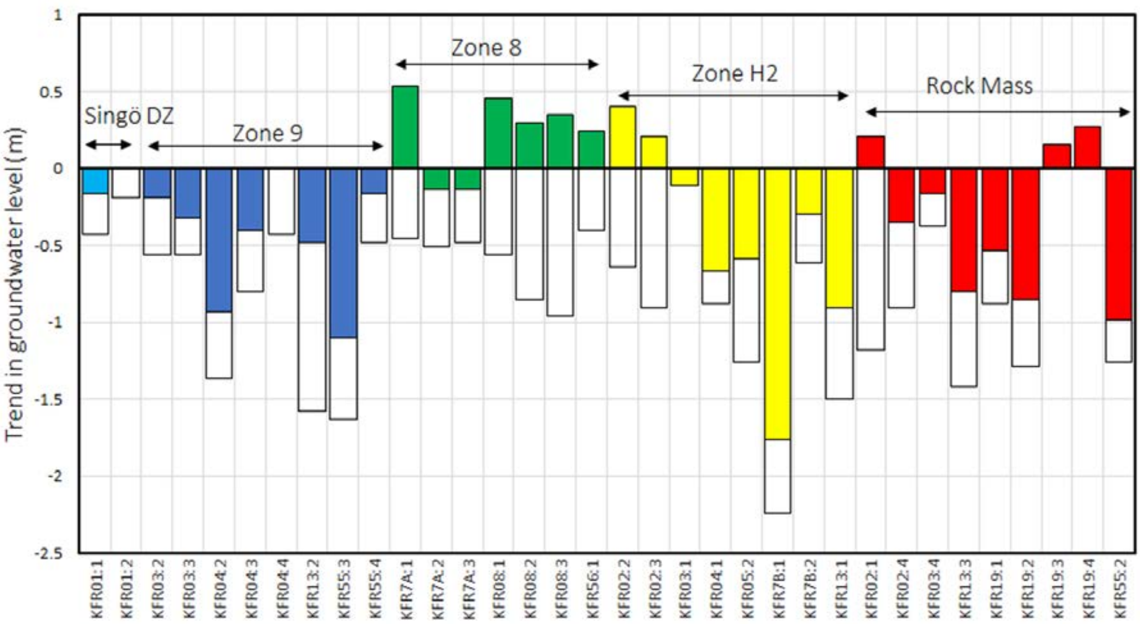

Figure 5-21. *Average trend in groundwater level in different boreholes in the Forsmark-SFR area during 2013 (coloured bars) and during 2012 (white bars). Data are divided into four categories of deformation zones (dark blue, purple, light blue, and yellow) and rock mass (orange).*

Besides major long-term trends, the annual report sent to SSM includes a description of the changes in average groundwater level in the bedrock since the previous annual report. Figure 5-21 shows an example from the annual report of 2013. The monitoring data are ranked according to geology (deformation zones and rock mass) and reveal different behaviour in different parts of the bedrock.

As described in Section 5.7.2, the site investigations for the extension of the SFR repository included drilling of new bedrock boreholes in the Forsmark-SFR area. Specifically, surface and tunnel boreholes were drilled in two campaigns, one in 2008–2009 and the other in 2014. All groundwater level monitoring in the Forsmark-SFR area from 2008 and onwards (including the monitoring reported to SSM, cf. above) has been presented in a separate series of annual reports. These reports were published as SKB P-reports for May 2008–August 2009 (Nyberg and Wass 2009e) and September 2009–August 2010 (Nyberg and Wass 2010c), and as internal SKBdoc reports after that (September 2010–August 2011: Wass (2012a), September 2011–August 2012: Wass (2013b), September 2012–August 2013: Wass (2014b), September 2013–August 2014: Wass (2015d), September 2014–August 2015: Wass (2016b). This reporting also includes the monitoring of three groundwater observation wells in regolith on the SFR pier (SFR000001-3), where measurements started in 2012.

Groundwater level data from the Forsmark-Lens area have been recorded since 2003. Quality assured data are stored in Sicada. Annual reports are available (at http://www.skb.com/publications/) as SKB P-reports (Nyberg et al. 2004a, Nyberg and Wass 2005a, 2006a, 2007a, 2008b, 2009b) and as SKB internal reports in SKBdoc since 2010 and onwards (2010: Nyberg and Wass (2010b), 2011: Wass (2013a), 2012: Wass (2015b), 2013: Wass (2014a), 2014: Wass (2015c)); the bedrock groundwater level data are presented in the same reports as the surface water and near-surface groundwater levels (Table 5-18).

Groundwater flow data from the Forsmark-Lens area have been recorded since 2005. Quality assured data are stored in Sicada. Annual reports are available (at http://www.skb.com/publications/) as SKB P-reports between 2006 and 2010 (Wass 2006, 2007, 2008, 2009, 2010), and after that in internal reports in SKBdoc (2010: Wass and Thur (2011a), 2011: Thur and Wass (2012), 2012: Ragvald and Wass (2014a), 2013: Wass (2015a), 2014–15: Wass (2016a)).

The annual report describing groundwater levels in the bedrock in the Forsmark-Lens area provides a status description of the technical installations and present time-series plots of all data, but it does not contain any evaluations or comparisons; neither long-term trends nor changes in average groundwater level since the previous annual report. With exception of some efforts focusing on the SFR area (within the SDM-PSU and SR-PSU projects), it is concluded that the ambition to improve the site understanding using acquired monitoring data appears to be dormant since the completion of the site investigation in 2007.

5.7.6 Evaluation

Aspects of relevance for the continued monitoring

Besides ordinary maintenance issues in both areas, there are two particular problems for the surface boreholes in the Forsmark-Lens area that require extra management and resources. Corrosion due to the content of dissolved solids is primarily affecting components made of aluminium, which for instance is used in the percussion-drilled boreholes. A more complex issue to deal with is the earth currents caused by the Fenno-Skan, which is a high voltage DC cable between Sweden and Finland. The earth currents interact with different electrical installations in the area and together these corrode components made of stainless steel, which are common in the multi-packer installations. As the level of corrosion varies from one borehole to the next in an irregular way, different types of experiments are ongoing to identify the reasons for this (see Section 4.3 for details).

Parameters and measurements

Figure 5-22 visualises the deformation zones in close proximity to the SFR 1 facility. Many of the monitoring sections that are part of the monitoring programme reported to SSM are chosen with regard to how the boreholes intercept interpreted deformation zones (cf. Figure 5-21). Once the excavations for the planned expansion, SFR 3, are decided it will be necessary to also expand the monitoring programme in the Forsmark-SFR area.

Figure 5-23 shows a NW-SE cross section through the target volume in the Forsmark-Lens area. The most significant deformation zones, ZFMA2 and ZFMENE0060A, will be accounted for in the final layout of the spent fuel repository. For the ongoing baseline data monitoring the present-day packer installations are considered relevant. However, there are a number of more or less significant deformation zones present in the target volume, see Figure 5-24. As the final layout of the repository is pending and the present-day packer installations were decided as long as more than ten years ago, depending on borehole, the present-day monitoring sections may not be optimal for observing the potential drawdowns caused by groundwater seepage into the underground openings.

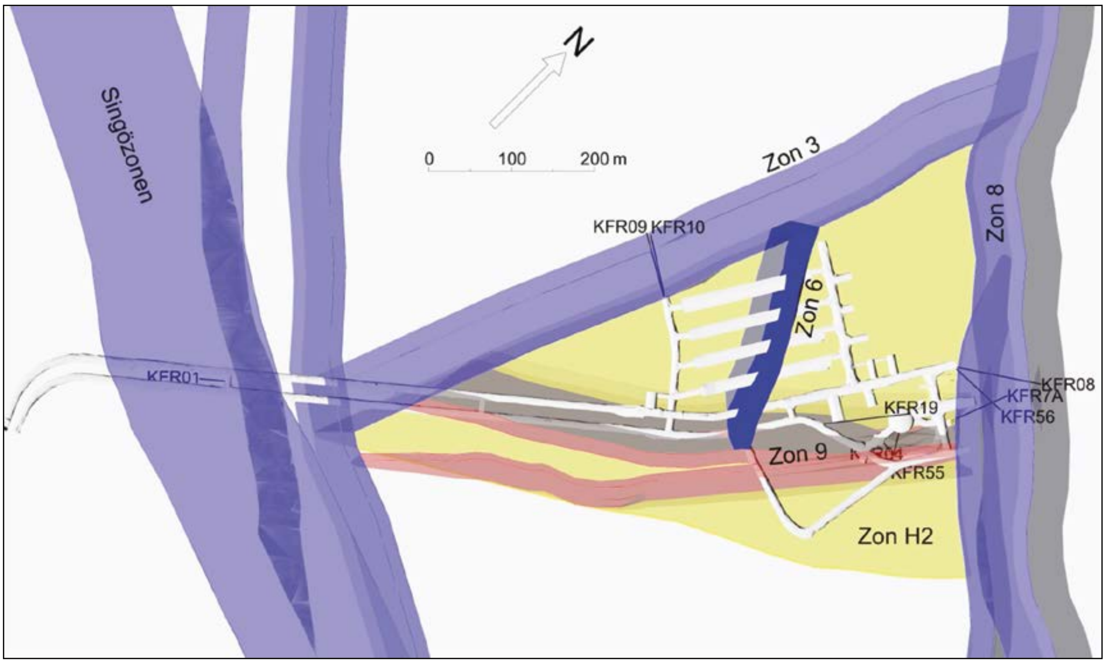

Figure 5-22. *Plan view of the Forsmark-SFR area showing the SFR 1 facility, major deformation zones (cf. Figure 5-21) and intersecting boreholes (cf. Figure 5-18).*

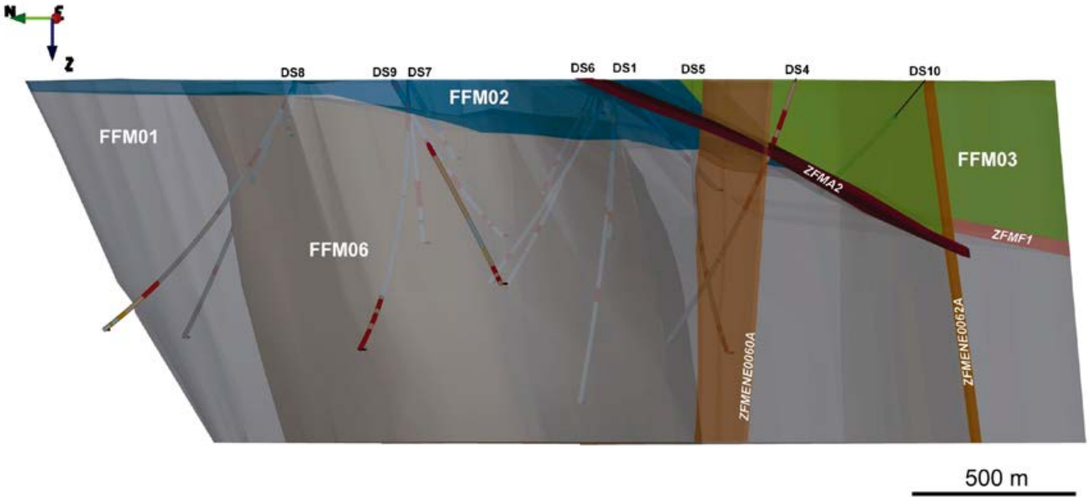

***Figure 5-23.** NW-SE cross section showing core-drilled boreholes in the target volume of the deep repository for spent nuclear fuel. Two large deformation zones control the layout, ZFMA2 and ZFNENE006A (from Olofsson et al. 2007).*

The decision not to measure the density of the groundwater in the bedrock in the Forsmark-SFR area should be scrutinised as the planned expansion, SFR 3, will be constructed at a greater depth than SFR 1. That is, as the groundwater density usually increases with depth comparisons of fresh-water head data (cf. Eq 5-2) recorded at different depths become unclear. In addition, it will be necessary to integrate bedrock hydrological data from the two areas before the permit is received to start the construction of the spent fuel repository in the Forsmark-Lens area. It might be found impractical, or at least confusing, to work with two hydraulic head definitions in parallel while interpreting and modelling groundwater levels in the "Forsmark area".

Temperature is currently not measured in the bedrock, neither in the Forsmark-SFR area nor in the Forsmark-Lens area. According to the temperature profile shown in Figure 5-15 groundwater of lower temperature might enter the spent fuel repository from above, whereas groundwater of higher temperature might enter from below. It is recommended to evaluate whether such data could be of value for the interpretation of potential hydrogeochemical disturbances during construction and operation. Measured temperature profiles in the bedrock (even by using the groundwater temperature as a proxy) would be useful data also for e.g. permafrost modelling.

Testing and inspections of equipment

In 2008, all borehole installations in the Forsmark-SFR area were replaced by new installations and a new data acquisition system was put into operation. The new monitoring equipment has increased the possibility of linking any changes in recorded pressures to events and activities in and around the existing SFR 1 facility. According to the most recent annual reports the monitoring system in the Forsmark-SFR area works as expected.

The monitoring equipment in the Forsmark-Lens area is still fairly new and the testing and inspection works well according to the annual reports. However, the aforementioned problem with corrosion associated with Fenno-Skan is challenging (Nissen et al. 2005) and must be resolved soon, otherwise important data of value for both Design and Safety Assessment may be lost. Under all circumstances, the existing installations and monitoring instructions should be checked and replaced/refurbished as needed, bearing in mind that new boreholes (or borehole sections) will probably be included in the future. The core-drilled borehole KFM11A and the percussion-drilled boreholes HFM33–35 (cf. Figure 5-12) are vital in such a case, as they intersect different parts of the Singö deformation zone, which separates the Forsmark-SFR area from the Forsmark-Lens area.

Data handling and reporting

It is recommended that the annual reports from the Forsmark-Lens area be enhanced to include a brief analysis and a summary of the main findings since the previous year. The annual reports of the Forsmark-SFR are much better in this regard and may be used as a basis for comparison.

It is possible that the construction works for the SFR 3 facility in the Forsmark-SFR area and the spent fuel repository in the Forsmark-Lens area will be run in parallel. If so, the hydrological disturbances in the bedrock will probably interfere (superimpose) to some extent. It is recommended to give consideration to whether there will be one monitoring programme for both areas or two separate programmes.

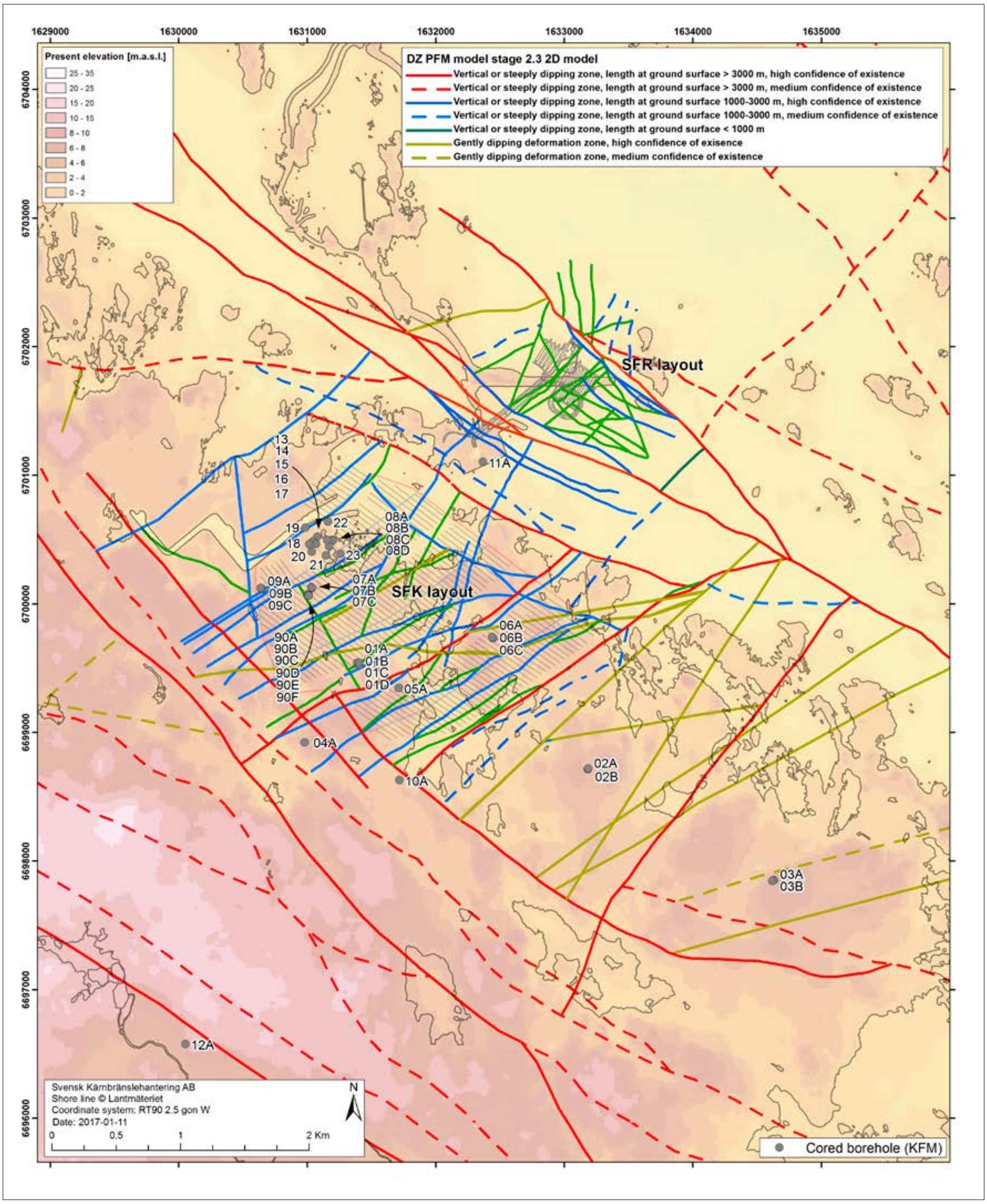

***Figure 5-24.** Overview map of deformation zones in the Forsmark-Lens and Forsmark-SFR areas. For reference, the map also shows core-drilled boreholes, the layout of the planned spent fuel repository ("SFK layout") and the layout of existing and planned parts of SFR. Besides the large deformation zones shown in Figure 5-23 a number of smaller deformation zones are also present in the target volume. The lineaments shown in this image indicate where the deformation zones outcrop below the regolith. The background corresponds to the digital elevation model for the site.*

6 Hydrochemical monitoring

6.1 Introduction

This chapter is divided into three parts dealing with data regarding 1) surface water (precipitation, lake, stream, and sea water), 2) near-surface groundwater (monitoring wells and private wells) and 3) groundwater in the bedrock (percussion-drilled and core-drilled boreholes). The reason for this division is mainly practical and follows the division of the current monitoring programme.

6.1.1 Overview of the hydrochemical monitoring programme

Hydrochemical monitoring has been conducted in the Forsmark area by SKB since the late 1980s when the SFR facility for low- and intermediate level radioactive waste was established. In 2002, when the site selection process for the KBS-3 repository for spent nuclear fuel was initiated, extensive site characterisation and monitoring programmes were started in both Forsmark and Laxemar-Simpevarp (Andersson et al. 2000, 2004, SKB 2001a, b, 2005). After the selection of Forsmark for the KBS-3 repository location, the hydrochemical monitoring was reduced in Forsmark and terminated in Laxemar-Simpevarp. In 2009, the investigations for the planned extension of the SFR facility implied drilling of new boreholes, mainly from the surface. Five of these boreholes were added to the monitoring programme. The construction and operational phases that is foreseen for both repositories may imply new requirements and issues not considered at the inception of the presently operated monitoring programme.

The ongoing hydrochemical monitoring covers water composition and isotopic signatures in a wide range of water types from precipitation to deep groundwater in the bedrock. The biosphere monitoring comprises measurements of surface water in precipitation, lakes, streams and the sea, as well as near-surface groundwater in the regolith. In the geosphere monitoring, groundwater in the bedrock is sampled in percussion-drilled boreholes that typically extend to 100–200 metres depth, and in telescopic and conventional, core-drilled boreholes that extend up to 1 000 metres vertical depth. Boreholes of the so called telescopic type comprise a percussion drilled wider first part (approximately 100 m), followed subsequently by a core drilled hole (often to around 1 000 m depth), see Section 6.4. Most percussion-drilled and all core-drilled boreholes are sectioned by inflatable packers in order to isolate groundwater-bearing fractures and geological entities of special interest. The different types of objects monitored are shown in the schematic cross-section in Figure 6-1.

The hydrochemical reporting by SKB is usually divided between the biosphere and the geosphere. The biosphere is further divided into the terrestrial, limnic and marine ecosystems. There is, however, no sharp boundary between the biosphere and the geosphere (nor the ecosystems) and many issues are relevant to both, for example discharge of deep groundwater and recharge of groundwater of meteoric origin entering the bedrock.

6.1.2 Hydrochemical data in this chapter

All hydrochemical data treated in the present chapter have been extracted from the database Sicada. All overviews and statistical evaluations were compiled in an Access database linked to the Sicada database. During the work, the content of the Access database was updated several times when additional or corrected data became available. The last update of the Access database was based on the Sicada delivery 15_064_2, which is described detail in Appendix 2.

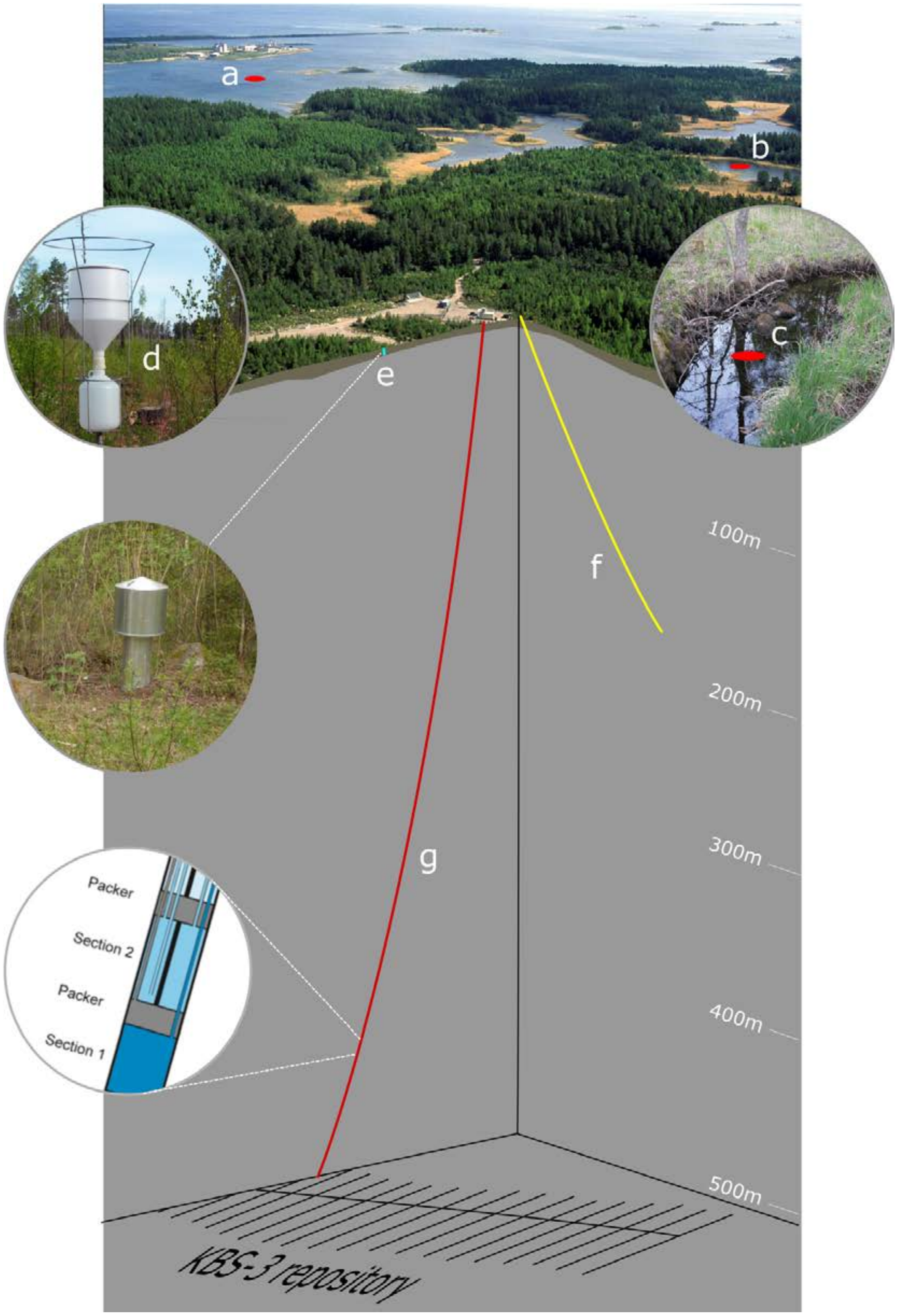

Figure 6-1. *Schematic representation of the different types of hydrochemical sampling locations. Surface water is sampled in the sea (a), in lakes (b), in streams (c), and in precipitation (d). Near-surface groundwater is sampled in monitoring wells located in the regolith (e) and in dug or drilled private wells (not shown). The groundwater in the bedrock is sampled in percussion-drilled boreholes (f) that usually extend to 100–200 m depth, and in telescopic, core-drilled boreholes (g) that extend up to 1 000 m vertical depth. Most percussion-drilled and all core-drilled boreholes are sectioned by inflatable packers in order to isolate groundwater-bearing fractures and different geological entities. Drill site 1, which is located right above the planned KBS-3 repository, is shown in the centre of the picture, see also Figure 5-11. In the upper left, the above-ground parts of the SFR repository are visible on the peninsula.*

6.1.3 Monitoring objectives and end-users

The overall key issues that the monitoring programme has to meet regarding safety assessments, environmental impact assessments and construction/operation of the repositories are specified in Section 3.4. In the list below, general objectives for the hydrochemical monitoring programme are specified based on these overall key issues. The specific hydrochemical issues identified from the general objectives and the possible end-users listed below are handled in each sub-section dealing with surface water, near surface groundwater and groundwater, respectively.

The main general objectives of the hydrochemical monitoring programme are as follows:

- To contribute to the general scientific understanding of the hydrochemical conditions at the site by giving input to the site modelling that identifies and describes the major processes forming the hydrochemical environments in the geosphere and biosphere, and
- more specifically, to characterise the natural variation to ensure that favourable hydrochemical conditions prevail and will be maintained at deposition depth with respect to the requirements of the safety functions of the engineered barriers.
- To give input to the assessments of the long-term integrity of the engineered barriers and the retardation and transport of radionuclides in the geosphere and the biosphere.
- To provide baseline data representing unaffected natural conditions prior to the construction/operation phase to be used for, among others, environmental impact assessments.

Several possible end-users of hydrochemical data can be identified based on scientific discipline, use of data and project/facility within the SKB organisation. These end-user categories below overlap and are mainly defined with regard to the SKB organisational structure. One important objective with the forthcoming revision of the monitoring programme, besides optimisation, is the identification of areas or measurements that are not covered by the present programme. The open-ended review starting from main objectives, the work performed in FEP analyses and process descriptions and the identification of different end-user needs is one attempt to find these uncovered areas.

The following possible end-users of hydrochemical monitoring data could be identified:

- Site descriptive models
  - Biosphere.
  - Geosphere.
- Long-term safety assessments
  - Near-zone specific issues for the KBS-3 repository for spent nuclear fuel.
  - Near-zone specific issues for the SFR repository for short lived radioactive waste.
  - Near-zone specific issues for the SFL repository for intermediate level radioactive waste.
  - Transport and retardation of radionuclides in the geosphere.
  - Transport and retardation of, and doses from radionuclides in the biosphere.
- Environmental impact assessments
  - For the construction and operation of the KBS-3 repository.
  - For the construction and operation of the extension of the SFR repository.
- Detailed investigations during construction/operation of the KBS-3 and SFR 3 repositories.
- Baselines for surveillance purposes after closure of the repositories.

The site descriptive models provide a multidisciplinary, broad scientific understanding of the site, which is the basis for the assessments of long-term safety and environmental impacts. The former focuses on the long-term safety over very long time perspectives of 100 000 to 1 000 000 years, whereas the latter focuses on the construction/operational period of about 100 years. Despite the different time perspectives, these two end-users share several data needs, especially in the biosphere. In addition, the environmental impact assessments for the construction/operational period, which mainly focus on the conditions at the surface, detailed investigations and evaluations will be performed during the construction of the KBS-3 and SFR 3 repositories that might require reference data representing undisturbed conditions.

Depending on the type of repository (KBS-3, SFR, SFL), there are different requirements for the so called near zone due to the specific technical barriers of each type of repository and due to the characteristics of the different types of waste to be deposited. The KBS-3 repository for spent nuclear fuel depends on copper canisters surrounded by bentonite placed at about 500 metres depth in the bedrock. The hydrochemical issues for this repository are to ensure that favourable chemical conditions prevail at repository depth, that the radionuclides are retarded in the geosphere, and that the doses are acceptable in the biosphere, if radionuclides are released. The existing SFR repository for low- and intermediate-level radioactive waste and the planned SFL repository for long lived intermediate level waste from the decommissioning of nuclear reactors depend on concrete barriers and retardation in the geosphere for radiological safety. These latter repositories also contain a different mixture of radionuclides and the physical and chemical forms are different from those in the spent fuel repository, and therefore other hydrochemical issues arise (SKB 2014d, Grahm et al. 2013).

In this chapter, the available hydrochemical data are evaluated with the focus on quality and coverage and an attempt is also made to foresee future needs of hydrochemical monitoring.

6.2 Surface water (lake, stream, sea, precipitation)

The hydrochemical monitoring programme in the surface environment is focused on characterising seasonal and long-term temporal variations in lakes, streams, sea water, and precipitation. To the present date, the major use of this information is to serve as input to the general site descriptive ecosystem models that constitute the basis for the assessments of long term safety of the repositories, and specifically, for the parameterisation of the radionuclide dose models (Andersson 2010, Aquilonius 2010, Nordén et al. 2010, Tröjbom et al. 2013). Time-series data have also been important input to transport calculations revealing the large-scale distribution of trace elements in the landscape (Tröjbom et al. 2007, Tröjbom and Grolander 2010). In the future, baseline data serving as input to assessments of environmental impacts during the construction phase will become more important.

Constructed and natural ponds have lately been added to the ongoing monitoring programme in order to meet specific requirements from the environmental impact assessments. The monitoring programme and monitoring data collected during the site investigations and the extended monitoring period 2007–2009 are described in a number of SKB reports. From 2010, monitoring data are presented in internal SKB reports (except for monitoring data from the small ponds which are described in public P-reports Qvarfordt et al. 2014a). In Table 6-1, reports and documents documenting the monitoring programme are listed in chronological order from 2002 until today (2016). The compilation contains recent activity plans, yearly data reports, data evaluation reports, and site descriptive model reports dealing with hydrochemical data from Forsmark.

Table 6-1. Compilation of reports and documents covering hydrochemical monitoring of surface waters (lakes, streams, sea water and precipitation) in chronological order. The 7-digit numbers in the “document” column refers to SKBdoc IDs. This compilation contains recent activity plans, yearly data reports (P-reports), data evaluation reports (R- and TR-reports), and site descriptive model reports (TR-reports) dealing with hydrochemical data from Forsmark. The activity plans are documents controlling the performance of each specific monitoring activity.

Year	Document	Doc. type	Title (reference)
2001	TR-01-29	TR-report	Site investigations. Investigation methods and general execution programme (SKB 2001a).
2002	R-01-42	R-report	Program för platsundersökningar vid Forsmark (SKB 2001b).
2002–2003	P-03-27	P-report	Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2002 to March 2003. Forsmark site investigations (Nilsson et al. 2003).
2002–2004	R-05-41	R-report	Chemical characteristics of surface waters in the Forsmark area. Evaluation of data from lakes, streams, and coastal sites (Sonesten 2005).
2003–2004	P-04-146	P-report	Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2003 to March 2004. Forsmark site investigation (Nilsson and Borgiel 2004).
2002–2005	R-06-19	R-report	Chemical characteristics of surface systems in the Forsmark area. Visualisation and statistical evaluation of data from shallow groundwater, precipitation, and regolith (Tröjbom and Söderbäck 2006).

Year	Document	Doc. type	Title (reference)
2002–2005	P-05-143	P-report	Sampling and analysis of precipitation, years 2002 to 2005. Forsmark site investigation (Nilsson 2005).
2004–2005	P-05-274	P-report	Sampling and analyses of surface waters. Results from sampling in the Forsmark area, March 2004–June 2005. Forsmark site investigation (Nilsson and Borgiel 2005b).
2005	R-05-14	R-report	Programme for further investigations of geosphere and biosphere Forsmark site investigation. (SKB 2005).
2002–2006	R-07-55	R-report	Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling SDM-Site Forsmark (Tröjbom et al. 2007).
2004–2006	R-10-27	R-report	Chemical conditions in present and future ecosystems in Forsmark – implications for selected radionuclides in the safety assessment SR-Site (Tröjbom and Grolander 2010).
2005–2006	P-07-95	P-report	Sampling and analyses of surface waters. Results from sampling in the Forsmark area, July 2005 – June 2006. Forsmark site investigation (Nilsson and Borgiel 2007).
2002–2007	TR-10-02	TR-report	The limnic ecosystems at Forsmark and Laxemar-Simpevarp (Andersson 2010).
2002–2007	TR-10-03	TR-report	The marine ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere (Aquilonius 2010).
2004	R-04-13	R-report	Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel (Bäckblom and Almén 2004).
2005–2007	P-07-170	P-report	Sampling and analysis of precipitation, September 2005 to June 2007. Forsmark site investigation (Berg 2007).
2006–2007	P-08-17	P-report	Sampling and analyses of surface waters. Results from sampling in the Forsmark area, July 2006–June 2007. Forsmark site investigation. (Nilsson and Borgiel 2008).
2007	P-08-55	P-report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from sampling in the Forsmark area, August 2007–December 2007. Forsmark site investigation. (Qvarfordt et al. 2008).
2002–2008	TR-13-28	TR-report	Precipitation of barite in the biosphere and its consequences for the mobility of Ra in Forsmark and Simpevarp (Jaremalm et al. 2013).
2008	P-09-51	P-report	Hydrochemical monitoring of groundwaters, surface waters and precipitation. Results from water sampling in the Forsmark area, January 2008–December 2008. Forsmark site investigation (Berg et al. 2008).
2007–2009	R-07-34	R-report	Programme for long-term observations of geosphere and biosphere after completed site investigations. Forsmark site investigation (SKB 2007).
2008–2009	P-10-25	P-report	Hydrochemical investigations in four calciferous lakes in the Forsmark area. Results from complementary investigations in the Forsmark area, 2008–2009. Monitering Forsmark (Qvarfordt et al. 2010).
2008–2009	P-09-66	P-report	Analysis of radioactive isotopes in near surface groundwater, surface water, biota and soil. Forsmark site investigation (Grolander and Roos 2009).
2009	P-10-40	P-report	Hydrochemical monitoring of groundwaters and surface waters. Results from water sampling in the Forsmark area, January–December 2009. Forsmark site investigation (Nilsson et al. 2010a).
2003–2010	P-11-23	P-report	Dissolved inorganic carbon and organic carbon in mires in the Forsmark area. A pilot study (Löfgren 2011).
2010	P-11-47	P-report	Hydrochemical investigations in four calciferous lakes in the Forsmark area. Results from the second year of a complementary investigation in the Forsmark area (Qvarfordt et al. 2011).
2010	SKBdoc 1334707	Data report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from the sampling period January 2010–December 2010 (Qvarfordt et al. 2012a).
1984–2011	TR-11-04	TR-report	Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark (SKB 2013b).
2011	SKBdoc 1386267	Data report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from the sampling period January 2011–December 2011 (Berg et al. 2015).
2012	SKBdoc 1390364	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January 2012–December 2012 (Borgiel et al. 2013).
2012–2013	P-14-01	P-report	Vattenkemiska undersökningar i sex gölar i Forsmark (Qvarfordt et al. 2014a).
2013	SKBdoc 1459921	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January to December 2013 (Borgiel et al. 2015).
2012–2014	SKBdoc 1357750	Activity plan	Hydrokemisk monitering av ytvatten 2012–2014 (internal document).
2013–2014	SKBdoc 1422519	Data report	Vattenkemiska undersökningar i sex nyanlagda gölar samt två befintliga småvatten i Forsmark. Resultat från provtagningar under perioden september 2013 till december 2014 (Wallin et al. 2017).
2014	SKBdoc 1422501	Activity plan	Hydrokemimonitering i sex gölar samt inledande vattenprovtagning i två nygrävda gölar i Forsmark april t o m december 2014 (internal document).
2014	SKBdoc 1459924	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January to December 2014 (Wallin et al. 2016a).
2015[1]	SKBdoc 1466721	Activity plan	Hydrokemiskt moniteringsprogram för gölar, ytvatten och ytnära grundvatten 2015 (internal document).

[1] Data report to be published as SKB P-report (2017).

6.2.1 Overview of sampling methods for surface water

Water samples are collected using a peristaltic pump system. Lake and sea water samples are collected close to the surface (at 0.5 m depth). In the case of ice coverage during winter, water is also collected from approximately 0.5 m above the lake or sea bottom, in order to sample water both above and below the stratification in the water body. Stream-water samples are collected at approximately 0.1 m depth. Depending on analysis, acidification and filtration (0.45 µm) is performed in the field (SKBdoc 1357750, internal document). Direct field measurements of pH, water temperature, atmospheric pressure, ORP (Oxidising Reducing Potential), PAR (Photosynthetic Active Radiation), turbidity, electrical conductivity (EC), salinity and dissolved oxygen are performed by multi-parameter probes at the sampling occasions (Figure 6-2). Profiles have been obtained at lake and sea sampling locations by measurements at each metre from the surface to the bottom. Continuous EC and temperature measurements are also conducted at the stream-gauging stations, cf. Section 5.4.

Figure 6-2. *Field probe measurements in Lake Norra Bassängen from the ice during winter (upper left). Sea water samples are filtered directly in the field (upper right). Sampling of the stream at the outlet of Lake Eckarfjärden is performed using of a peristaltic pump at a depth of c 0.1 m. The multi-parameter probe YSI 6600 EDS was used for field measurements until 2013 when it was replaced with InSitu Troll9500.*

6.2.2 The current hydrochemical surface-water monitoring programme

The hydrochemical monitoring includes a total of 21 sampling locations in four lakes, eight ponds, four small streams and two sampling locations in a shallow sea bay (Figure 6-3):

- Water sampling and probe measurements are performed in three different lakes: Lake Bolundsfjärden, Lake Eckarfjärden and Lake Labboträsket (Figure 6-7 and Figure 1-2). In order to monitor salinity changes, automatic measurements of electrical conductivity (EC) were performed in the channel between Lake Norra Bassängen and the upstream Lake Bolundsfjärden. The automatic EC measurements provided reliable data until 2009. Since 2010 they have been replaced by manual measurements 10–12 times per year (cf. Section 5.4.2).
- One regular sampling location in sea water represents a shallow sea bay (Forslingens grund). Due to observed enhanced tritium contents in the surface waters close to the nuclear power plant, samples for tritium analyses are also collected each month close to the cooling water outlet in Lake Biotestsjön.
- Sampling of stream water is conducted at four localities (Kungsträsket, Bolundsskogen, Norr Eckarfjärden and Öster Gunnarsbo).
- Six constructed ponds and two natural ponds (for comparison) are sampled eight times per year in order to meet the needs of the environmental impact assessment. The constructed ponds are supposed to constitute replacement habitats for the endangered pool frog for those that will disappear during the construction of the surface facilities for the spent fuel repository. At present, none of these ponds is included in the regular surface-water monitoring programme.

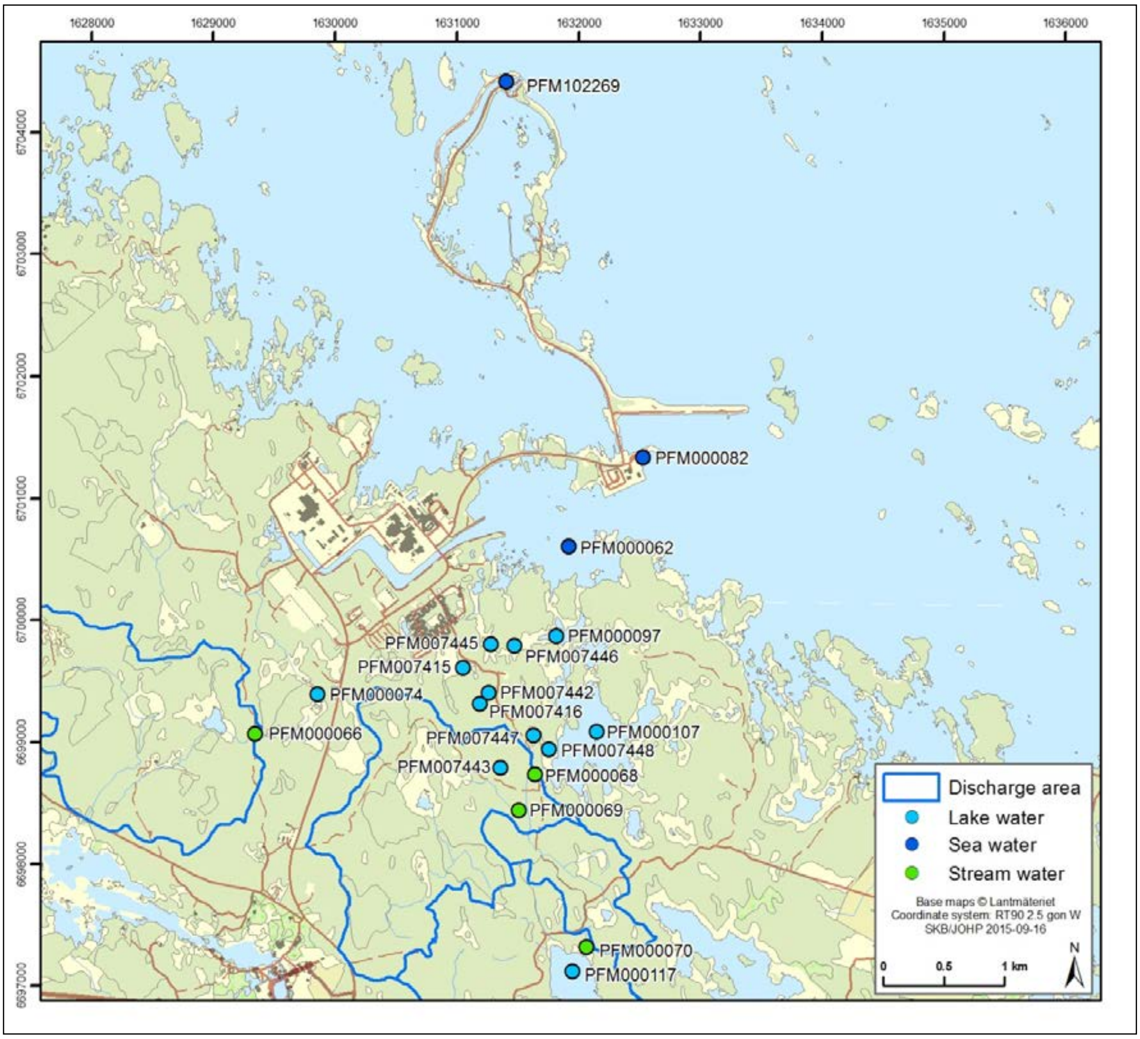

Figure 6-3. Map showing the surface-water sampling locations of the current monitoring programme.

In Table 6-2, the number of samples collected during 2014 is shown for each sampling location and component group. A component group is a set of components that are handled together (either they are included or excluded) and the components included in each component group are listed in Table 6-3.

Table 6-2. The current hydrochemical surface-water monitoring programme, including the number of annual samples per component group (cf. Table 6-3).

				Component groups																						
objectType	IDCODE	Description	depthInfo	Anions1	Anions2a	Anions2a_I	Anions2b_I	Carbon1	Carbon2	Carbon3	Cations1	Chlorophyll	Colour	EnvironIso1	EnvironIso2	EnvironMet2	FieldSonde2	Nutrient1	Nutrient2	Nutrient3	Nutrient4	Nutrient5	Oxygen	ParticulateCNP	Susp&colour	Trace2
Lake water	PFM000074	Labboträsket	surface	4		4			4	4	4	4		4	4	4	4		4			4	4	4	4	4
Lake water	PFM000074	Labboträsket	bottom	2					2	2	2								2			2	2	2	2	
Lake water	PFM000097	Norra Bassängen	surface														4									
Lake water	PFM000107	Bolundsfjärden	surface	4		4			4	4	4	4		4	4	4	4		4			4	4	4	4	4
Lake water	PFM000107	Bolundsfjärden	bottom	2					2	2	2								2			2	2	2	2	
Lake water	PFM000117	Eckarfjärden	surface	4		4			4	4	4	4		4	4	4	4		4			4	4	4	4	4
Lake water	PFM000117	Eckarfjärden	bottom	2					2	2	2								2			2	2	2	2	
Lake water	PFM007415	Artificial pond 2014	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007416	Artificial pond 2014	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007442	Reference pond	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007443	Reference pond	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007445	Artificial pond	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007446	Artificial pond	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007447	Artificial pond	surface	8	8			8		8	8		8				8	8				8				
Lake water	PFM007448	Artificial pond	surface	8	8			8		8	8		8				8	8				8				
Sea water	PFM000062	Forslings grund	surface	4		4			4	4	4	4		4	4	4	4		4			4	4	4	4	4
Sea water	PFM000062	Forslings grund	bottom	2					2	2	2								2			2	2	2	2	
Sea water	PFM000082	Piren, SFR	surface	4		4			4	4	4	4		4	4	4	4		4			4	4	4	4	4
Sea water	PFM000082	Piren, SFR	bottom	2					2	2	2								2			2	2	2	2	
Sea water	PFM102269	Biotestsjön	surface												4											
Stream water	PFM000066	Öster Gunnarsbo		11	11		4		11	11	11			4	4	11	11			4	11	11	11	11	11	4
Stream water	PFM000068	Kungsträsket		11	11		4		11	11	11			4	4	11	11			4	11	11	11	11	11	4
Stream water	PFM000069	Bolundsskogen		11	11		4		11	11	11			4	4	11	11			4	11	11	11	11	11	4
Stream water	PFM000070	Norr Eckarfjärden		11	11		4		11	11	11			4	4	11	11			4	11	11	11	11	11	4

Table 6-3. Definition of surface-water component groups, that is sets of components that go together. The "compGrp" column contains the short names used in other tables in this report, "Parameter group" is a general group description, and "Component group" is the denotation used in activity plans. The "Component List"-column lists the components included in each component group.

compGrp	Parameter group	Component Group	ComponentList
Anions1	Chemical environment	Anions1	Alkalinity (HCO3), pH, conductivity
Anions2a	Major constituents	Anions2a	Cl, F, SO4, Br
Anions2a_I	Major constituents	Anions2a	Cl, F, SO4, Br, I
Anions2b_I	Major constituents	Anions2b	I
Carbon1	Nutrients and carbon	Dissolved organic carbon, dissolved inorganic carbon	DOC
Carbon2	Nutrients and carbon	Dissolved organic carbon, dissolved inorganic carbon	DOC, DIC
Carbon3	Nutrients and carbon	Total organic carbon	TOC
CarbonIso	Light isotopes	Carbon isotopes	13C, 14C
Cations1	Major constituents	Cations, Si and S, class 3	Na, K, Ca, Mg, Li, Sr, Si-tot, S-tot
ChlorineIso	Light isotopes	Chlorine-37	37Cl
Chlorophyll	Chlorofyll and pheophytin	Chlorophyll	Chlorofyll a, chlorofyll c, pheophytin
Colour	Suspended matter and water colour	Colour	Absorbance
EnvironIso1	Environmental isotopes	Environmental isotopes	2H, 18O
EnvironIso2	Environmental isotopes	Tritium	3H
EnvironMet2	Environmental metals	Environmental metals	Al, As, B, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, P, Pb, V, Zn
FieldSonde2	Field measurements	YYY-sonde	Temperature, pH, conductivity, turbidity, light, oxygen, chlorofyll, redox
HeavyIso1	Heavy isotopes	Radon and radium isotopes	226Ra, 222Rn
HeavyIso3	Heavy isotopes	Uranium and thorium isotopes	230Th, 232Th, 234U, 235U, 238U
Nutrient1	Nutrients and carbon	Nutrient salt and silicate	NH4N, NO2N, NO3N, PO4P, NO2NO3N, SiO4Si
Nutrient2	Nutrients and carbon	Nutrient salt and silicate	NO2, NO3, NO2NO3N, NH4N, PO4P, SiO4
Nutrient3	Nutrients and carbon	Nutrient salt and silicate	NO2, NO3
Nutrient4	Nutrients and carbon	Nutrient salt and silicate	NO2NO3N, NH4N, PO4P, SiO4
Nutrient5	Nutrients and carbon	Total concentrations of nitrogen and phosphorus	TN, TP
Oxygen	Oxygen	Oxygen	O2
ParticulateCNP	Nutrients and carbon	Particulate carbon, nitrogen and phosphorus	POP, PON, POC
StrontiumIso	Light isotopes	Strontium isotopes	87Sr
SulphurIso	Light isotopes	Sulphur isotopes	34S
Susp&colour	Suspended matter and water colour	Suspended matter and water colour	Suspendend matter, absorbance
Trace2	Trace elements	Trace elements	U, Th, Sc, Rb, Y, Sb, Cs, La, Hf, Tl, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

6.2.3 Hydrochemical monitoring of surface waters 2002–2014

The monitoring of hydrochemical parameters in lakes, streams, sea water and precipitation started in 2002 within the site characterisation programme for the spent fuel repository. The extensive hydrochemical investigation campaigns for surface waters continued until 2004, when the programme was revised and a long-term monitoring programme was initiated for a smaller number of objects until the site investigations were completed in June 2007. After this date, the monitoring programme was revised and extended for two more years until the site selection process was completed in 2009. Since 2010, the long-term monitoring programme in Forsmark has continued until today with only minor revisions. Previous and present sampling locations are shown in Figure 6-4.

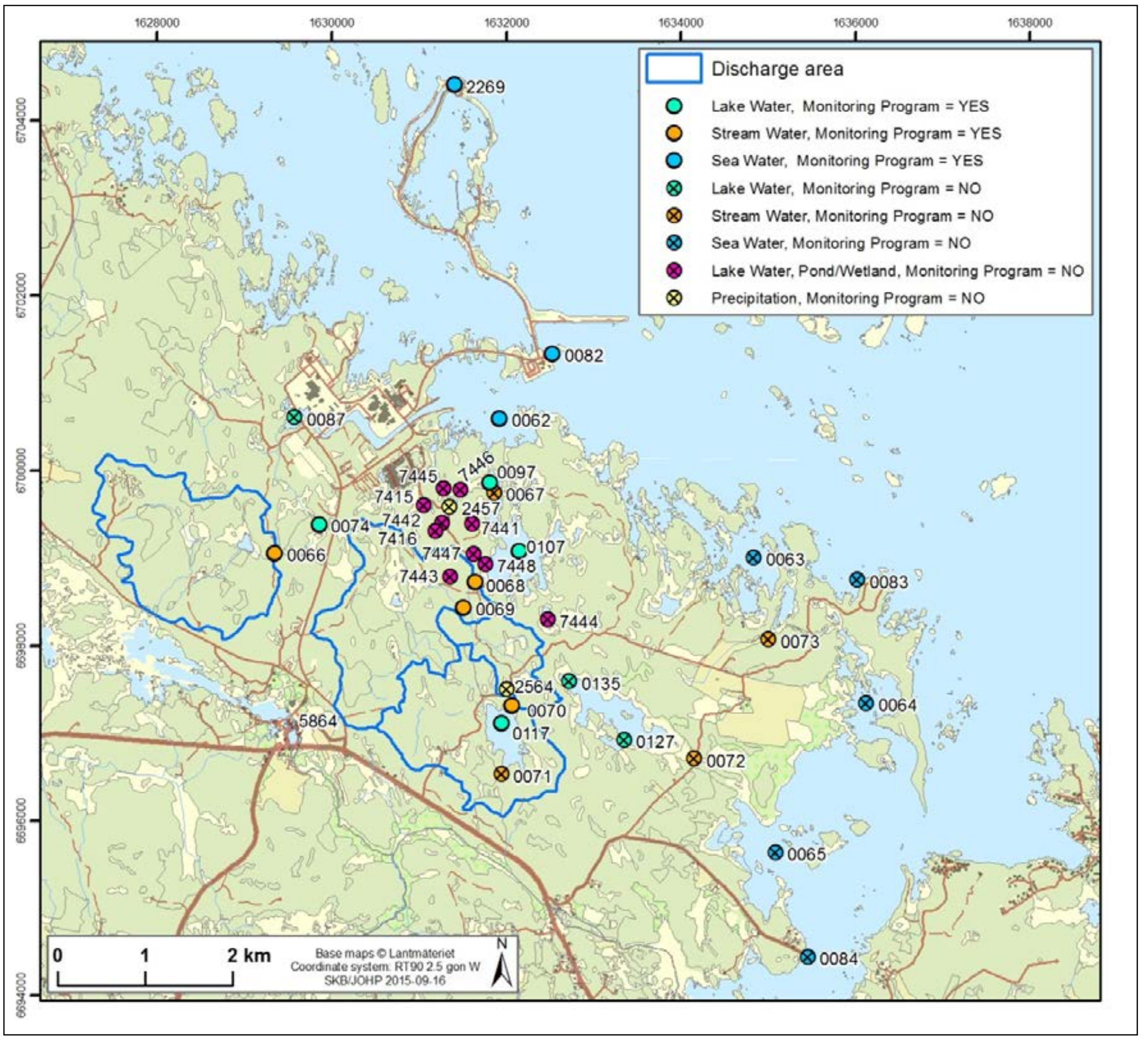

Figure 6-4. *All sampling locations in surface waters during the period 2002–2014. Previous sampling locations excluded from the ongoing monitoring programme are shown with crosses in the circular symbols.*

The development of the monitoring programme over time is shown in Table 6-4, based on statistics of data reported to the Sicada database. The objects included in the current programme are denoted by "y" in the monitoring column. In Table 6-5, the same information is presented but for a representative component per component group for all objects together. The rightmost columns denote the percentage of the samples each year that were analysed for each component group. This table adds information as to how the total number of samples per component group has changed over time, and emphasises where there have been changes within the programme.

Table 6-4. Overview of 1) the number of samples per year and monitored object (the leftmost columns) and 2) the number of analyses for a representative component in each component group (see Table 6-3), in percent of the total number of samples 2002 to 2014 (the columns to the right of the orange total column). Objects with time series comprising five samples or more are included and the ones that are still monitored in the ongoing monitoring programme are denoted “y” in the monitoring column. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

W_TYPE	IDCODE	CorrDepth	MonitProg	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1(pH)	Anions2a(Cl)	Anions2b_I(I)	Carbon1(DOC)	Carbon2(DIC)	Carbon3(TOC)	CarbonIso(14C)	Cations1(Na)	Cations2(Fe)	ChlorineIso(37Cl)	Chlorophyll(ChlA)	EnvironIso1(2H)	EnvironIso2(3H)	EnvironMet2(Zn)	FieldSonde1(pH_field)	FieldSonde2(Redox_field)	HeavyIso1(226Ra)	HeavyIso3(230Th)	Nutrient1(SiO2_bio)	Nutrient2(PO4P)	Nutrient5(N)	Oxygen(O2)	ParticulateCNP(POP)	StrontiumIso(87Sr)	Sulphide(S_2-)	SulphurIso(34S)	Susp&colour(Susp)	Trace2(Rb)
Lake Water	PFM000074	no_info	y											3	5	3	11	100	100	100	100	100	100		100	100		100	100	100	100	91	82			100	100	100		100				100	82
Lake Water	PFM000074	Surface	y	11	17	15	13	11	10	9	11	4	4	1			106	97	99	79	99	99	99	9	99	47	10	96	38	37	35	87	80	5	6	98	98	98	31	97	9	1	9	36	20
Lake Water	PFM000087	Surface	n	14	16	9											39	92	97	74	97	97	97	13	97	31	21	97	26	26	18	82	62		3	97	97	95	46	97	10	3	13		18
Lake Water	PFM000087	Bottom	n	14	8	4											26	88	96	65	96	96	96	19	96	38	19	96	27	27	15	77	42		4	96	96	92	88	96	12	4	12		12
Lake Water	PFM000097	Surface	y	13	16	9											38	92	97	76	97	97	95	11	97	24	13	95	24	21	18	89	66		3	97	97	95	55	97	5	3	8		16
Lake Water	PFM000107	no_info	y											3	6	5	14	100	93	100	100	100	100		100	100		100	100	100	100	86	71			100	100	100		100				100	86
Lake Water	PFM000107	Surface	y	15	16	15	13	10	11	9	11	4	4	1			109	97	98	78	98	97	98	10	99	46	11	96	36	36	34	85	76	6	7	98	98	97	27	98	8	1	9	36	19
Lake Water	PFM000107	Bottom	y	14	5	5	4	2	2	1	3	1	1	1			39	92	97	72	97	97	97	10	97	46	10	97	28	28	23	82	59		3	97	97	95	74	95	3	3	3	23	15
Lake Water	PFM000117	no_info	y											3	6	5	14	100	100	100	100	100	100		100	100		100	100	100	100	86	71			100	100	100		100				100	86
Lake Water	PFM000117	Surface	y	14	15	15	13	10	10	9	11	4	4	1			106	96	99	76	98	98	98	9	98	44	8	98	35	35	32	85	77	6	8	99	99	98	24	97	8		7	36	20
Lake Water	PFM000117	Bottom	y	14	5	5	4	2	2	1	3	1	1	1			39	90	97	72	92	92	92	10	97	41	3	95	26	26	23	79	59		3	95	95	92	74	92	3			23	15
Lake Water	PFM000127	Surface	n	9	6												15	73	93	87	93	93	93	13	93	20	20	93	20	20	7	73	40			93	93	87	53	93	7		7		
Lake Water	PFM000127	Bottom	n	9	1												10	70	90	80	90	90	90	20	90	30	30	90	30	30	30	60	10			90	90	80	80	90	10		10		10
Lake Water	PFM000135	Surface	n	2	3	14											19	95	100	84	100	100	100	11	100	26	11	100	26	26	26	95	89	5	11	100	100	100	16	95	16		16		21
Lake Water	PFM007415	no_info	n													8	8	100	100		88		88		100	100						100	100			88	88	88							
Lake Water	PFM007416	no_info	n													8	8	100	100		88		88		100	100						100	100			88	88	88							
Lake Water	PFM007441	Surface	n							1	6	6					13	100	100		100	8	100		100	100		8				100	100			15	100	100	23						
Lake Water	PFM007442	Surface	n							1	6	6					13	100	100		100	8	100		100	100						100	100			15	100	100	23						
Lake Water	PFM007442	no_info	n											7	11	7	25	100	96		96		96		100	100						92	84			76	96	96							
Lake Water	PFM007443	Surface	n							1	6	6					13	100	100		100	8	100		100	100						100	100			15	100	100	23						
Lake Water	PFM007443	no_info	n											7	11	7	25	100	100		96		96		100	100						92	84			76	96	96							
Lake Water	PFM007444	Surface	n							1	4	4					9	100	100		100		100		100	100						100	100			11	100	100	11						
Lake Water	PFM007445	no_info	n											8	11	6	25	100	92		96		96		100	100						92	84			72	96	96	4						

W_TYPE	IDCODE	CorrDepth	MonitProg	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1(pH)	Anions2a(Cl)	Anions2b_I(I)	Carbon1(DOC)	Carbon2(DIC)	Carbon3(TOC)	CarbonIso(14C)	Cations1(Na)	Cations2(Fe)	ChlorineIso(37Cl)	ChlorophyllI(ChlA)	EnvironIso1(2H)	EnvironIso2(3H)	EnvironMet2(Zn)	FieldSonde1(pH_field)	FieldSonde2(Redox_field)	HeavyIso1(226Ra)	HeavyIso3(230Th)	Nutrient1(SIO2_bio)	Nutrient2(PO4P)	Nutrient5(N)	Oxygen(O2)	ParticulateCNP(POP)	StrontiumIso(87Sr)	Sulphide(S_2-)	SulphurIso(34S)	Susp&colour(Susp)	Trace2(Rb)
Lake Water	PFM007446	no_info	n											8	11	6	25	100	100		96		96		100	100						92	84			72	96	96	4						
Lake Water	PFM007447	no_info	n											8	11	6	25	100	96		96		96		100	100						92	84			72	96	96	4						
Lake Water	PFM007448	no_info	n											8	11	6	25	100	100		96		96		100	100						92	84			72	96	96							
Precipitation	PFM002457	no_info	n	2	4												6	100	100		100				100	100			100	100															
Precipitation	PFM002564	no_info	n		2	11	6	5	6	3		5	4	3			45	100	98	27	38				100	100			100	100	27							11							27
Precipitation	PFM102271	no_info	n					3	4								7												57	100															
Sea Water	PFM000062	no_info	y											3	5	3	11	100	100	100	100	100	100		100	100		100	100	100	100	91	82			100	100	100		100				100	82
Sea Water	PFM000062	Surface	y	16	14	13	12	9	12	11	11	4	4	1			107	96	98	76	97	97	96	8	98	45	10	95	36	36	36	87	77	6	7	97	97	96	14	96	8		9	40	20
Sea Water	PFM000062	Bottom	y	16	1	1											18	78	89	56	83	83	89	11	89	28	17	89	17	17	17	78	17		6	89	89	83	83	83	6	6	6		11
Sea Water	PFM000063	Surface	n	16	17	9											42	90	95	76	93	93	93	10	95	24	14	95	21	21	21	81	57		5	93	95	93	45	90	10		12		19
Sea Water	PFM000063	Bottom	n	16	3	4											23	78	91	61	91	91	91	13	91	26	9	87	17	17	17	78	35		4	91	91	87	74	87	4		4		13
Sea Water	PFM000064	Surface	n	16	14	9											39	90	95	79	95	92	95	8	95	26	15	95	21	21	21	85	56		3	95	95	92	41	92	8		10		18
Sea Water	PFM000064	Bottom	n	16	2	3											21	76	90	57	90	90	90	14	90	24	14	86	19	19	19	81	29		5	90	90	86	67	86	5		5		14
Sea Water	PFM000065	Surface	n	14	16	8											38	89	95	79	95	95	95	11	95	24	18	92	26	24	24	84	61		5	95	95	92	42	95	11		13		21
Sea Water	PFM000082	Surface	y	2	4	2	1	3									12	100	100	67	92	92	92	17	100	50	17	100	25	25	17	83	75			100	100	100	42	100	8		8		17
Sea Water	PFM000082	Bottom	y	2	4	2	1	2									11	100	100	64	91	91	91	18	100	45	18	100	18	18	9	82	73		9	100	100	100	55	100	9		9		18
Sea Water	PFM000084	Surface	n	2	2	1											5	100	100	60	100	100	100	20	100	40	20	100	20	20		80	60			100	100	100	80	100					20
Sea Water	PFM000084	Bottom	n	2	2	1											5	100	100	60	100	100	100	20	100	40	20	100	20	20		60	40			100	100	100	80	100					20
Sea Water	PFM102269	Surface	y				1	12	12	11	11	11	11	11	11	10	101	57	55	1					1	1			1	98		77	77												
Stream Water	PFM000066	Surface	y	12	16	13	12	8	9	10	11	11	10	11	10	9	142	99	99	61	99	99	98	2	99	57	4	9	30	30	42	88	82			99	99	99	22	97	1	1	2	55	17
Stream Water	PFM000067	Surface	n	18	18	9											45	91	93	73	98	98	98	9	98	27	13	38	24	22	18	87	60			98	98	96	56	96	7		9		11
Stream Water	PFM000068	Surface	y	17	17	15	13	9	11	10	11	11	11	11	10	10	156	99	99	63	98	98	99	3	99	53	4	10	31	31	40	89	80	1	1	99	99	99	19	97	2	1	3	53	15
Stream Water	PFM000069	Surface	y	17	17	15	13	8	10	10	11	11	11	11	10	10	154	99	99	63	99	99	99	3	99	55	3	11	28	27	37	88	80			99	99	99	29	97	1		1	53	12
Stream Water	PFM000070	Surface	y	11	16	15	13	9	9	10	11	11	10	11	10	10	146	99	99	62	99	99	99	2	99	55	3	8	30	29	41	90	84			99	99	99	16	97	1		1	54	16
Stream Water	PFM000071	Surface	n	11	14	9											34	97	97	68	97	97	97	9	97	26	6	32	12	9	6	82	65			97	97	97	44	94					
Stream Water	PFM000072	Surface	n	14	18	9											41	98	95	71	49	95	95	10	98	29	15	32	24	24	15	85	63			98	98	98	71	93	7	5	10		12
Stream Water	PFM000073	Surface	n	7	8	8											23	100	100	70	100	100	100	4	100	22	13	35	17	17	13	91	70			100	100	100	43	96	4		9		13

The revisions of the monitoring programme described above are depicted by the data in Table 6-4. After the revision 2004, the number of sampling locations in lakes was reduced from 7 to 3, in streams from 8 to 4, and in sea water from 7 to 2. The number of sampling occasions per year was also reduced, especially the collection of samples from lake and sea bottom was reduced from all sampling occasions to a few occasions per year (lakes) or omitted (sea water). From 2006, the number of sampling occasions per year was further cut down and this programme has continued until today. Sampling and hydrochemical analysis of precipitation in Forsmark was performed from 2002 to 2008 within the site characterisation programme. Since the traffic increased 2003 close to sampling location PFM002457, a new location, PFM002564, was selected in order to avoid the risk of contamination by dust from the road. In 2010 to 2012, the sampling of precipitation was temporarily resumed with a focus on trace elements. The third sampling location for precipitation (PFM102271) represents a special sampling campaign for tritium at a location far from any nuclear power plants in the middle of Småland (Qvarfordt et al. 2008).

In addition to the changes in sampling frequency and the reduced number of sampling locations, the parameters included in the monitoring programme have also been revised during the period 2002–2014. Some component groups have been analysed on all occasions (marked in blue in the rightmost columns in Table 6-5), whereas other parameters were analysed frequently during the first years of the site investigation and after that at lower frequency, or not at all.

Major constituents and nutrients have been included at all surface water sampling locations, except for Lake Biotestsjön where only the tritium content is monitored. Complete sample time-series are available for the major constituents (Na, K, Ca, Mg, Li, Sr, Si-tot, pH, alkalinity, EC, Cl, F, SO_4 and Br). Iron and manganese data for lakes, streams and sea water are only available from the first years of the site investigations, whereas the lately initiated measurements of the ponds also include these ions. Iodine (I) has also been measured at lower frequency in lakes, streams and sea water, and not at all in the small ponds. The analyses of precipitation included the major constituents Na, K, Ca, Mg, Al, Fe, NH_4, Br, Cl, SO_4, NO_3 and HCO_3, pH and EC.

Complete time series of the nutrient salts and carbon species (NO_2, NO_3, $NO_2 + NO_3$, NH_4, total N, particulate organic N (PON), PO_4, total P, particulate organic P (POP), SiO_4, total organic C (TOC) and dissolved organic C (DOC)), are available for all surface water locations but not for precipitation. Dissolved inorganic carbon (DIC), i.e. mainly bicarbonate, is available for lakes, streams and sea water, but not for the ponds. Chlorophyll (Chl a) has been determined at most sampling occasions in the lakes, at fewer occasions in sea water and only at the beginning of the site investigation programme for streams.

Trace metals and environmental metals were analysed frequently in surface waters during the first two years of the site investigation programme and less frequently later on. The temporary sampling campaign for precipitation during 2010 focused on these metals, as they had not been included in the previous sampling.

The environmental isotopes, δ^2H, $\delta^{18}O$ and ^3H, have been determined less frequently than the major constituents during the sampling period 2002–2014. However, they have been determined in all precipitation samples collected in 2002 to 2008 as well as 2010 to 2012. These isotopes are not included in the programme for the ponds. Several stable and radioactive isotopes have been included in the monitoring programme over time, e.g. $\delta^{13}C$, ^{14}C (as percent modern carbon or pmC), $^{10}B/^{11}B$, $^{87}Sr/^{86}Sr$, $\delta^{37}Cl$, ^{226}Ra, ^{238}U etc., and most of these analyses were conducted in the beginning of the site investigation programme. None of these isotopic analyses have been included in the monitoring programme after 2009 and instead archive samples are stored for possible future use.

Multi-parameter probes have been used for field measurements of pH, ORP (Oxidising Reducing Potential), PAR (Photosynthetically Active Radiation), turbidity, EC, salinity, dissolved oxygen and chlorophyll during the period 2002–2014. Field measurements were planned to be conducted at every sampling occasion and the discrepancy from 100 % coverage for these measurements is mainly explained by occasional technical problems with the probes.

Table 6-5. Overview of analysis extent per year (2002–2014): The leftmost columns give the number of samples per year and for a typical component in each component group (Table 6-3). The rightmost columns present the percentage of analyses per component group in relation to the total number of samples each year. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

W_TYPE	compGrp	TypicalMetaAbb	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Lake Water	Anions1	pH	106	107	90	47	36	35	33	62	36	14	60	83	67	776	77	99	98	100	100	100	100	100	100	100	100	100	100
Lake Water	Anions2a	Cl	128	107	92	47	36	35	33	62	36	14	60	81	64	795	93	99	100	100	100	100	100	100	100	100	100	98	96
Lake Water	Anions2b_Br	Br	124	108	91	47	36	35	33	62	36	14	60	83	66	795	90	100	99	100	100	100	100	100	100	100	100	100	99
Lake Water	Anions2b_I	I	69	90	91	44	36	29	14	14	14	14	14	17	13	459	50	83	99	94	100	83	42	23	39	100	23	20	19
Lake Water	Carbon1	DOC	126	107	91	47	36	35	33	61	36	14	60	83	59	788	91	99	99	100	100	100	100	98	100	100	100	100	88
Lake Water	Carbon2	DIC	126	107	91	47	36	34	29	39	17	14	14	17	13	584	91	99	99	100	100	97	88	63	47	100	23	20	19
Lake Water	Carbon3	TOC	125	107	91	47	36	35	33	61	36	14	60	83	59	787	91	99	99	100	100	100	100	98	100	100	100	100	88
Lake Water	CarbonIso	14C	32	9	4	3	3	3	3	3						60	23	8	4	6	8	9	9	5					
Lake Water	Cations1	Na	128	108	92	47	36	35	33	61	36	14	60	83	67	800	93	100	100	100	100	100	100	98	100	100	100	100	100
Lake Water	Cations2	Fe	32	29	30	26	36	12	18	36	36	14	60	83	67	479	23	27	33	55	100	34	55	58	100	100	100	100	100
Lake Water	ChlorineIso	37Cl	27	15	6	3	3	3	2	3						62	20	14	7	6	8	9	6	5					
Lake Water	Chlorophyll	ChlA	127	106	90	47	34	35	29	37	15	14	14	17	13	578	92	98	98	100	94	100	88	60	42	100	23	20	19
Lake Water	EnvironIso1	2H	32	26	22	14	11	10	14	14	14	14	14	17	13	215	23	24	24	30	31	29	42	23	39	100	23	20	19
Lake Water	EnvironIso2	3H	32	24	22	14	11	10	14	14	14	14	14	17	13	213	23	22	24	30	31	29	42	23	39	100	23	20	19
Lake Water	EnvironMet2	Zn	14	22	23	14	11	10	14	14	14	14	14	17	13	194	10	20	25	30	31	29	42	23	39	100	23	20	19
Lake Water	FieldSonde1	pH_field	96	94	89	21	33	35	33	62	36	14	60	66	67	706	70	87	97	45	92	100	100	100	100	100	100	80	100
Lake Water	FieldSonde2	Redox_field	9	94	89	21	33	35	33	62	36	14	60	49	67	602	7	87	97	45	92	100	100	100	100	100	100	59	100
Lake Water	HeavyIso1	226Ra			4	3	3	3	3	2						18			4	6	8	9	9	3					
Lake Water	HeavyIso3	230Th		8	4	3	3	3	3	5						29		7	4	6	8	9	9	8					
Lake Water	Nutrient1	SiO2_bio	127	107	91	47	36	35	29	39	21	14	26	83	59	714	92	99	99	100	100	100	88	63	58	100	43	100	88
Lake Water	Nutrient4	NO23N	127	107	91	47	36	35	33	61	36	14	60	83	59	789	92	99	99	100	100	100	100	98	100	100	100	100	88
Lake Water	Oxygen	O2	121	43	23	13	11	2		13	10	5	3			244	88	40	25	28	31	6		21	28	36	5		
Lake Water	ParticulateCNP	POP	124	107	90	47	36	32	29	39	14	14	14	17	13	576	90	99	98	100	100	91	88	63	39	100	23	20	19
Lake Water	StrontiumIso	87Sr	4	14	10	3	3	3	3	3						43	3	13	11	6	8	9	9	5					
Lake Water	Sulphide	S_2-	6													6	4												
Lake Water	SulphurIso	34S	4	18	8	3	3	3	3	2						44	3	17	9	6	8	9	9	3					
Lake Water	Susp&colour	Susp						35	29	39	11	14	14	17	13	172						100	88	63	31	100	23	20	19
Lake Water	Trace2	Rb	8	22	19	6		3	3	4	14	14	14	14	10	131	6	20	21	13		9	9	6	39	100	23	17	15
Precipitation	Anions1	pH	2	6	11	6	5	6	3		5	4	3			51	100	100	100	100	63	60	100		100	100	100		
Precipitation	Anions2a	Cl	2	6	11	6	5	5	3		5	4	3			50	100	100	100	100	63	50	100		100	100	100		
Precipitation	Anions2b_Br	Br	2	6	11	6	5	6	3		5	4	3			51	100	100	100	100	63	60	100		100	100	100		
Precipitation	Anions2b_I	I									5	4	3			12									100	100	100		
Precipitation	Carbon1	DOC	2	6	11	4										23	100	100	100	67									
Precipitation	Cations1	Na	2	6	11	6	5	6	3		5	4	3			51	100	100	100	100	63	60	100		100	100	100		
Precipitation	Cations2	Fe	2	6	11	6	5	6	3		5	4	3			51	100	100	100	100	63	60	100		100	100	100		
Precipitation	EnvironIso1	2H	2	6	11	6	7	8	3		5	4	3			55	100	100	100	100	88	80	100		100	100	100		
Precipitation	EnvironIso2	3H	2	6	11	6	8	10	3		5	4	3			58	100	100	100	100	100	100	100		100	100	100		
Precipitation	EnvironMet1	Al	2	6	11	4	5	4	3							35	100	100	100	67	63	40	100						
Precipitation	EnvironMet2	Zn									5	4	3			12									100	100	100		
Precipitation	Nutrient5	N		1		4										5		17		67									
Precipitation	Trace2	Rb									5	4	3			12									100	100	100		
Sea Water	Anions1	pH	97	82	56	15	29	24	22	22	15	4	4	5	3	378	76	100	100	100	100	100	100	100	100	27	27	31	23
Sea Water	Anions2a	Cl	113	82	56	15	27	24	22	22	15	4	4	5	3	392	89	100	100	100	93	100	100	100	100	27	27	31	23
Sea Water	Anions2b_Br	Br	113	82	56	13	26	24	22	21	15	4	4	5	3	388	89	100	100	87	90	100	100	95	100	27	27	31	23
Sea Water	Anions2b_I	I	56	72	56	13	17	9	4	4	4	4	4	5	3	251	44	88	100	87	59	38	18	18	27	27	27	31	23
Sea Water	Carbon1	DOC	110	80	53	14	17	12	11	11	4	4	4	5	3	328	87	98	95	93	59	50	50	50	27	27	27	31	23

W_TYPE	compGrp	TypicalMetaAbb	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Sea Water	Carbon2	DIC	110	79	53	14	17	12	11	11	4	4	4	5	3	327	87	96	95	93	59	50	50	50	27	27	27	31	23
Sea Water	Carbon3	TOC	111	79	53	14	17	12	11	11	4	4	4	5	3	328	87	96	95	93	59	50	50	50	27	27	27	31	23
Sea Water	CarbonIso	14C	26	5	1	1	1	1	1	1						37	20	6	2	7	3	4	5	5					
Sea Water	Cations1	Na	113	82	56	15	17	12	11	11	4	4	4	5	3	337	89	100	100	100	59	50	50	50	27	27	27	31	23
Sea Water	Cations2	Fe	27	21	19	10	17	4	4	4	4	4	4	5	3	126	21	26	34	67	59	17	18	18	27	27	27	31	23
Sea Water	ChlorineIso	37Cl	25	13	7	1	1	1	1	1						50	20	16	13	7	3	4	5	5					
Sea Water	Chlorophyll	ChlA	112	81	52	14	17	12	11	10	4	3	4	5	3	328	88	99	93	93	59	50	50	45	27	20	27	31	23
Sea Water	EnvironIso1	2H	27	18	15	5	7	4	4	4	4	4	4	5	3	104	21	22	27	33	24	17	18	18	27	27	27	31	23
Sea Water	EnvironIso2	3H	27	17	15	5	19	16	15	15	15	15	15	16	11	201	21	21	27	33	66	67	68	68	100	100	100	100	85
Sea Water	EnvironMet2	Zn	21	17	12	4	7	4	4	4	4	4	4	5	3	93	17	21	21	27	24	17	18	18	27	27	27	31	23
Sea Water	FieldSonde1	pH_field	89	73	49	6	24	24	22	22	15	15	15	4	3	361	70	89	88	40	83	100	100	100	100	100	100	25	23
Sea Water	FieldSonde2	Redox_field	7	73	49	6	24	24	22	22	15	15	15	3	3	278	6	89	88	40	83	100	100	100	100	100	100	19	23
Sea Water	HeavyIso1	226Ra			4	1	1	1	1	1						9			7	7	3	4	5	5					
Sea Water	HeavyIso3	230Th	7	4	4	1	1	1	1	2						21	6	5	7	7	3	4	5	9					
Sea Water	Nutrient4	NO23N	113	81	56	14	17	12	11	11	4	4	4	5	3	335	89	99	100	93	59	50	50	50	27	27	27	31	23
Sea Water	Oxygen	O2	109	31	1											141	86	38	2										
Sea Water	ParticulateCNP	POP	106	81	53	14	17	12	11	11	4	4	4	5	3	325	83	99	95	93	59	50	50	50	27	27	27	31	23
Sea Water	StrontiumIso	87Sr	7	9	8	1	1	1	1	1						29	6	11	14	7	3	4	5	5					
Sea Water	Sulphide	S_2-	1													1	1												
Sea Water	SulphurIso	34S	7	13	8	1	1	1	1	1						33	6	16	14	7	3	4	5	5					
Sea Water	Susp&colour	Susp						12	11	11	4	4	4	5	3	54						50	50	50	27	27	27	31	23
Sea Water	Trace2	Rb	20	17	11	2		1	1	1	4	3	4	4	2	70	16	21	20	13		4	5	5	27	20	27	25	15
Stream Water	Anions1	pH	95	124	93	51	34	39	40	44	44	42	44	40	39	729	89	100	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Anions2a	Cl	99	121	93	51	34	39	40	44	44	42	44	40	39	730	93	98	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Anions2b_Br	Br	99	124	93	51	34	39	40	44	44	42	44	40	39	733	93	100	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Anions2b_I	I	37	103	93	43	34	31	4	12	16	38	16	16	31	474	35	83	100	84	100	79	10	27	36	90	36	40	79
Stream Water	Carbon1	DOC	97	124	93	51	34	39	40	44	44	42	44	40	39	731	91	100	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Carbon2	DIC	96	124	93	51	34	39	40	44	43	42	44	40	39	729	90	100	100	100	100	100	100	98	98	100	100	100	100
Stream Water	Carbon3	TOC	97	124	93	51	34	39	39	44	44	42	44	40	39	730	91	100	100	100	100	100	98	98	100	100	100	100	100
Stream Water	CarbonIso	14C	26													26	24												
Stream Water	Cations1	Na	100	124	93	51	34	39	40	44	44	42	44	39	39	733	93	100	100	100	100	100	100	98	100	100	100	98	100
Stream Water	Cations2	Fe	27	30	28	20	32	4	3	16	44	41	44	39	39	367	25	24	30	39	94	10	8	36	100	98	100	98	100
Stream Water	ChlorineIso	37Cl	21	10	6											37	20	8	6										
Stream Water	Chlorophyll	ChlA	64	39	1	2										106	60	31	1	4									
Stream Water	EnvironIso1	2H	26	25	20	15	8	11	12	16	16	14	16	16	12	207	24	20	22	29	24	28	30	36	36	33	36	40	31
Stream Water	EnvironIso2	3H	24	23	20	15	8	11	12	16	16	14	16	16	12	203	22	19	22	29	24	28	30	36	36	33	36	40	31
Stream Water	EnvironMet2	Zn	9	23	16						44	42	44	40	39	257	8	19	17						100	100	100	100	100
Stream Water	FieldSonde1	pH_field	72	118	88	21	30	39	40	44	41	42	44	36	39	654	67	95	95	41	88	100	100	98	93	100	100	90	100
Stream Water	FieldSonde2	Redox_field	8	118	88	21	30	39	40	44	41	42	44	24	39	578	7	95	95	41	88	100	100	98	93	100	100	60	100
Stream Water	HeavyIso1	226Ra								2						2								4					
Stream Water	HeavyIso3	230Th								2						2								4					
Stream Water	Nutrient4	NO23N	100	124	93	51	34	39	40	44	44	42	44	40	39	734	93	100	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Nutrient5	N	97	124	93	51	34	39	40	44	44	42	44	40	39	731	91	100	100	100	100	100	100	98	100	100	100	100	100
Stream Water	Oxygen	O2	91	54	17	9	7			4	6	11	9			208	85	44	18	18	21			9	14	26	20		
Stream Water	ParticulateCNP	POP	89	124	93	51	32	36	40	44	44	41	42	40	39	715	83	100	100	100	94	92	100	98	100	98	95	100	100
Stream Water	StrontiumIso	87Sr	4	5	6											15	4	4	6										
Stream Water	Sulphide	S_2-	4													4	4												
Stream Water	SulphurIso	34S	4	11	5											20	4	9	5										
Stream Water	Susp&colour	Susp						39	40	44	36	42	40	40	39	320						100	100	98	82	100	91	100	100
Stream Water	Trace2	Rb	1	16	16						24	10	16	12	8	103	1	13	17						55	24	36	30	21

6.2.4 Conditions and aspects of importance when interpreting hydrochemical surface-water data

Identified practical problems and other conditions of varying importance that may have had an impact on the samples, analyses and measurements for surface waters are described below.

Filtration in field: The samples are filtered in the field (0.45 µm), which means that they should represent the dissolved species in the water (cf. Figure 6-2). However, a varying fraction of the colloidal fraction passes the filter and will be included or partly included in the analyses. Thus, the samples represent something between the dissolved fraction and the total fraction depending on the measured element/component (Nilsson 2011a).

Sea water intrusion: The flat topography in the Forsmark area leads to sea water intrusion into near-coastal, low-lying lakes during periods of high sea levels (Figure 6-5). This was especially evident in Lake Bolundsfjärden after the storm Gudrun in January 2005. Regular EC measurements have been performed until 2009 at Lake Norra Bassängen to enable monitoring of such events that may influence Lake Bolundsfjärden, Lake Norra Bassängen and to some extent Lake Fiskarfjärden (Tröjbom et al. 2007, Nilsson et al. 2010a).

Measurements with field probe: There have been several problems with the field probes. At some occasions, some of the parameters have not stabilised; they showed unreliable values or calibration control parameters were out of range. Poor sensitivity in clear waters with negative turbidity measurements has also occurred. Since new probes were obtained in 2013, these problems have not been repeated. Chlorophyll measurements with the probes have been problematic due to the fact that humic substances and chlorophyll have similar fluorescence at the wavelength used by the probe, which implies that the amount of chlorophyll tends to be overestimated. The field probe that has been in use since 2013 does not include chlorophyll measurements. Chlorophyll analyses in batch samples are considered more reliable than the probe measurements.

Tritium emissions: There are occasional increases in the content of tritium in sea water due to emissions in the cooling water from the adjacent nuclear power plant. In 2004–2005, a relation was observed between the tritium content in the sea and the distance from the nuclear power reactors. Therefore, regular sampling in order to monitor possible tritium contamination has been performed since 2005 close to the cooling water outlet from the nuclear power plant (Figure 6-6). Significantly elevated tritium concentrations have been observed on several occasions. It was suspected that the tritium content could be enhanced also in the precipitation due to the closeness to the power plant.

Figure 6-5. *At high sea level, Lake Bolundsfjärden is occasionally influenced by sea water intrusions via Lake Norra Bassängen due to the very flat topography (red arrow). The normal level of Lake Bolundsfjärden is less than 1 m above normal sea level.*

Figure 6-6. *Tritium is sampled near the outlet of Lake Biotestsjön that receives cooling water from the nuclear power plants. Cool sea water reaches the reactors along the yellow line via the inlet canal. Heated cooling water is led to the lake via tunnels below the sea floor according to the schematic dashed red lines. Cooling water from reactor 1 and 2, and 3, respectively, mix when the separate currents reach the Baltic Sea (solid red lines).*

In order to check this condition, a sampling location was therefore established in the middle of Småland (PFM102271) far from any nuclear reactors. The sampling at this location went on for two years and showed similar values and seasonal trends to the precipitation samples from Forsmark (Qvarfordt et al. 2008, Berg et al. 2009) which indicated insignificant impacts from the power plants on the tritium values in the precipitation also in Forsmark.

Oxygen concentrations: Initially, all surface water samples were analysed for oxygen both with the multi-parameter probe in the field and at the laboratory. Since 2003, laboratory measurements for oxygen have only been conducted when the field-measurements fall below 4 mg/L. To obtain a complete and correct representation of the oxygen concentrations, it is therefore necessary to combine both field measurements and laboratory measurements from separate tables in the Sicada database.

Sampling of precipitation: The first location of the samplers for collecting rain and snow was a small glade close to a gravelled road, which may have caused contamination of the sample water by dust. Therefore, in 2003 the sampling location for precipitation was changed from PFM002457 to PFM002564 (Figure 6-7). The first samplers that were used for collecting the precipitation were very simple and they were changed for more adequate ones in 2007 (Berg 2007). The samplers in the field have been emptied with different frequencies and different procedures/systems for pooling of sample portions have been used over time. This may have affected the concentrations measured due to varying influence from evaporation. There have been difficulties to analyse trace metals and obtain values due to the low concentrations in precipitation. During 2010–2012, a special campaign was carried out in order to obtain at least some concentration values, albeit very uncertain, for several trace elements. The analytical values were reported even if they were below the reporting limit (RL) stated by the laboratory for accredited analyses (the reporting limit is defined as 10 standard deviations while the detection limit is 3 standard deviations).

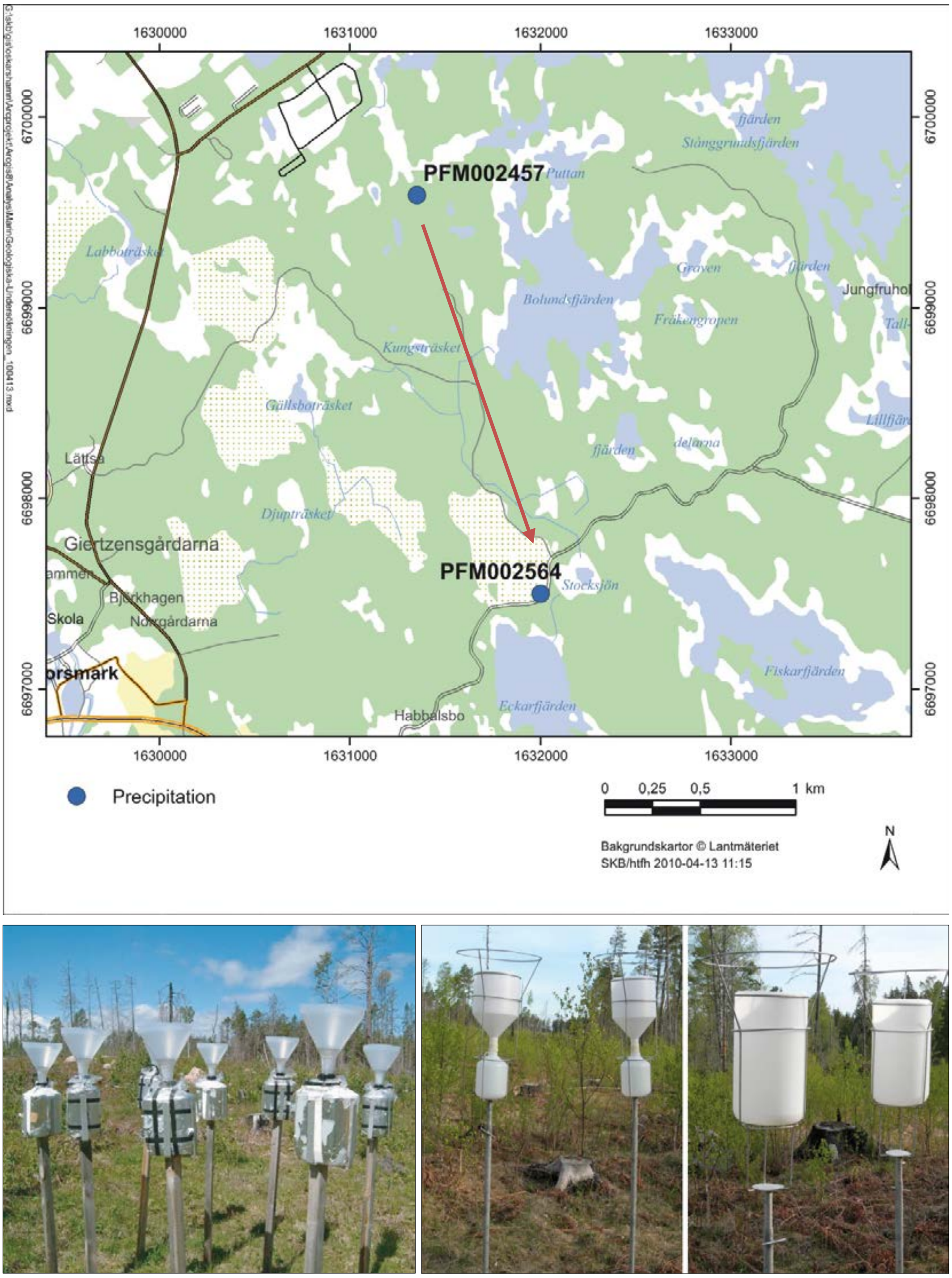

Figure 6-7. *In 2003, the sampling location for precipitation was moved from PFM002457 to PFM002564 due to suspected dust contamination from a gravelled road with increasing traffic. The first samplers that were used for collecting the precipitation were very simple (to the left) and they were changed for more adequate ones in 2007 (middle and right). Different types were used for collecting rain (middle) and snow (right). No sampling of precipitation for hydrochemical analyses has been performed since 2012.*

6.2.5 Statistical evaluation of hydrochemical data from surface water

This section summarises the results from the statistical evaluation of hydrochemical data of lake water, stream water, sea water and precipitation. The comprehensive statistical overviews of the data in Appendix 3 reflect different aspects of data quality, general patterns of variability, representativity of chemical data and long-term temporal changes with the main purpose of evaluating data quality and inconsistencies amongst sampled objects and analysed parameters. In contrast to the analysis and modelling underpinning most site descriptive models, the current evaluation comprises all quality controlled data in Sicada, in order to objectively describe the total dataset rather than adding new interpretations of the data. The purpose of this evaluation is, however, to systematically go through and compile the data in order to judge if the current monitoring programme is sufficient regarding sampling frequency, temporal and spatial representativity, and if it is suitable for answering the general questions at issue.

The evaluation is based on five major data compilations briefly described in the list below. These compilations contribute different complementary aspects to the extensive hydrochemical dataset (regarding number of records/samples and number of determined parameters) from the Forsmark area. The results from each of these statistical analyses are summarised below and the tables are found in Appendix 3.

1. The total number of observations per parameter and object (sampling location and sampling depth).
2. The fraction of the observations per parameter and object that fall below reporting limits.
3. The coefficient of variation (CV) for all parameters and objects. This compilation shows the relative variance among parameters and objects. The information could be used to identify objects or parameters with, for some reason, increased variation. For parameters or objects with large inherent variation, longer time series and/or more frequent sampling is needed in order to detect significant deviations. Low inherent variation could, consequently, imply a possibility to decrease the sampling frequency.
4. Normalised means based on all data from similar objects (lake water, sea water, stream water and precipitation). Independent of the absolute parameter values, this compilation shows where the mean values for individual objects are located on the total range for all similar objects for each parameter. This information could be used to identify specific objects with deviating chemistry and also to show common patterns among several parameters.
5. The results from a regression analysis with the purpose to identify significant temporal trends in the data. Trends over time could be an indication of methodological, climatic or anthropogenic factors that influence data over time.

Total number of observations (cf. Appendix 3, Table A3-1): The overview of the total number of data for all parameters and all surface sampling locations including precipitation during the period 2002–2014 shows the development of the monitoring and site characterisation programmes over time. The objects included in the current monitoring programme are easily identified since they have many more observations and longer time series. Among lake and sea water sampling locations the lower number of bottom samples is evident, which is due to early changes in the monitoring programme according to the overview in Section 6.2.3. Several observations in lakes are marked as "X" in the "corrSec" column, which means that they have not been correctly categorised as bottom or surface samples in the Sicada database.

Among the parameters, the total number of available data differs significantly due to varying extent of the hydrochemical investigation activities including the monitoring programmes over time. Major constituents, nutrients and carbon species (Na, K, Ca, Mg, Cl, SO_4, Br, HCO_3, Li, tot-N, tot-P, NH_4, NO_3, PO_4, particulate organic N (PON), particulate organic P (POP), dissolved organic carbon (DOC), total organic carbon (TOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC)) are analysed at all sampling occasions, whereas for example trace elements (e.g. Cu, Pb, Cd, Ni, La, Sc, Nd, U, Th) and environmental isotopes ($\delta^{2}H$, $\delta^{18}O$, ^{3}H) are analysed at a lower frequency. Some parameters have been determined on a few occasions in the beginning of the site characterisation programme, or in separate campaigns with specific purposes. A number of isotopes (^{10}B, $\delta^{13}C$, ^{14}C, $\delta^{34}S$, $\delta^{37}Cl$, ^{87}Sr) were determined at the beginning of the site investigation programme in order to establish a baseline or at least make a screening of the levels. Later on they were excluded mainly due to costs. A number of radionuclides (^{222}Rn, ^{226}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{235}U, ^{236}U, ^{238}U) were also sampled early in the site investigation programme and in separate campaigns (cf. Tröjbom and Grolander 2010, Grolander and Roos 2009).

The evaluation of the total number of samples shows that some of the trace elements have only been sampled at a few occasions in the beginning of the site investigation programme and were after that excluded for reasons that are unclear (B, Nb, In, Se). The stable isotopes of Nb and Se are possible important analogues of radionuclides included in the long term safety assessments of the spent fuel repository. Inclusion of these elements in the updated monitoring programme should be considered together with other elements with potentially important radionuclides, i.e. Ag, Pd and Sn, for which no data are available.

Analyses below reporting limits (Appendix 3, Table A3-2): If a large fraction of the analyses fall below the reporting limit it could be an indication that the analytical method is inappropriate. Among the water types, sea water samples show the highest percentage of analyses below reporting limits. This is mainly due to the difficulties to analyse some of the trace elements in water with high ionic strength. In precipitation, the inherent low concentrations of most elements are the main cause for the high percentage of analyses below reporting limits.

The parameters that often show values below the reporting limits are Cs and Th, irrespective of water type. Most of the Chlorophyll c analyses fall below the reporting limit and approximately half of the pheopigment (pheo_bio) analyses. In lake- and stream water and especially in the ponds, many of the analyses of Br, Li, and F and to some extent iodide fall below the reporting limits. About half of the analyses of suspended matter fall below the reporting limit, irrespective of water type. The radionuclides ^{222}Rn and ^{226}Ra also have a large fraction of the analyses below the reporting limit.

A varying fraction of the rare earth metals, REE, fall below the reporting limits (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu). REE have very similar chemical properties and the occurrences of these elements are usually highly correlated, but the individual elements occur at very different total concentrations. For the least occurring elements of this group (e.g. Tb, Ho, Tm, and Lu), most of the analyses from all water types fall below the reporting limit. The inherent low concentrations of these geogenic elements in precipitation explain the large fraction below the reporting limits, whereas in sea water it is probably attributed to the difficulties of analysing REE in water of high ionic strength.

The evaluation of reporting limits with respect to the monitoring programme identifies some problems like Cs and Th in all water types, bromide and iodide in lake water (especially the ponds), and REE especially in sea water. Suspended matter determinations have quite often given values below the official reporting limit of the laboratory, but they are, generally, above the detection limit. By a special agreement between SKB and the laboratory, suspended matter values are reported also below the official reporting limit, although the results fall outside of their accreditation.

Comparisons of variation (Appendix 3, Table A3-3): The coefficient of variation (CV), which is defined as the ratio between the arithmetic standard deviation and the arithmetic mean, represents the relative variance among parameters and objects. This information could be used to identify objects and parameters with, for some reason, increased inherent variation.

From the analysis of CV it could be concluded that several objects show similar variance irrespective of water type, and that several parameters show similar general variance. There is a general tendency for lower variance in sea water compared with the fresh water types which is expected considering the stable conditions in such a large water reservoir which does not show very much seasonal variation.

The major constituents Ca and HCO_3 show low variance, compared to most other parameters, which probably reflects the constant supply of these elements from calcite dissolution in the regolith. Major constituents of marine origin, such as Cl, Br, Mg and Na show relatively low variance for most objects except for Lake Bolundsfjärden and Lake Norra Bassängen (PFM000107 and PFM000097, respectively), where occasional sea water intrusions contribute to the increased variance. The total nutrient concentrations (tot-N and tot-P) show lower variance than the nitrogen and phosphorus species (NO_3, NH_4 and PO_4), and the particulate fractions of C, N and P, as well as Si and chlorophyll measurements (Chl a, Chl c) that show large variance due to the seasonal growth cycles. The redox sensitive elements Fe and Mn, and the geogenic element Al show increased variance. ^{3}H show increased variance in Lake Biotestsjön (PFM102269) due to the influence from the nuclear power plant. There are no indications from the variance patterns that lakes, streams, sea water or precipitation are influenced by this local source of ^{3}H.

The general conclusion from the CV evaluation is that the variance of the objects included in the current monitoring programme does not differ from the majority of the objects included in the initial site investigation programme. The variance of several major constituents and total concentrations of nutrients and carbon are relatively low and constant among the objects and parameters, whereas some nitrogen, phosphorus and carbon species are attributed a larger variance due to seasonal cycles. Most trace elements show an increased variance compared with most major constituents, probably reflecting the larger analytical uncertainties and in some cases higher contamination risks for this group of elements.

Comparisons among normalised means (Appendix 3, Table A3-4): The major purpose of comparisons among normalised means is to relate the individual objects, for example the objects included in the current monitoring programme, to all similar objects in order to identify objects with generally deviating chemistry. This might give information on whether the selected sampling locations reflect the relevant spatial variation in the Forsmark area, and if there are previously sampled objects with deviating chemistry that are not included in the current monitoring programme.

The general conclusion from the evaluation of normalised means is that the present single sampling location for sea water (PFM000062) is representative for sea water close to the coastline in the Forsmark area. There is a tendency for higher concentrations of marine ions in Lake Bolundsfjärden (PFM000107) and Lake Norra Bassängen (PFM000097) compared with the other lakes, due to sea water intrusion and the fact that these lakes recently were sea bays. The current monitoring programme does not include water types corresponding to the nutrient rich conditions in for example Lake Fiskarfjärden and the location PFM000073 in a small stream, characterised by high concentrations of total nitrogen, chlorophyll, silicon, particulate species of carbon, nitrogen and phosphorus, and elevated pH probably due to high primary production. The ponds deviate by higher contents of organic carbon and higher absorbance compared to the larger lakes, thus representing a surface water type that has not been included earlier in the monitoring programme, or during the site investigation.

Evaluation of time series (Appendix 3, Table A3-5): The evaluation of time series by a linear, parametric regression analysis is a screening method with the purpose to find trends in data not explained by chance. It is expected that most of the time series show no trends if they reflect baselines at undisturbed conditions. On the contrary, a significant trend or variation could be an indication of such effects, disturbed conditions or methodological bias. As this analysis catches stepwise shifts, gradual trends and influences from individual outliers, the results must be checked by time-series plots. It should also be kept in mind that an evaluation of a large number of relationships implies that a portion of these are falsely recognised as significant. The regression analysis has been applied to all time series comprising of at least 10 observations ranging over a time period of four years, or longer. The statistics given in Table A3-15 in Appendix 3, represent the probabilities for the hypothesis that there is no time-trend in data, i.e. values between –0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign of the probabilities represents the direction of the trends based on the sign of the correlation coefficients.

Among the objects and parameters that fulfil the criteria of enough data for the analysis (at least ten observations over a period longer than four years), weakly increasing trends are observed for organic carbon, silicon, and absorbance. According to Figure 6-8, the increasing trend for TOC is mainly explained by a stepwise shift during 2006, when a new baseline seems to have been established (marked by the dashed line). Also Ca and HCO_3, which originate from weathering of the regolith, show increasing trends over the studied time period. In Figure 6-9, these trends are weaker but perhaps also show a stepwise shift in the baseline. Stepwise shifts of this type could be an indication of methodological changes in sampling or analysis. The pH values show decreasing trends for several sampling locations. In the streams, where most of the significant trends are found, the deviating observations during the first year probably explain most of the trend (Figure 6-10). For some parameters, changes in sampling frequency could also cause apparent trends in the statistical analysis, e.g. Ca in lake- and sea water.

According to Figure 6-11, tritium (^3H) shows a decreasing trend for most sampling locations. The fact that the trends are very similar for all objects indicates that they are all influenced by a common factor, which is the radioactive decay of ^3H in the atmosphere and not a diminishing local influence from the nuclear power plant. Episodes of very elevated ^3H activities are registered in Lake Biotestsjön, where the cooling water from the nuclear power plants is returned. No similar events are noted for ^3H at the other sampling locations.

The decreasing trends for dissolved oxygen (O_2_bio, which is analysed in the laboratory) are methodological artefacts. As mentioned previously, O_2 (lab) was initially analysed for all surface water samples, but from 2003 analyses are only conducted when the measured concentration in the field is below 4 mg/L. The omitted values above this threshold since 2003 generate the apparent trend. To obtain a complete and correct representation of the oxygen concentrations, it is therefore necessary to combine both field measurements and laboratory measurements from separate tables in the Sicada database.

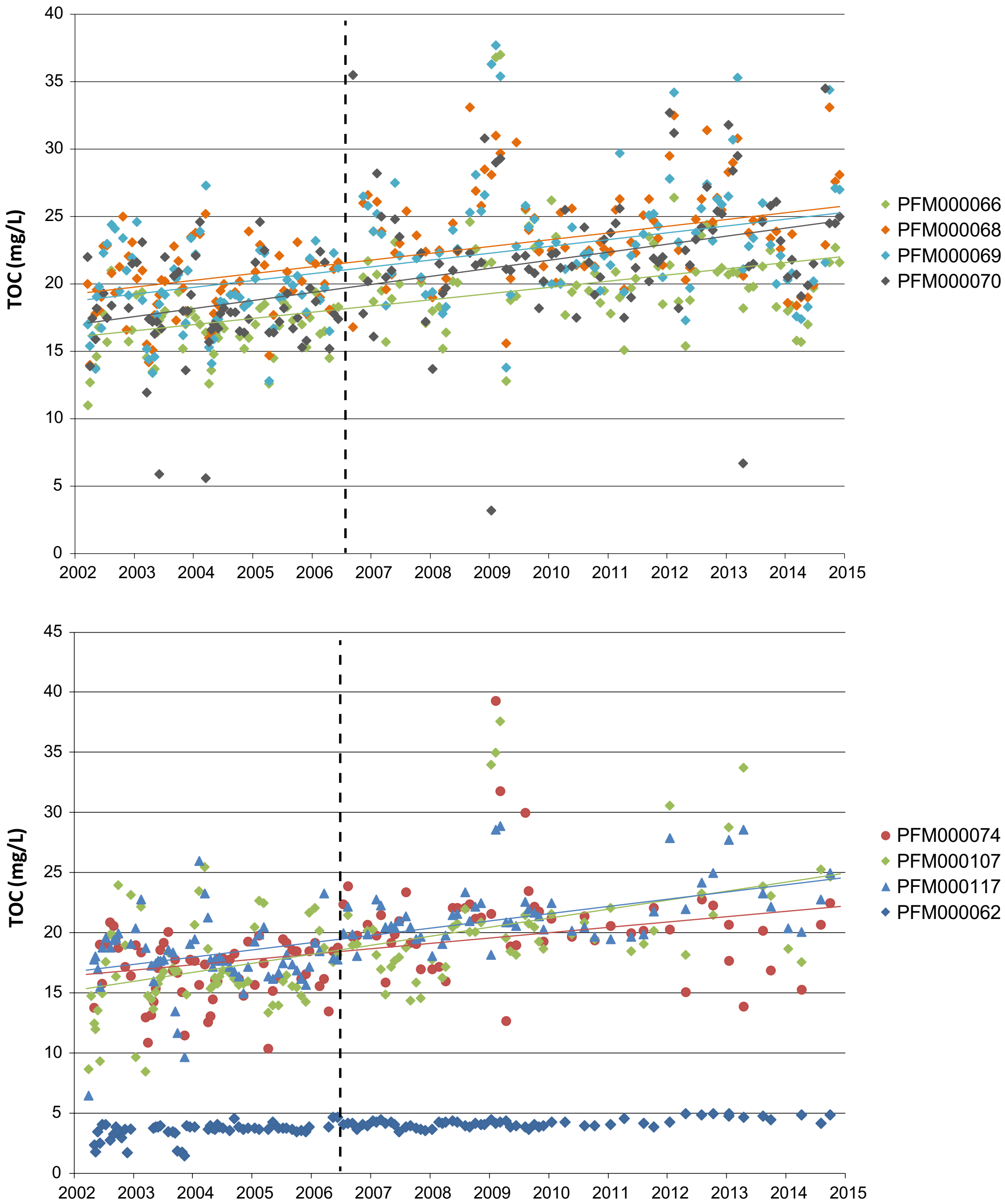

Figure 6-8. *TOC concentrations over time in streams (upper), lakes and the sea (lower). The broken line marks possible stepwise shifts in the concentrations where a new baseline seems to have been established. The lines represent statistically significant trends according to the regression analysis ($p < 0.05$). Stepwise shifts of this type could be an indication of methodological changes in sampling or analysis.*

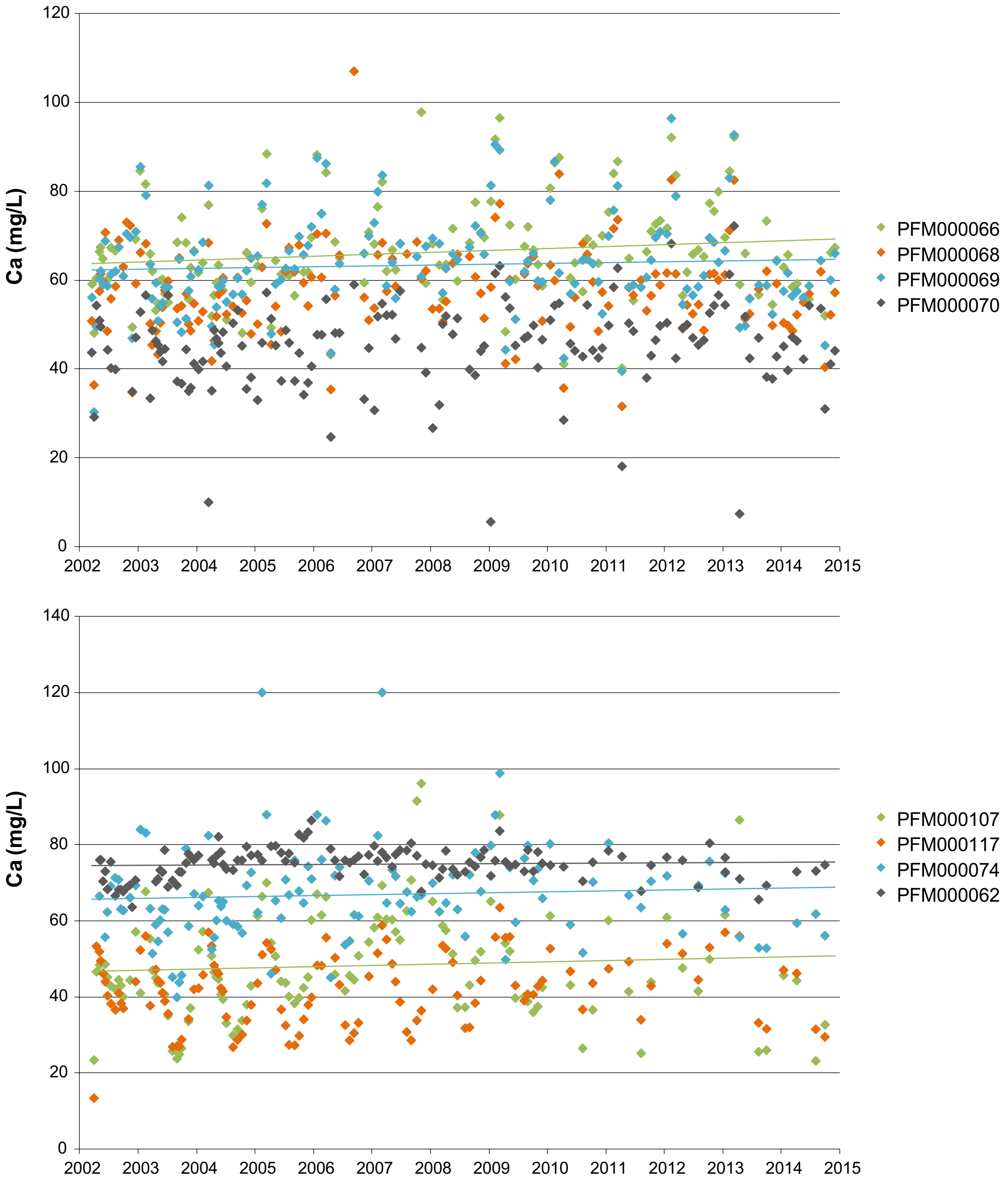

Figure 6-9. *Ca concentrations over time in streams (upper), lakes and the sea (lower). In the streams a possible stepwise shift in 2006, similar to TOC (Figure 6-8), could explain the trend, whereas the lowered sampling frequency in lakes and the sea from 2010 explains the apparent trends for these water types. The lines represent statistically significant trends according to the regression analysis ($p < 0.05$).*

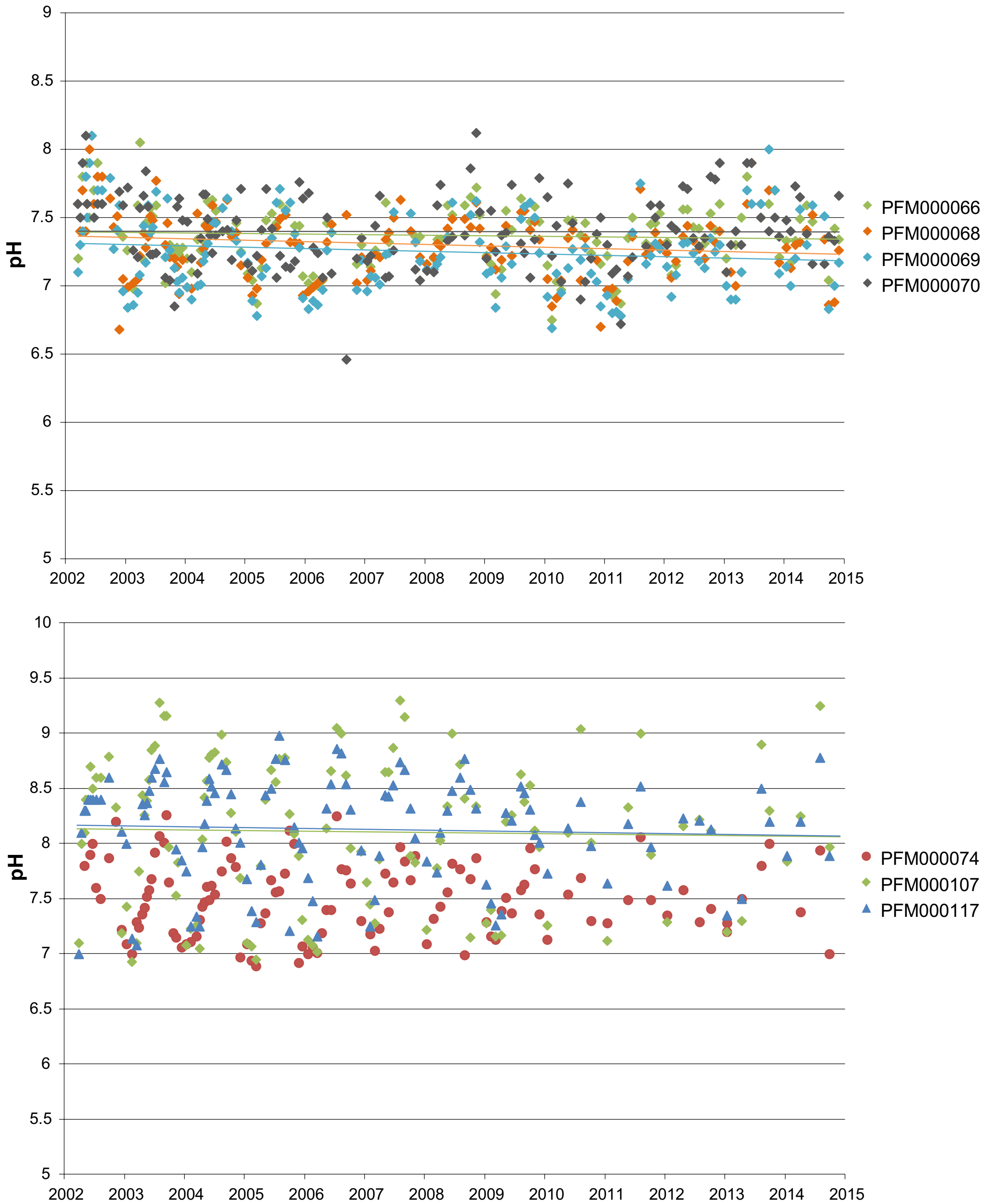

Figure 6-10. *Laboratory-measured pH over time in streams (upper), lakes and the sea (lower). The deviating observations during the first year in the streams probably explains most of the significant pH-trends according to the regression analysis. In lakes and the sea, the lowered sampling frequency from 2010 explains the apparent trend for these waters (i.e. samples at the lower frequency is seasonally biased relative to the higher frequency). The lines represent statistically significant trends according to the regression analysis ($p < 0.05$).*

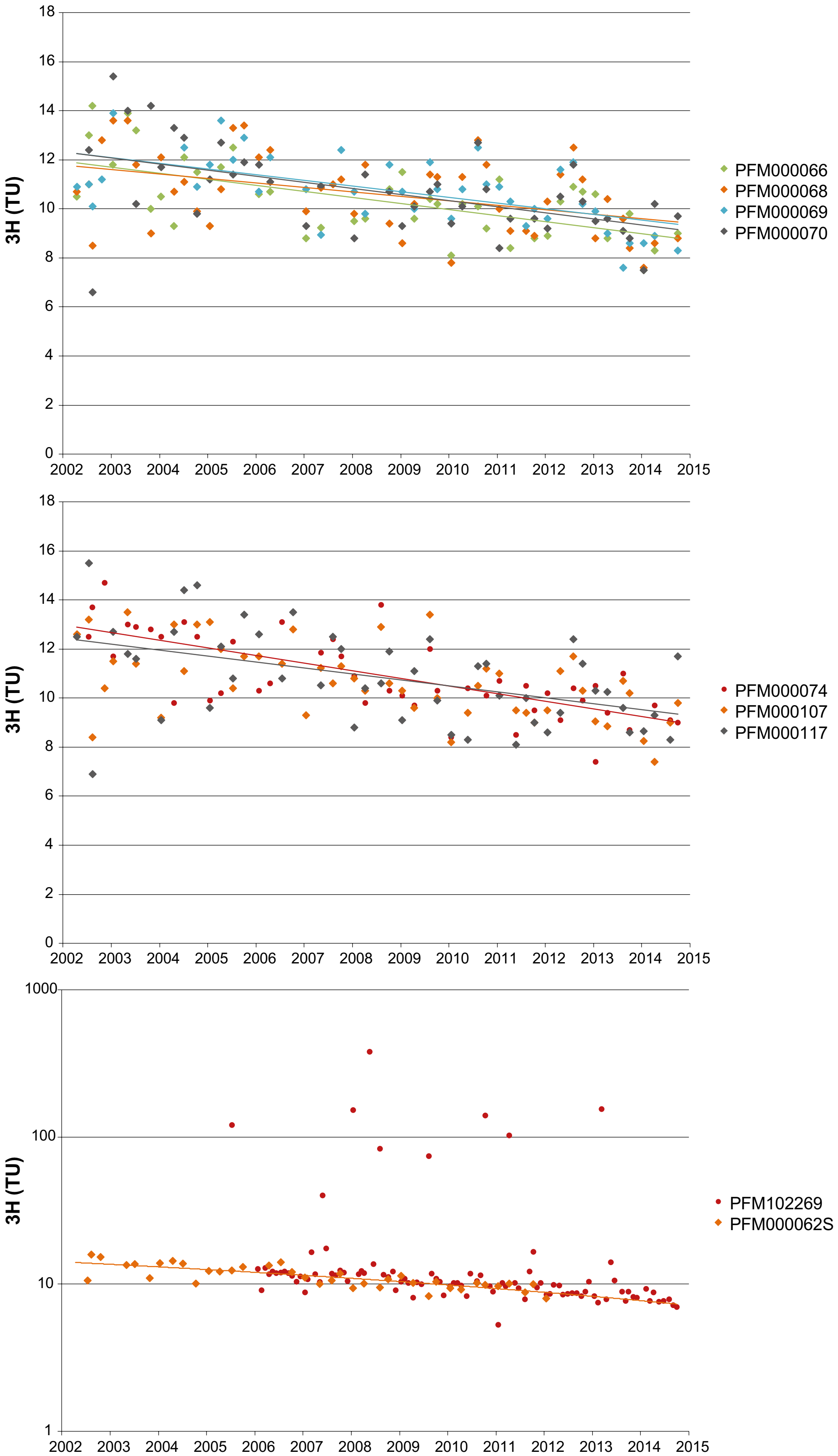

Figure 6-11. *^{3}H concentrations over time in streams (upper), lakes (middle) and sea (lower). The decreasing trends are explained by the ongoing radioactive decay of ^{3}H in the atmosphere with a half-life of 12 years. The occasionally elevated activities at the cooling water outlet (PFM102269) are caused by emissions from the nuclear power plants.*

6.2.6 Reference data

Regional and local reference data may be important in order to put the local measurements in a context. Regional reference data might contribute with longer time series that explain long-term temporal variations, whereas local undisturbed reference data might serve as a reference during the construction and operational phases of the repositories.

Besides comparable data from sampling locations outside the Forsmark area, there are surface water locations with early chemistry data from 2002 to 2007 within the investigated site that will not be influenced by future construction and operation activities in the two repositories. Some of these locations are suitable as reference objects and the proposed additional sampling locations to the updated monitoring programme, representing the different object types (lakes, streams and seawater), are presented in Section 8.3.2.

Regional reference data for surface water are available from three data sources. Monthly time series of regional reference data are available for two stations in streams (Forsmarksån and Olandsån), see Figure 6-12. These streams have significantly larger catchment areas, and thus higher discharge, compared with the very small streams in the Forsmark area. Moreover, the analyses comprise only a limited number of hydrochemical parameters, mainly major constituents, nutrients and some environmental metals (SLU n d). No comparisons have been made between these time series and local data, but due to the very different sizes of the streams, these data are probably of limited value as reference for the very small streams in the Forsmark area (Figure 6-13).

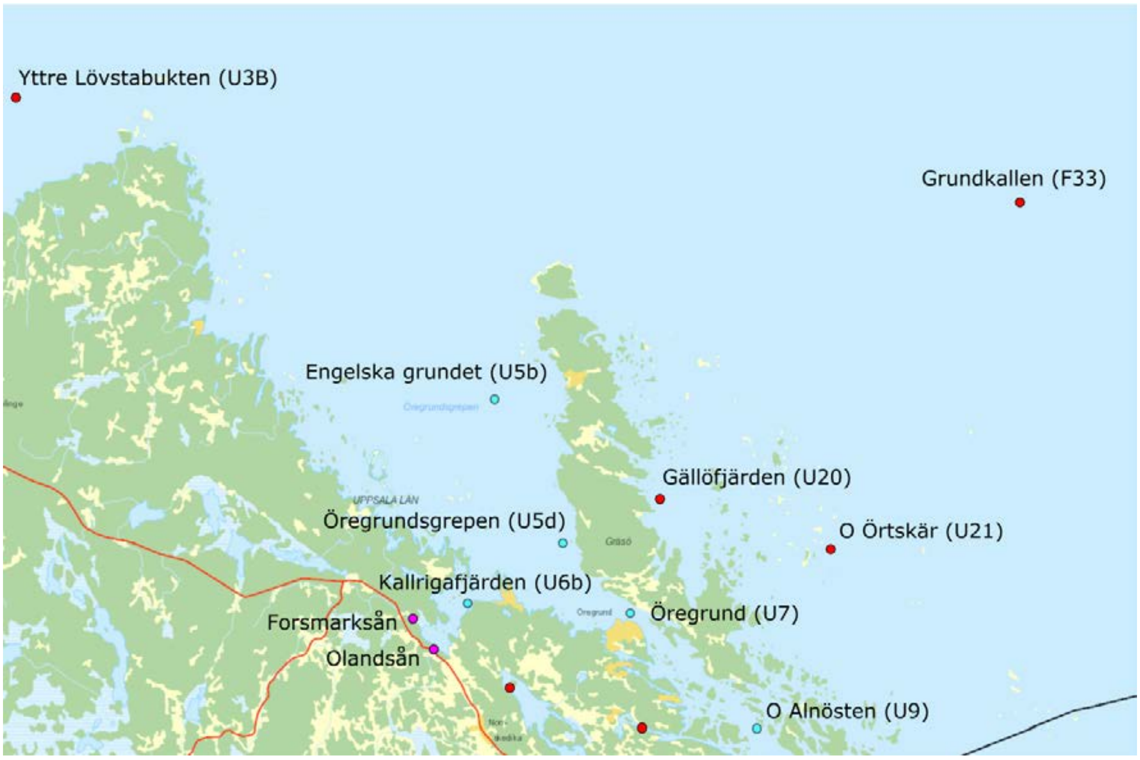

Figure 6-12. *Regional sampling locations with hydrochemical time series data close to the Forsmark area. There are two sampling locations in streams, Forsmarksån and Olandsån, which both discharge into the sea bay Kallrigafjärden. There are several sampling locations in the sea outside of the Forsmark area. At the sea locations marked by red dots (e.g. Yttre Lövstabukten, Grundkallen and Gällöfjärden), the time series comprise monthly analyses of nutrients, pH and salinity. At the sea locations marked with blue dots, sampling is performed twice a year, in July and August, for example at the stations Engelska grundet, Öregrundsgrepen and Kallrigafjärden.*

Figure 6-13. *The stream Forsmarksån at Johannisfors (upper) contains several brown-water lakes in the large catchment. The largest stream location (PFM000068) in the Forsmark site investigation area (lower, left). Many small streams are completely dry during summer (lower, right).*

The hydrochemistry of several lakes and small streams in the region are monitored within the national survey of lakes, in a synoptic study at one sampling occasion every fifth year (SLU n d). The analyses comprise major constituents, nutrients and a selection of environmental metals. The ranges obtained for these lakes could serve as reference for the lakes in Forsmark. For a local long-term monitoring programme ranging over several decades, lakes from this survey might serve as time-series references to the lakes in the Forsmark area if the monitoring continues and the objects and methods do not change.

Regional sea water data are available for a few sampling locations outside the Forsmark area, see Figure 6-12. The organisation "Svealands Kustvattenvårdsförbund" (SKVVF) measures hydrochemical parameters at several locations inside and outside the bay Öregrundsgrepen. At the locations marked by red dots in Figure 6-12 (e.g. Yttre Lövstabukten, Grundkallen and Gällöfjärden), the time series comprise monthly analyses of nutrients, pH and salinity (SMHI n d). These data may be important as references for the local sampling locations close to the coast, in order to elucidate the variation of the regional input of for example nitrogen compounds. At locations marked with blue dots, for example at the stations Engelska grundet, Öregrundsgrepen and Kallrigafjärden close to the Forsmark area, sampling is performed twice a year in July and August (SKVVF 2015).

Comparisons of the local time series in streams, lakes and sea water and the available regional reference data might reveal long-term trends not yet visible in the shorter, local time series. This information might be useful when selecting undisturbed local references.

6.3 Near surface groundwater (monitoring wells and private wells)

The hydrochemical monitoring programme for near-surface groundwater is focused on characterising seasonal and long-term temporal variation in the chemical composition of groundwater in monitoring wells installed in the regolith (in previous reporting the monitoring wells have been called soil tubes or soil pipes). In addition, the drinking water quality is monitored in a few private wells to be able to check possible future impacts from SKB activities.

To the present date, near-surface groundwater data have contributed to the general understanding of the evolution of the chemical environment in the surface system due to the ongoing land uplift and other driving processes (e.g. Tröjbom et al. 2007, Werner et al. 2007, Johansson 2008, Löfgren 2010, Hedenström and Sohlenius 2008). Characterisation of the chemical properties of shallow groundwater has also been important for the modelling of the mobility and retardation/transport properties of radionuclides in the regolith in order to understand processes that occur at the interface between the geosphere and the biosphere (Jaremalm et al. 2013, Piqué et al. 2010, 2013, Sena et al. 2008, Grandia et al. 2007), which in turn is crucial input to formulation and parameterisation of radionuclide dose models (Nordén et al. 2010, Tröjbom and Nordén 2010, Tröjbom et al. 2013). There is still uncertainty about the future evolution of the chemical environment in the surface system, with implications to the understanding of future ecosystem succession and radionuclide transport properties.

During the construction phase of the repositories, hydrochemical monitoring of near-surface groundwater might be used to detect environmental impacts, for example the effects of groundwater drawdown (Nilsson 2009). New groundwater monitoring locations below or adjacent to ponds have lately been added to the hydrological monitoring programme for environmental protection purposes (Chapter 5). Hydrochemical parameters have not been monitored in these monitoring wells so far except for two initial samples. The conceptual understanding of the hydrology, chemistry and ecology of the ponds and adjacent wetlands might also be important for the safety assessments, either as potential biosphere objects where radionuclides might discharge (or analogues of such objects), or for the understanding of the formation of groundwater recharging to the bedrock.

The monitoring programme and data collected during the site investigations and the extended monitoring period 2007–2009 are described in a number of SKB reports. From 2010, monitoring data are documented in internal SKB reports and activity plans. In Table 6-6, reports and documents describing the monitoring programme from 2002 until 2014 are listed in chronological order. This compilation contains recent activity plans, yearly data reports, data evaluation reports, and site descriptive model reports dealing with hydrochemical data for near-surface groundwater from Forsmark.

Table 6-6. Compilation of reports and documents concerning monitoring of near-surface groundwaters (monitoring wells and private wells). The list is sorted in chronological order based on the year when the data were obtained. The 7-digit numbers in the "document" column refers to SKBdoc IDs. This compilation contains recent activity plans, yearly data reports (P-reports), data evaluation reports (R- and TR- reports), and site descriptive model reports (TR-reports) dealing with hydrochemical data from Forsmark. The activity plans are controlling documents for the performance of monitoring activities.

Year	Document	Doc. type	Title (reference)
2002	P-03-64	P-report	Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. Forsmark site investigation (Johansson 2003).
2001	TR-01-29	TR-report	Site investigations. Investigation methods and general execution programme (SKB 2001a).
2002	R-01-42	R-report	Program för platsundersökningar vid Forsmark (SKB 2001b).
2003–2005	P-05-171	P-report	Sampling and analyses of near surface groundwaters. Results from sampling of shallow soil monitoring wells, BAT pipes, a natural spring and private wells, May 2003–April 2005. Forsmark site investigation (Nilsson and Borgiel 2005a).
2002–2005	R-06-19	R-report	Chemical characteristics of surface systems in the Forsmark area. Visualisation and statistical evaluation of data from shallow groundwater, precipitation, and regolith (Tröjbom and Söderbäck 2006).
2005	R-05-14	R-report	Programme for further investigations of geosphere and biosphere. Forsmark site investigation (SKB 2005).

Year	Document	Doc. type	Title (reference)
2005–2006	P-06-304	P-report	Hydrochemical monitoring of near surface groundwaters. Results from sampling of five shallow soil monitoring wells, one BAT pipe and three private wells. July 2005–April 2006. Forsmark site investigation (Berg et al. 2006).
2002–2006	R-08-75	R-report	Evaluating hydrochemical data from shallow groundwater in Forsmark from a microbiological perspective (Hallbeck 2008).
2002–2006	R-07-08	R-report	Recharge and discharge of near-surface groundwater in Forsmark. Comparison of classification methods (Werner et al. 2007).
2002–2006	R-07-55	R-report	Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling SDM-Site Forsmark (Tröjbom et al. 2007).
2004–2006	R-10-27	R-report	Chemical conditions in present and future ecosystems in Forsmark – implications for selected radionuclides in the safety assessment SR-Site (Tröjbom and Grolander 2010)..
2002–2007	TR-10-01	TR-report	The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere (Löfgren 2010)..
2004	R-04-13	R-report	Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel (Bäckblom and Almén 2004).
2006–2007	P-07-124	P-report	Hydrochemical monitoring of near surface groundwaters. Results from sampling of shallow soil monitoring wells, BAT pipes and private wells. Summer 2006–spring 2007. Forsmark site investigation (Berg et al. 2008).
2007	P-08-55	P-report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from sampling in the Forsmark area, August 2007–December 2007. Forsmark site investigation (Qvarfordt et al. 2008).
2007	R-07-64	R-report	Quantitative assessment of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data (Grandia et al. 2007).
2002–2008	TR-13-28	TR-report	Precipitation of barite in the biosphere and its consequences for the mobility of Ra in Forsmark and Simpevarp (Jaremalm et al. 2013).
2008	P-09-51	P-report	Hydrochemical monitoring of groundwaters, surface waters and precipitation. Results from water sampling in the Forsmark area, January 2008–December 2008. Forsmark site investigation (Berg et al. 2009).
2008	R-08-107	R-report	Complementary modelling of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data (Sena et al. 2008).
2008	R-08-08	R-report	Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark (Johansson 2008).
2007–2009	R-07-34	R-report	Programme for long-term observations of geosphere and biosphere after completed site investigations. Forsmark site investigation (SKB 2007).
2008–2009	P-09-66	P-report	Analysis of radioactive isotopes in near surface groundwater, surface water, biota and soil. Forsmark site investigation (Grolander and Roos 2009).
2009	P-10-40	P-report	Hydrochemical monitoring of groundwaters and surface waters. Results from water sampling in the Forsmark area, January–December 2009. Forsmark site investigation (Nilsson et al. 2010a).
2008–2009	R-09-47	R-report	Radon as a groundwater tracer in Forsmark and Laxemar (Grolander 2009).
2010	SKBdoc 1334707	Data report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from the sampling period January 2010–December 2010 (Qvarfordt et al. 2012a).
2010	R-10-30	R-report	Conceptual and numerical modelling of radionuclide transport in near-surface systems at Forsmark. SR-Site Biosphere (Piqué et al. 2010).
1984–2011	TR-11-04	TR-report	Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark (SKB 2013b).
2011	SKBdoc 1386267	Data report	Hydrochemical monitoring of near surface groundwater, surface waters and precipitation. Results from the sampling period January 2011–December 2011 (Berg et al. 2015).
2012	SKBdoc 1390364	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January 2012–December 2012 (Borgiel et al. 2013).
2013	SKBdoc 1459921	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January to December 2013 (Borgiel et al. 2015).
2013	R-13-02	R-report	Updated model for radionuclide transport in the near-surface till at Forsmark. Implementation of decay chains and sensitivity analyses (Piqué et al. 2013).
2012–2014	SKBdoc 1357753	Activity plan	Hydrokemisk monitering av ytnära grundvatten 2012–2014 (internal document).
2014	SKBdoc 1459924	Data report	Hydrochemical monitoring of near surface groundwater and surface waters. Results from the sampling period January to December 2014 (Wallin et al. 2016a).
2015[1]	SKBdoc 1466721	Activity plan	Hydrokemiskt moniteringsprogram för gölar, ytvatten och ytnära grundvatten januari 2015 till juni 2016 (internal document).

[1] Data report to be published as SKB P-report (2017).

6.3.1 Overview of sampling methods for near-surface groundwater

Near-surface groundwater is sampled in monitoring wells installed at varying depths in the regolith. The monitoring well installations are of different types.

1) Single monitoring wells made of HDPE with or without sump (Claesson and Nilsson 2003a, b, c). In the latter case, the filtered part does not reach to the bottom of the HDPE tube and the distance from the filter to the bottom (approx. 1 m) will house deposited sediments. This diminishes the risk of filtering problems or turbid samples with enhanced colloid contents.
2) Double monitoring wells (1 m sump) made of HDPE where one of the wells is equipped with a transducer for logging the groundwater level and the other well is intended for hydrochemical sampling (e.g. Johansson 2003).
3) Monitoring wells made of ordinary, non-stainless iron installed in lake sediment or in till below fen (Johansson 2003).
4) Monitoring wells equipped with BAT-filter tips (Johansson 2004).

Schematic figures of type 1) and type 4) are shown in Figure 6-14.

Groundwater samples are collected using a submersible electrical pump connected to a polyamide-tube and with a flow rate of maximum 1 L/min. The water volume of the monitoring wells is exchanged three to five times depending on the exchange/recovery time prior to the actual sampling. Monitoring wells equipped with a BAT-filter tip are sampled with an evacuated vial that sucks water from the regolith, through the filter and the needle, into the vial. A total of four sample containers (500 mL) are filled from the BAT filter in order to obtain enough water for the analyses. The first filled sample container is not used for analyses but for exchange of the water volume in the BAT pipe before collecting the samples to be analysed. The sampling methods are briefly described in the activity plans (SKBdoc 1357753, internal document) and work has been initiated to develop complete method descriptions.

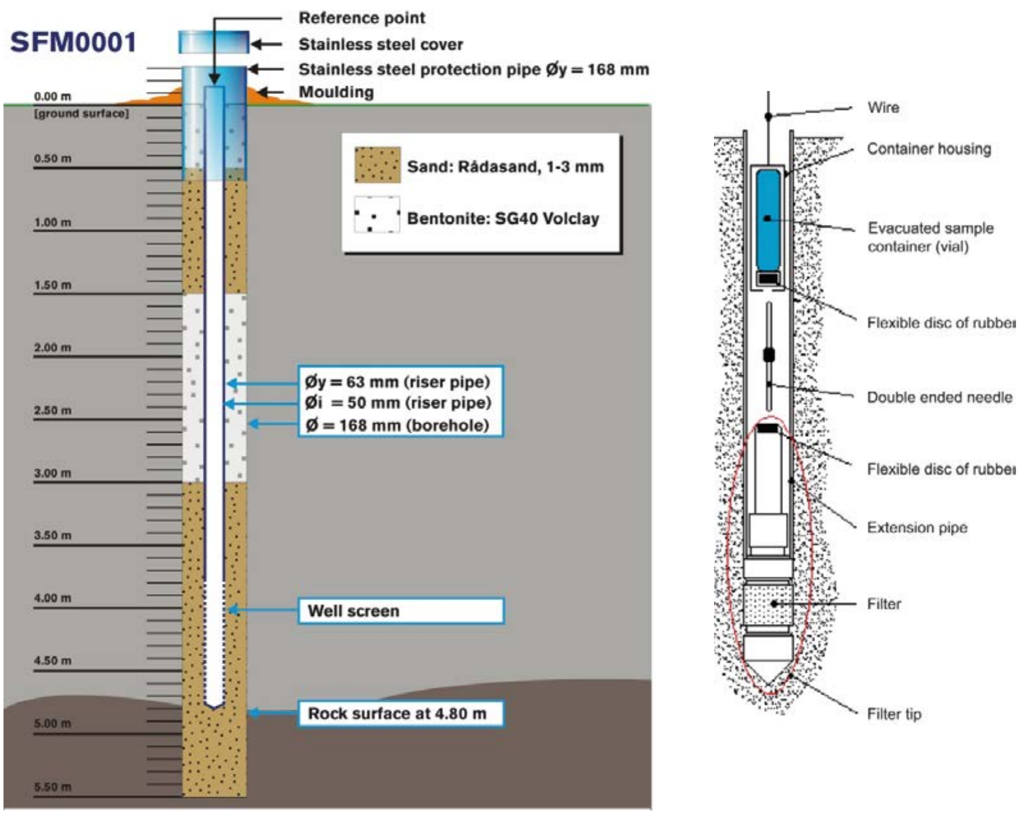

Figure 6-14. Schematic figure of the monitoring well SFM0001 (left), and the principle behind the monitoring well with BAT filter tip (right). Monitoring wells equipped with a BAT filter tip are sampled with an evacuated vial that sucks water from the groundwater aquifer, through the filter and the needle, into the vial.

Figure 6-15. Field measurements of pH, water temperature, oxygen, ORP (redox potential) and electrical conductivity (EC) are performed at the ground surface with a multi-parameter probe mounted in a flow-through cell (left). The monitoring wells are located in different environments: in open water installed in the regolith below lake sediments (from boat in the upper left and from ice in the lower middle), in wet environments (right middle), and in drier areas (lower right).

Field measurements of pH, water temperature, oxygen, ORP (redox potential) and EC are performed at the ground surface with a multi-parameter probe mounted in a flow-through cell (SKBdoc 1357753, internal document). The equipment is shown in Figure 6-15 together with examples of monitoring wells in different environments.

6.3.2 Current near-surface groundwater monitoring programme

The current hydrochemical monitoring programme for near-surface groundwater includes a total of nine sampling locations, distributed over five monitoring wells in regolith and one monitoring well of BAT type in fine-grained sediments. For private wells (generally at summer cottages) no data are available from 2012–2014 due to difficulties to obtain access to the wells when the well owners were not present.

In Table 6-7, the number of samples during 2014 is presented for each sampling location and component group. A component group is a set of components that go together, meaning that they are either included or excluded in the analysis protocol (see Table 6-8). The sampling locations are shown in Figure 6-16.

Table 6-7. The sampling locations in the ongoing hydrochemical monitoring programme for near-surface groundwater, with the number of samples 2014 per component group. The component groups are defined in Table 6-8.

					Component groups																
objectType	IDCODE	Description	SECUP	SECLOW	Anions1	Anions2a	Anions2b_BrI	Carbon1	Carbon3	Cations2	DrinkingQty1	DrinkingQty2	EnvironIso1	EnvironIso2	EnvironMet1	EnvironMet2	IronSpecies	Nutrient1	Nutrient5	Sulphide	Trace1
Near surface GW	SFM0001	Monitoring well at drill site	3.8	4.8	4	4	4	4	4	4			4	4		2	2	4	4	2	2
Near surface GW	SFM0023	Monitoring well in till below open water	3.32	4.32	4	4	4	4	4	4			4	4		2	2	4	4	2	2
Near surface GW	SFM0032	Double monitoring well down to bedrock	1.94	2.94	4	4	4	4	4	4			4	4		2	2	4	4	2	2
Near surface GW	SFM0037	Double monitoring well down to bedrock	1.1	2.1	4	4	4	4	4	4			4	4		2	2	4	4	2	2
Near surface GW	SFM0049	Double monitoring well down to bedrock	2.9	3.9	4	4	4	4	4	4			4	4		2	2	4	4	2	2
Near surface GW	SFM0051	BAT- tip at drill site 1	4.32	4.48	4	4	4			4			4	4		4	4				4
Groundwater	PFM000001	F3:3, 45 m drilled private well	n	n							1	1			1						
Groundwater	PFM000009	F3:34, 70 m drilled private well	n	n							1	1			1						
Groundwater	PFM006382	F3:38, 60 m drilled private well	n	n							1	1			1						

Table 6-8. Definition of component groups for near-surface groundwater. The compGrp column contains the short names used in the tables in this report, "parameter group" gives a common parameter description and "component group" shows the notations generally used in activity plans controlling the monitoring activities. In the componentList-column, all components in each compGrp are listed.

compGrp	Parameter group	Component Group	ComponentList
Anions1	Chemical environment	Anions1	Alkalinity (HCO3), pH, conductivity
Anions2a	Major constituents	Anions2a	Cl, F, SO4, Br
Anions2b_BrI	Major constituents	Anions2b	Br, I
Carbon1	Nutrients and carbon	Dissolved organic carbon , dissolved inorganic carbon	DOC
Carbon3	Nutrients and carbon	Total organic carbon	TOC
Cations2	Major constituents	Cations, Si and S, class 4&5	Na, K, Ca, Mg, Li, Sr, Si-tot, S-tot, Fe, Mn
DrinkingQty1	Drinking water quality	Drinking water quality	Hbakt, Kbakt, Ecoli, lukt, turbiditet, färg, grumlighet
DrinkingQty2	Drinking water quality	Drinking water quality	Hårdhet
EnvironIso1	Environmental isotopes	Environmental isotopes	2H, 18O
EnvironIso2	Environmental isotopes	Tritium	3H
EnvironMet1	Environmental metals	Environmental metals	Al, Cu, Zn
EnvironMet2	Environmental metals	Environmental metals	Al, As, B, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, P, Pb, V, Zn
FieldSonde2	Field measurements	YYY-sonde	Temperature, pH, conductivity, oxygen, redox
IronSpecies	Redox indicators	Iron species	Fetot, FeII
Nutrient1	Nutrients and carbon	Nutrient salt and silicate	NH4N, NO2N, NO3N, PO4P, NO2NO3N, SiO4Si
Nutrient5	Nutrients and carbon	Total concentrations of nitrogen and phosphorus	TN, TP
Sulphide	Redox indicators	Hydrogen sulphide	HS
Trace1	Trace elements	Trace elements	U, Th

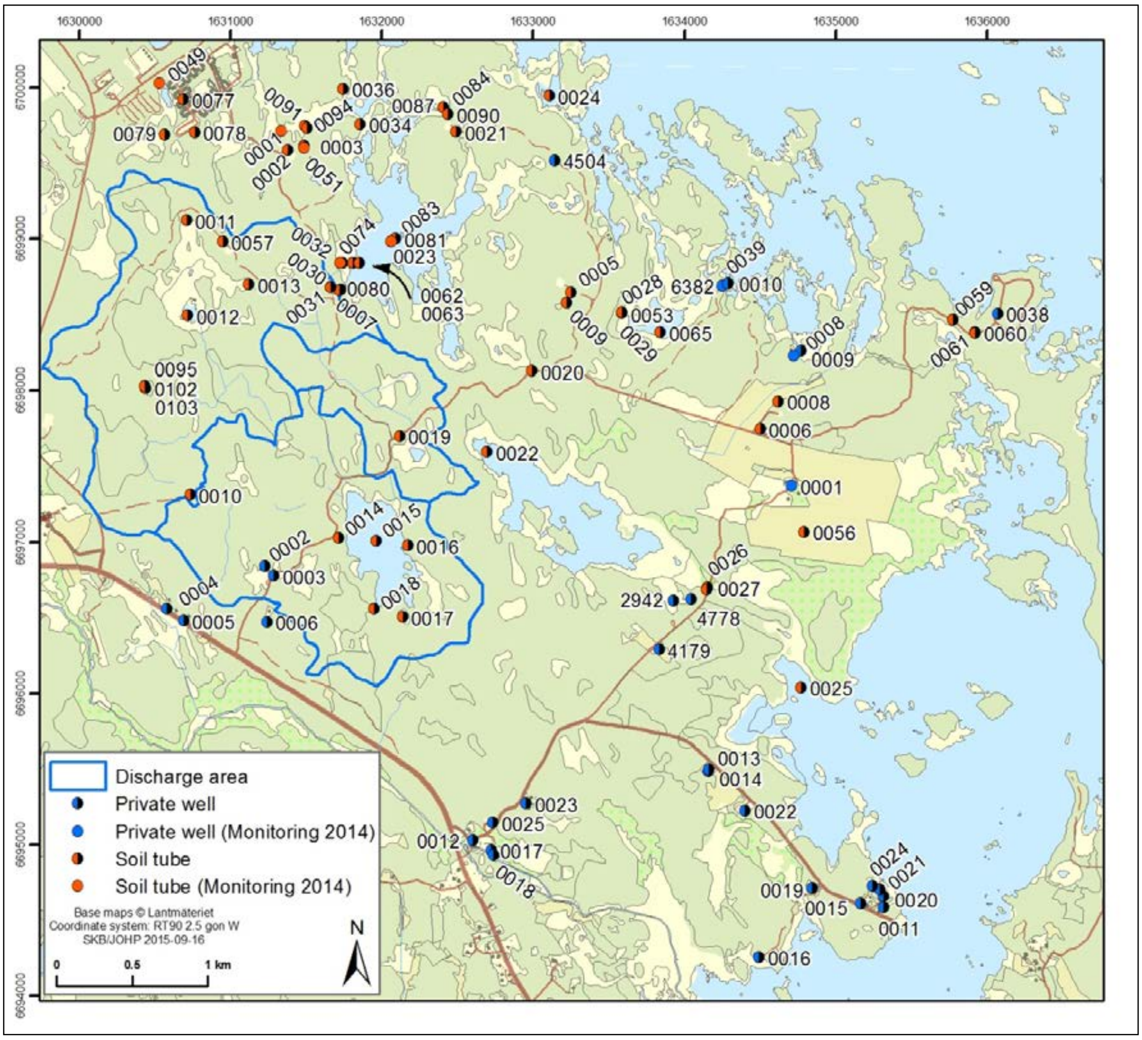

Figure 6-16. *Location of the sampling objects for near-surface groundwater. The undivided circular symbols represent objects included in the ongoing monitoring programme. The labels denote the four last digits in the id codes for the objects, for monitoring wells SFMXXXX and for private wells PFM00XXXX.*

6.3.3 Hydrochemical monitoring of near-surface groundwater 2002–2014

Sampling of hydrochemical parameters in near-surface groundwater started in 2002 with a broad characterisation over two years including a large number of objects. The extensive chemical investigation campaigns continued until 2005 in selected monitoring wells. The programme was revised and a long-term monitoring programme was initiated for a smaller number of objects until the site investigations were completed in June 2007. The monitoring programme for near-surface groundwater was then revised and prolonged without changes for two more years until the site selection process was completed in 2009.

Since 2010, the long-term monitoring programme in Forsmark has continued until today with only minor revisions. A specific campaign with the purpose of investigating the interface between discharging groundwater and surface water was initiated in 2006 and ended in 2008 (the GBIZ project, SFM0081 to SFM0102, cf. Werner et al. 2006, Berg et al. 2009). Monitoring of shallow groundwater in monitoring wells close to small ponds has been added lately in order to meet the needs of the environmental impact assessment (EIA), but hydrochemical parameters are not routinely measured.

The development of the monitoring programme for near-surface groundwater over time is shown in Table 6-9. The objects included in the current monitoring programme are denoted by "y" in the monitoring column. The leftmost columns show the number of samples per year for each sampling location, whereas the columns to the right of the orange total column show the percentage of analyses per component group, in relation to the total number of samples for the entire monitoring period. A 100 % value means for example that this component group was analysed in all samples from this specific object between 2002 and 2014.

In Table 6-10, the same information is instead presented for a representative element per component group for all objects together. The rightmost columns denote the percentage of the samples each year that were analysed for each component group. This table adds information on how the total number of samples per component group has changed over time, and emphasises any changes within the programme.

The revisions of the monitoring programme described above are depicted by the data in Table 6-9 and Table 6-10 are studied. After the revision of 2005, the number of sampling locations in monitoring wells was reduced from 23 to six and in private wells from five to three. The number of sampling occasions per year in the monitoring wells has remained unchanged until today. For private wells, no data are available from 2012–2014 due to restricted access to the wells. The sampled and the discarded sampling locations are shown in Figure 6-16.

In addition to the changes in sampling frequency and number of sampling locations, the parameters included in the monitoring programme have also been revised during the period 2002–2014. Some component groups have been analysed at all sampling occasions, whereas other parameters were analysed only during the first years of the site investigation and after that at lower frequency, or not at all.

Major constituents and environmental isotope data exist for all sampling locations during the period 2002–2014. The major constituents (Na, K, Ca, Mg, Li, Sr, Si-tot, pH, alkalinity, conductivity, Cl, F, SO_4, and Br) and the environmental isotopes (^{2}H, ^{3}H and ^{18}O) are available as complete time series. Analyses of the minor constituents (Fe and Mn), the environmental metals (e.g. Al, Zn, Pb, Cu, Cd, etc.) and the trace elements (e.g. U, Th, La and Rb) are less abundant and are not available from all objects and all sampling occasions. Other isotopes (e.g. ^{14}C, ^{37}Cl, ^{226}Ra, ^{87}Sr and ^{34}S) have been determined in a limited number of objects, and were excluded from the monitoring programme after 2009.

Field measurements of pH, ORP, and electrical conductivity have been performed in parallel with the sampling for laboratory analysis. The compilation indicates that field data are available for less than 100 % of the sampling occasions. Field measurements are planned to be conducted at every sampling occasion and the discrepancy from 100 % coverage for these measurements is mainly explained by occasional technical problems with the probes.

Table 6-9. Near-surface groundwater samples from private wells (Idcode PFMxxxxxx) and monitoring wells (Idcode SFMxxxx). The leftmost columns show the number of samples per year for all sampling locations, whereas the rightmost columns show the number of analyses per component group (see Table 6-8), as percent of the total number of samples from the entire monitoring period. SECUP and SECLOW denotes upper and lower section limit, here the position of the filter part along the pipe. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

IDCODE	SECLOW	SECUP	MonitProg	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
PFM000001	4.1		y	1		2	3	1	1	1	1	1	1					12
PFM000007			n	1		2	3											6
PFM000008			n	1		2	3											6
PFM000009			y	1		2	3	1	1	1	1	1	1					12
PFM000039	60		n			3	3											6
PFM006382	4.1	3.7	y					1	1	1	1	2	1					7
SFM0001	4.95	3.8	y		3	3	4	4	4	4	4	4	4	4	4	4	4	50
SFM0002	5.21	4.21	n		3	3	4	2										12
SFM0003	10.98	8.98	n		3	3	4	2										12
SFM0005	3.21	2.21	n		1	1	3	2										7
SFM0006	4.21	3.21	n			2	2	2										6
SFM0008	6.14	5.14	n			3	4	2										9
SFM0009	3	2	n			3	4	2										9
SFM0012	6.35	5.35	n			4	4	2										10
SFM0015	7.34	6.34	n			4	3	2										9
SFM0023	5.42	3.32	y			3	4	4	3	4	4	4	4	3	4	4	4	45
SFM0025	7.06	6.06	n			3	4	2										9
SFM0027	8	7	n			3	4	2										9
SFM0029	8	7	n			2	4	2										8
SFM0031	4.5	3.5	n			2	4	2										8
SFM0032	4	1.94	y			3	5	4	4	4	4	4	4	4	4	4	4	48
SFM0037	3	1.1	n			2	4	4	4	4	4	4	4	4	4	4	4	46

IDCODE	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon2 (DIC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	FieldSonde2 (Redox_field)	HeavyIso1 (226Ra)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient1 (SiO2_bio)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	Nutrient5 (N)	Oxygen (O2)	ParticulateCNP (POP)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace2 (Rb)
PFM000001	100	100	25		25	25	25		92	75		25	25	8		25	17				25	50	25	17						
PFM000007	100	100	50		50	50	50		83	50		50	50	17		50	33				50	50	50	33						
PFM000008	100	100	50		50	50	50		83	50		50	50	17		50	33				50	50	50	33						
PFM000009	100	100	25		25	25	25		92	75		25	25	8		25	17				25	50	25	17						
PFM000039	83	100	67	17	67	67	67		83	33		67	67			50	33				67	50	67	50						
PFM006382	100	100							100	100												100								
SFM0001	100	100	100	84	98	96	98	22	100	86	30	100	100	62	58	92	84	14	12	50	98	50	96	96	12	6	24	54	26	54
SFM0002	100	100	100	92	100	92	100	58	100	75	100	100	100	50	50	92	58	33	25	58	100	100	92	92	42	17	75	33	83	58
SFM0003	100	100	100	92	54	92	54	58	100	75	92	100	100	67	67	92	58	33	25	58	100	100	92	92	42	25	75	67	83	58
SFM0005	100	100	100	100	86	86	100	43	100	86	100	100	100	71	71	71	57	14	14	71	100	100	100	86	43	14	71	71	86	57
SFM0006	100	100	100	83	100	100	100	50	100	83	100	100	100	67	67	83	50	17	17	67	100	100	100	100	50	17	67	83	100	67
SFM0008	100	100	100	78	100	100	100	44	100	78	100	100	100	67	67	78	56	33	22	78	100	100	100	89	22		89	56	100	67
SFM0009	100	100	100	89	89	89	89	44	100	67	89	100	100	67	67	89	56	22	11	67	89	89	89	78	11		89	56	89	67
SFM0012	100	100	100	70	90	90	90	60	100		80	100	100	10	10	80	60	10	10		90	90	90	80	20		80	10	90	10
SFM0015	100	100	100	78	89	89	89	67	100		78	100	100	11	11	78	56	11	11		89	89	89	78	22		78	11		11
SFM0023	100	100	100	71	89	93	93	7	98	4	16	98	89	2	2	98	89				93	91	91	91	2		18	9	18	2
SFM0025	100	100	100	67	89	89	89	44	100		78	100	100	11	11	89	56				89	89	89	78	11		89		89	11
SFM0027	100	100	100	78	89	89	89	44	100	67	89	100	100	67	67	78	67	22	11	56	89	89	89	78	11		89	44	89	67
SFM0029	100	100	100	75	88	88	88	38	100	75	100	100	100	75	75	100	75	25	13	75	88	88	88	75	13		100	63	100	75
SFM0031	100	100	100	75	100	100	100	50	100	75	100	100	100	75	75	100	75	25	13	75	100	100	100	88	13		100	50	100	75
SFM0032	100	100	100	81	94	94	94	15	100	79	23	100	100	60	60	94	88	10	8	52	94	94	92	92	4		23	52	23	54
SFM0037	100	100	100	80	98	98	98	15	100	83	24	100	100	61	61	98	89	11	9	52	98	98	98	96	7		24	50	24	54

IDCODE	SECLOW	SECUP	MonitProg	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
SFM0049	5	2.9	y			1	3	4	4	4	4	4	4	4	4	4	4	44
SFM0051 BAT	5.18	4.32	y			2	4	4	4	4	4	4	4	4	4	4	3	45
SFM0053 BAT	6.17	6.01	n			2	4	2										8
SFM0056 BAT	6.17	6.01	n			2	4	2										8
SFM0057	4.55	3.45	n			1	4	2										7
SFM0060	7.6	6.6	n				3	2										5
SFM0074	4.7	2	n				11											11
SFM0081	5.25	4.85	n							4	2							6
SFM0083	2.7		n						1	3	2							6
SFM0084	4.1	3.7	n						3	4	2							9
SFM0087	2.3	2	n						3	4	2							9
SFM0091	2.3	1.9	n						3	4	2							9
SFM0095	6	5	n						2	4	2							8
SFM0102	2.25	2.09	n						1	3	2							6

IDCODE	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon2 (DIC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	FieldSonde2 (Re-dox_field)	HeavyIso1 (226Ra)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient1 (SiO2_bio)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	Nutrient5 (N)	Oxygen (O2)	ParticulateCNP (POP)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace2 (Rb)
SFM0049	100	100	100	82	93	93	93	11	100	84	16	100	100	61	61	93	91	9	9	48	93	93	91	93	5		16	50	7	55
SFM0051 BAT	100	100	100	71				13	100	93	16	100	100	96	96		2			67							18			84
SFM0053 BAT	100	100	100	38				75	100	63	88	100	100	75	75					75							100			75
SFM0056 BAT	100	100	100	50					88	63	13	100	100	75	75												13			75
SFM0057	100	100	100	71	100	100	100	57	86	86	86	100	100	86	86	100	71	29	14	86	100	100	100	86	14		100	71	100	86
SFM0060	100	100	100	100	100	100	100	60	100	80	100	100	100	80	80	80	60	20	20	80	100	100	100	100	20		100	40	100	80
SFM0074	100	100	100	100					100			100	100																	
SFM0081	100	100	100	50	100	100	100		100			100	100			100	100				100	100	100	100						
SFM0083	100	100	100	50	83	83	83		100	50		100	100	50	50					17	83	83	83	83						50
SFM0084	100	100	100	44	78	78	78		100			78	78			78	78				78	78	78	78						
SFM0087	100	89	100	56	78	78	78	11	100	56	11	78	78	56	56	78	78	11	11	44	78	78	78	78			11	44	11	56
SFM0091	100	100	100	44	78	78	78		100			78	78			78	78				78	78	78	78						
SFM0095	100	100	100	63	88	88	88	13	100	63	13	88	88	63	63	88	88	13	13	63	88	88	88	88			13	63	13	63
SFM0102	100	100	100	67	100	100	100		100	67		100	100	67	67						100	100	100	100						67

Table 6-10. Overview of extent of the analyses by year (2001–2014): The leftmost columns give the number of samples per year for a typical component in each component group (see Table 6-8). The rightmost columns present the percentage of analyses per component group in relation to the total number of samples each year. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

compGrp	TypicalMetaAbb	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Anions1	pH	25	10	86	128	60	51	57	41	28	27	23	24	24	26	610	100	100	98	100	100	100	100	100	100	100	100	100	100	100
Anions2a	Cl	25	10	86	128	60	51	57	40	28	27	23	24	24	26	609	100	100	98	100	100	100	100	98	100	100	100	100	100	100
Anions2a_I	I		10	55	86	48	25	41	16	14	19	23	24	24	16	401		100	63	67	80	49	72	39	50	70	100	100	100	70
Anions2b_Br	Br		10	83	122	57	48	54	38	24	24	23	24	24	24	555		100	94	95	95	94	95	93	86	89	100	100	100	104
Anions2b_BrI	I		10	55	86	48	25	41	16	14	19	23	24	24	16	401		100	63	67	80	49	72	39	50	70	100	100	100	70
Anions2b_I	I		10	55	86	48	25	41	16	14	19	23	24	24	16	401		100	63	67	80	49	72	39	50	70	100	100	100	70
Carbon1	DOC		10	49	87	44	27	50	33	20	20	19	19	20	20	418		100	56	68	73	53	88	80	71	74	83	79	83	87
Carbon2	DIC		6	49	87	44	28	50	34	20	20	19	19	20	20	416		60	56	68	73	55	88	83	71	74	83	79	83	87
Carbon3	TOC		11	49	88	44	28	50	34	20	20	19	19	20	20	422		100	56	69	73	55	88	83	71	74	83	79	83	87
CarbonIso	14C		5	33	42	22		5	3	4						114		50	38	33	37		9	7	14					
Cations1	Na	25	10	83	126	60	51	57	41	28	27	22	23	24	24	601	100	100	94	98	100	100	100	100	100	100	96	96	100	104
Cations2	Fe	25	10	23	76	32	27	33	18	16	23	20	20	20	21	364	100	100	26	59	53	53	58	44	57	85	87	83	83	91
ChlorineIso	37Cl		10	36	80	43		6	4	4						183		100	41	63	72		11	10	14					
Chlorophyll	ChlA		1													1		10												
EnvironIso1	2H		10	82	120	57	33	54	38	24	24	22	24	24	23	535		100	93	94	95	65	95	93	86	89	96	100	100	100
EnvironIso2	3H		10	83	117	57	33	54	38	24	24	22	22	24	21	529		100	94	91	95	65	95	93	86	89	96	92	100	91
EnvironMet1	Al	25	7	11	73	27	23	30	16	12	16	12	12	12	11	287	100	70	13	57	45	45	53	39	43	59	52	50	50	48
EnvironMet2	Zn	25	5	11	73	27	23	30	16	12	16	12	12	12	11	285	100	50	13	57	45	45	53	39	43	59	52	50	50	48
EnvironMet3	Ni		3	11	73	27	23	30	16	12	16	12	12	12	11	258		30	13	57	45	45	53	39	43	59	52	50	50	48
FieldSonde1	pH_field		5	41	85	45	27	44	30	20	20	19	19	15	22	392		50	47	66	75	53	77	73	71	74	83	79	63	96
FieldSonde2	Redox_field			20	68	40	27	44	30	20	20	19	19	11	22	340			23	53	67	53	77	73	71	74	83	79	46	96
HeavyIso1	226Ra		3	19	14			6	4	4						50		30	22	11			11	10	14					
HeavyIso2	234U		3	8	14			6	4	4						39		30	9	11			11	10	14					
HeavyIso3	230Th		3	8	14			6	4	4						39		30	9	11			11	10	14					
IronSpecies	Fe_tot			16	61	29	23	26	11	11	5	10	5		11	208			18	48	48	45	46	27	39	19	43	21		48
Nutrient1	SiO2_bio		10	49	87	44	28	50	34	20	20	19	19	20	20	420		100	56	68	73	55	88	83	71	74	83	79	83	87
Nutrient2	PO4P	25	11	54	93	47	31	53	36	24	23	19	19	20	20	475	100	100	61	73	78	61	93	88	86	85	83	79	83	87
Nutrient4	NO23N		8	49	87	44	28	50	30	20	20	19	19	20	20	414		80	56	68	73	55	88	73	71	74	83	79	83	87
Nutrient5	N		9	26	87	44	28	50	34	20	20	19	19	20	20	396		90	30	68	73	55	88	83	71	74	83	79	83	87
Oxygen	O2		10	8		19						3		3		43		100	9		32						13		13	
ParticulateCNP	POP		9	1												10		90	1											
StrontiumIso	87Sr		3	35	80	44		6	4	4						176		30	40	63	73		11	10	14					
Sulphide	S_2-		6	16	34	23	19	21	10	9	9	5	8	4	4	168		60	18	27	38	37	37	24	32	33	22	33	17	17
SulphurIso	34S		3	37	69	35		6	4	3						157		30	42	54	58		11	10	11					
Trace1	U		3	11	73	27	23	30	16	12	16	12	12	12	5	252		30	13	57	45	45	53	39	43	59	52	50	50	22
Trace2	Rb		3	11	73	27	23	30	16	12	10	12	12	12		241		30	13	57	45	45	53	39	43	37	52	50	50	

6.3.4 Conditions and aspects of importance when interpreting hydrochemical near-surface groundwater data

Identified practical problems and other conditions of varying importance that might have had an impact on the samples, analyses and measurements for near-surface groundwaters are described below.

Representative groundwater composition: There is a risk that samples may contain a mixture of the stagnant water in the standpipe above the screened part and the more representative water from the screened part due to lowering/raising of equipment and/or too high pumping flow rate followed by insufficient purging (exchange of water) of the standpipe.

Suspension of solids during sampling: Suspension of solids/particles from the bottom of the monitoring well due to stirring/perturbation caused by too high a pumping flow rate or lowering and raising of equipment might influence the water composition. This may be a larger problem in monitoring wells without a sump.

Exchange of water prior to sampling: Water standing in the well casing is considered non-representative of the groundwater in the regolith and therefore wells are generally purged prior to sampling. The common procedure has been to purge the standpipe using a high-speed pump and to remove 3–5 casing volumes prior to the sampling. This may probably increase the turbidity and it is not the ideal procedure from representativity aspects (cf. Figure 6-17). However, the water in the screened interval may be quite representative depending on well construction and hydrogeology (Puls and Barcelona 1996) and the need for, as well as the extent of the purging is worth considering.

Slow water-level recovery: Clogging of the screen interval with fine-grained clays resulting in extremely slow water recovery may obstruct groundwater sampling. This was the case for several pipes in the GBIZ programme (SFM0081 to SFM0102, cf. Figure 6-18 for an example of a BAT installation in Lake Bolundsfjärden).

Enhanced initial concentrations after installation: Enhanced concentrations of trace metals (often aluminium) may occur initially when the monitoring wells are installed. The reason is not quite clear but it is possible that the perturbation from the drilling and the installation work may contribute to this initial effect (Figure 6-19).

Filtration in field: The samples are filtered in the field (0.45 µm), which means that they should represent the dissolved contents in water. However, a varying fraction of the colloidal fraction passes the filter and will be included, or partly included, in the analyses, for example large organic molecules, clay minerals etc. that may have aluminium, iron and other trace metals bound to them. Thus, the samples represent something between the dissolved fraction and the total fraction depending on the measured constituent (cf. Nilsson 2011a).

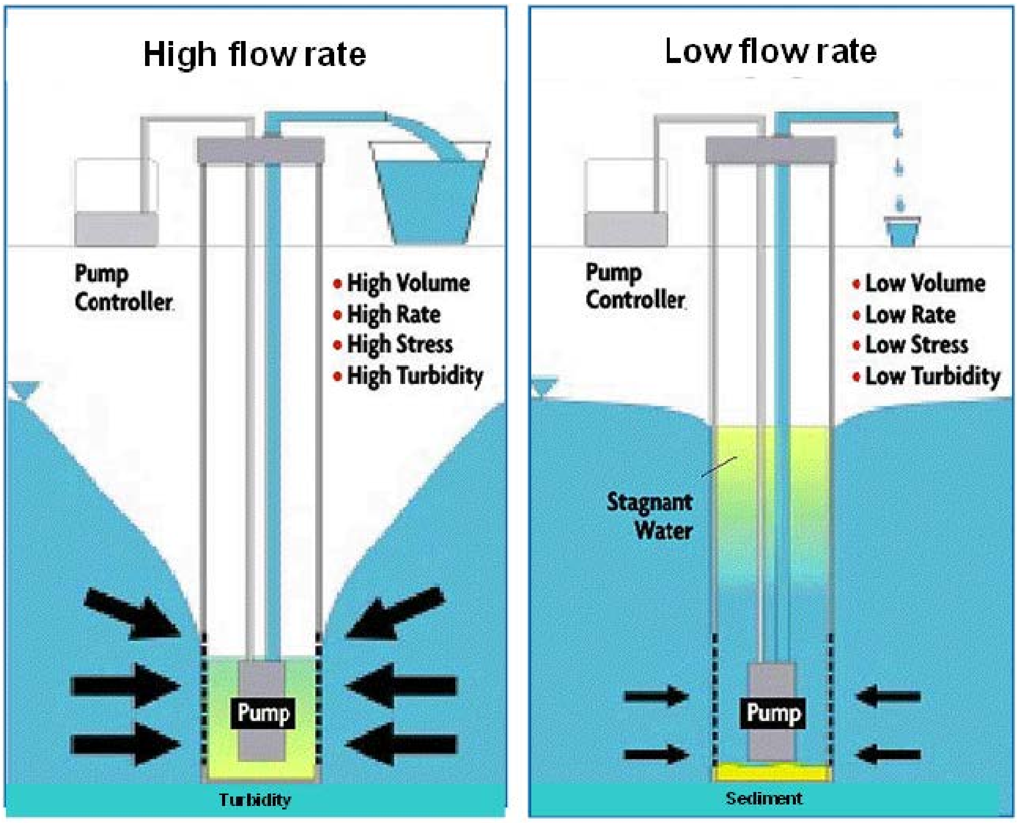

***Figure 6-17.** Comparison between high flow and low flow purging and sampling procedures.*

Figure 6-18. Groundwater monitoring well SFM0081 (middle), BAT filter tip SFM0082 for pore pressure measurements (left) and BAT filter tip SFM0083 for water sampling (right), installed below open water in Lake Bolundsfjärden. The picture shows sampling from the ice during winter.

Figure 6-19. Auger drilling was used during installation of the monitoring wells (left). The right picture shows installation of the HDPE well screen, riser pipes, sand filter and bentonite sealing in a groundwater monitoring well inside a temporary steel casing. The snap-shot illustrates the bentonite being emplaced between the riser pipe and the temporary steel casing used to facilitate the filling.

Sampling in steel pipes (Figure 6-20): Iron and other trace metals cannot be analysed in samples collected in monitoring wells made of iron due to contamination. There may also be other impacts on the groundwater composition due to corrosion and other ongoing processes in these wells.

Oxidation and degassing: Introduction of air or degassing from the sample water may occur during sample handling and transport, which may alter the water composition especially for redox sensitive elements. Secondary effects, such as co-precipitation, are possible and may decrease trace element concentrations.

Private wells: The use of the private wells varies and the groundwater exchange is unknown and depends on the season as well as other circumstances. Furthermore, the sampled groundwater is assumed to represent the total depth of the well since no other information is available. Therefore, the analytical data may not be used for general hydrogeochemical modelling. The purpose of the sampling is to observe possible impacts on the drinking water quality that may be caused by SKB or by other activities in the area (Figure 6-21).

Representative groundwater depth: In the Sicada database, there has been some confusion regarding the zero level, that is, whether the filter/screen level is measured from Top of Casing (ToC) or from the ground surface. This affects the filter/screen level measured from this zero point and also the section limits.

Measurements with field probe: There have been several problems with the field probes (Figure 6-22). On occasion, some of the parameters have not stabilised, showed unreliable values or calibration control parameters out of range. Since new probes were obtained in 2013, these problems have not occurred. Redox measurement (ORP) may require more time to obtain representative values than available. The measurements may seem stable, but stepwise decreases often occur and therefore it may be difficult to judge when to stop measuring.

Figure 6-20. *Defrosting ice inside a steel monitoring well located in a lake, using an LPG burner.*

Figure 6-21. *Sampling of private wells PFM000039 and PFM000009.*

Figure 6-22. The probes used for measurements in surface water (left) and near surface groundwater (right). The rightmost probe is equipped with a flow-through cell and a submersible pump (white) for measurements in monitoring wells.

6.3.5 Statistical evaluation of hydrochemical near-surface groundwater

This section summarises the results from the statistical evaluation of hydrochemical data for near-surface groundwater in monitoring wells and private wells. The comprehensive statistical overviews of the data in Appendix 3 reflect different aspects of data quality, general patterns of variability, representativity of chemical data and long-term temporal changes with the main purpose of evaluating data quality and inconsistencies amongst sampled objects and analysed parameters. In contrast to the analysis and modelling underpinning most site descriptive models, the current evaluation comprises all quality controlled data in Sicada, in order to objectively describe the total dataset rather than adding new interpretations of the data. The evaluation is a tool in order to judge if the current monitoring programme is optimised regarding sampling frequency as well as temporal and spatial representativity, and if it is appropriately related to the general questions at issue.

The evaluation is based on the five major data compilations briefly described in the list below. These compilations contribute different complementary evaluations of the extensive and multidimensional hydrochemical dataset from the Forsmark area. The results from each of these analyses are summarised below and the tables are found in Appendix 3.

1. The total number of observations per parameter and object (sampling location).
2. The fraction of observations per parameter and object that fall below the reporting limits.
3. The coefficient of variation (CV) for all combinations of parameters and objects. This compilation show the relative variance among parameters and objects, and this information could be used to identify objects with, for some reason, increased variation. For parameters or objects with high inherent variation, longer time series and/or more frequent sampling is needed in order to detect significant deviations. Low inherent variation could, conversely permit the possibility of lowering the sampling frequency.
4. Normalised means based on all data from similar objects (near surface groundwater and groundwater in private wells). Independent of the absolute parameter values, this compilation shows where the mean values of individual objects are located on the total range of all similar objects for each parameter. This information could be used to identify specific objects with deviating chemistry and also to show common patterns among several parameters.
5. The results from a regression analysis with the purpose of identifying time trends in the data. Significant trends over time could be an indication of methodological, climatic or anthropogenic factors that influence data over time.

Total number of observations (Appendix 3, Table A3-6): The overview of the total number of data for all parameters and objects during the period 2002 to 2014 reveals the development of the monitoring and site characterisation programmes over time. The objects included in the current monitoring programme are easily identified by showing significantly more observations due to the longer time series (green). Shorter time series from the site investigation and the GBIZ campaign (monitoring wells SFM0081 to SFM0102, cf. Werner et al. 2006) are distinguished by orange/yellow colours, whereas objects with single samples from the first phase of the site investigation are coloured red.

The total number of available data differs significantly between the different parameters due to the varying extent of the hydrochemical investigation activities including the monitoring programmes over time. Major constituents (Na, K, Ca, Mg, Si, Li, Sr, Cl, SO_4, Br, HCO_3, pH) and environmental isotopes (^{2}H, ^{3}H and ^{18}O) have been determined at all sampling occasions whereas trace elements have been included less often and this also differs depending on object. Some parameters have only been included on a few occasions at the beginning of the site characterisation programme, or in separate campaigns with specific purposes. A number of isotopes (^{10}B, ^{13}C, ^{14}C, ^{34}S, ^{36}Cl, ^{37}Cl, ^{87}Sr) were only determined at the beginning of the site characterisation programme in order to achieve a baseline and then excluded mainly due to costs. A number of radionuclides (^{222}Rn, ^{226}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{235}U, ^{236}U, ^{238}U) were also included early in the site characterisation programme and in separate campaigns (Grolander and Roos 2009).

The major conclusion from this exercise is that a few trace elements were only determined on a few occasions at the beginning of the site characterisation programme (B, Nb, In, Se), and were then excluded without motivation for so doing. The stable isotopes of Nb and Se are important analogues to radionuclides included in the assessments for long term safety of the spent fuel repository (cf. Nordén et al. 2010, Tröjbom et al. 2013).

Analyses below reporting limits (Appendix 3, Table A3-7): If a large fraction of the analyses fall below the reporting limit, it could be an indication that the analytical method is inappropriate. None of the shallow groundwater sampling locations stands out by showing an elevated proportion of analyses below the reporting limit compared with the general pattern. On the other hand, there are clear differences among the parameters, and in a few cases the majority of the analyses are below the reporting limits.

The Cs, Hg, Th, Tl and In analyses are generally below the reporting limit, as well as a minor fraction of the analyses of Br, F and Li. Also most of the analyses for the radionuclides ^{235}U, ^{230}Th and ^{232}Th fall below the reporting limits. For rare earth metals, REE (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu), a varying fraction of the analyses fall below the reporting limits. These elements have very similar chemical properties and the concentrations are usually highly correlated, although they are present in very different concentration ranges. For the rarer elements in this group (e.g. Tb, Ho, Tm, Lu) most of the analyses are below the reporting limits due to the generally low concentrations. Nitrite and nitrate (NO_2, NO_3) data are below the reporting limits for half of the monitoring wells.

The general conclusion from this exercise, focusing on data quality and reporting limits, is that the reporting limits should be evaluated for Cs and Th since very few actual values exist. If possible, also bromide, iodide and the nitrogen species NO_2 and NO_3 would benefit from lower reporting limits.

Comparisons of variation (Appendix 3, Table A3-8): The coefficient of variation, which is defined as the ratio between the arithmetic standard deviation and the arithmetic mean, indicates the relative variance among parameters and objects. This information could be used to identify objects and parameters with, for some reason, increased inherent variation. From the CV analysis it could be concluded that many objects show similar variance, and also that several parameters show similar general variance.

The major constituents Ca and HCO_3 and to some extent also Si show low variance, compared with most other parameters, which probably reflects the constant supply of these elements from weathering of the regolith. For the major constituents (Na, Cl, Br, K, Li, SO_4), there are distinct differences in variance among the monitoring wells, indicating varying contribution of water of marine origin.

Redox sensitive parameters such as NH_4/NO_3, Fe, Mn and S^{2-} generally show high variance, indicating varying redox conditions over time or sensitivity to contamination or disturbances.

For total phosphorus (P_bio), there are large differences in variance among the monitoring wells. A similar, but not so pronounced pattern is also seen for phosphate (PO_4-P). ^{37}Cl shows varying and sometimes very high variance, which indicates high uncertainties in this parameter. Al shows generally increased variance compared with other geogenic elements. In most monitoring wells, ^{3}H shows low variance, except for the monitoring wells installed in sediments below lakes (e.g. SFM0012, -15, -23 and -25). The mean values are also lower for these objects, which indicate that the groundwater at these locations generally is rather old and of a different origin, but that mixing with a more common younger groundwater component occurs on some occasions.

Among the monitoring wells included in the current monitoring programme, SFM0001, and to some extent also SFM0037, show larger variance than most other monitoring wells. This probably reflects the varying conditions in recharging groundwater compared with the more stable conditions of discharging groundwater (cf. Figure 6-23 to Figure 6-25).

The general conclusion from this evaluation is that the variance among the sampling locations included in the current monitoring programme does not differ significantly from that of the majority of objects within the site characterisation programme, except for a number of metals that show slightly higher variance (Zn, Cu, Cd, and Pb). The variance of several major constituents is larger in shallow groundwater than in surface water, which probably reflects higher seasonal variability due to varying dilution and mixing of water of different origins.

Comparisons among normalised means (Appendix 3, Table A3-9): The major purpose of the comparisons of normalised means is to relate the individual objects, for example the objects included in the current monitoring programme, to all similar objects in order to identify objects with deviating chemistry (i.e. this is not a method for detecting sample outliers in data). This gives information whether the selected sampling locations reflect the relevant spatial variation in the Forsmark area, and if there are previously sampled objects with deviating chemistry which are not included in the current monitoring programme.

The general conclusion from the evaluation of normalised means is that the monitoring wells included in the current monitoring programme, with a few exceptions, are representative for the entire range of near-surface groundwaters in the Forsmark area. The ongoing monitoring programme does not include any groundwaters representing oxidising redox conditions in recharge areas of the landscape (for example SFM0005, SFM0006, and SFM0057). For instance, these monitoring wells are characterised by low contents of Fe and elevated REE contents. It has been argued that the focus should be on discharging groundwater where radionuclides from the deep depository are most likely to appear. Knowledge of recharging groundwater can, however, be valuable when the influence from meteoric recharge during construction is evaluated.

Evaluation of time series (Appendix 3, Table A3-10): The evaluation of time series by a linear, parametric regression analysis is a screening method with the purpose to find trends in data not explained by chance. It is expected that most of the time series show no trends if they reflect baselines at undisturbed conditions. On the contrary, a significant trend or variation could be an indication of such effects, disturbed conditions or methodological bias. As this analysis catches stepwise shifts, gradual trends and influences from individual outliers, the results must be checked by time-series plots. It should also be kept in mind that an evaluation of a large number of relationships implies that a portion of these are falsely recognised as significant. The regression analysis has been applied to all time series comprising of at least 10 observations ranging over a time period of four years, or longer. The statistics given in Table A3-10 in Appendix 3, represent the probabilities for the hypothesis that there is no time-trend in data, i.e. values between -0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign of the probabilities represents the direction of the trends based on the sign of the correlation coefficients.

Three of the monitoring wells show decreasing trends for conductivity and several major ions, such as Cl, and Na, whereas SFM0032 shows a slightly increasing trend (Figure 6-23). The explanations for these long-term changes are not obvious, but it could not be excluded that they are effects of the pumping and sampling activities themselves. In the case of SFM0023, dilution of the originally stagnant, brackish groundwater by lake water intrusion due to the pumping/sampling could explain the trend. In SFM0051, the decreasing trend is even more pronounced for Cl, where a shift downwards took place during 2008. Altered hydrology or altered influence from the gravel road and Drill site 1 nearby are possible explanations of this effect. Most parameters in SFM0051 show decreasing trends which indicates altered hydrological conditions and increased dilution.

Organic carbon (TOC, DOC) shows increasing trends in four of the monitoring wells but no trend in SFM0023, where the groundwater is more isolated (Figure 6-24). The increasing trends can be explained by a stepwise shift during 2006/2007 that could have methodological reasons, similar to surface water where some shifts were also distinguished (cf. Section 6.2.5).

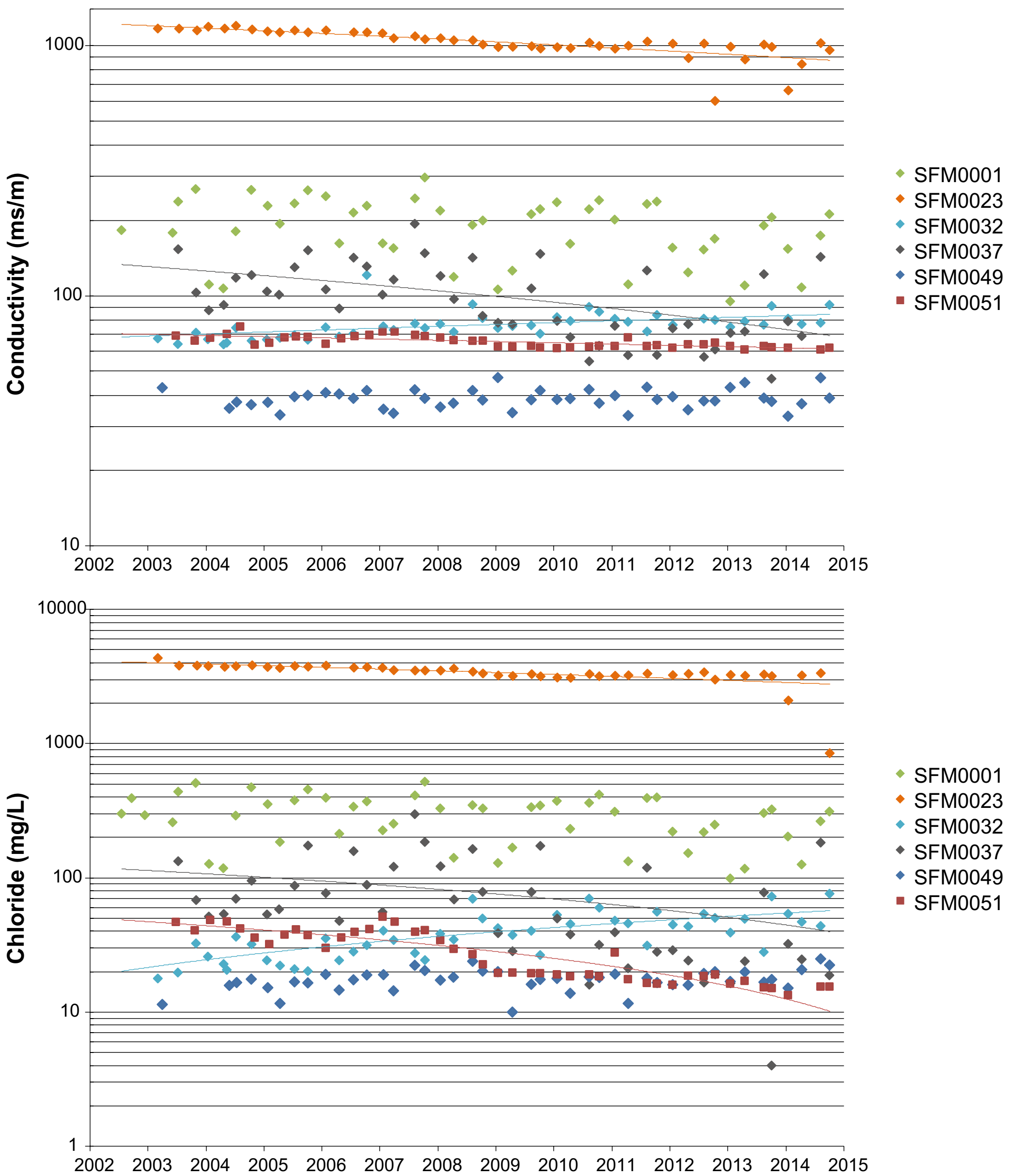

Figure 6-23. *Electrical Conductivity (EC, upper), chloride (lower) versus date for shallow groundwater in the regolith. Note the logarithmic scales. In the case of SFM0023, dilution of the originally stagnant, brackish groundwater by lake water drawn down could explain the trends for EC and Cl. In SFM0051, the descending trend is even more pronounced for Cl, where a shift downwards took place during 2008. Altered hydrology or altered influence from the gravel road and Drill site 1 nearby are possible explanations of this effect. In contrast SFM0032 shows increasing trends towards higher contents of dissolved ions and Cl. The explanation for these trends is not obvious. The lines mark the statistically significant trends according to the regression analysis ($p < 0.05$).*

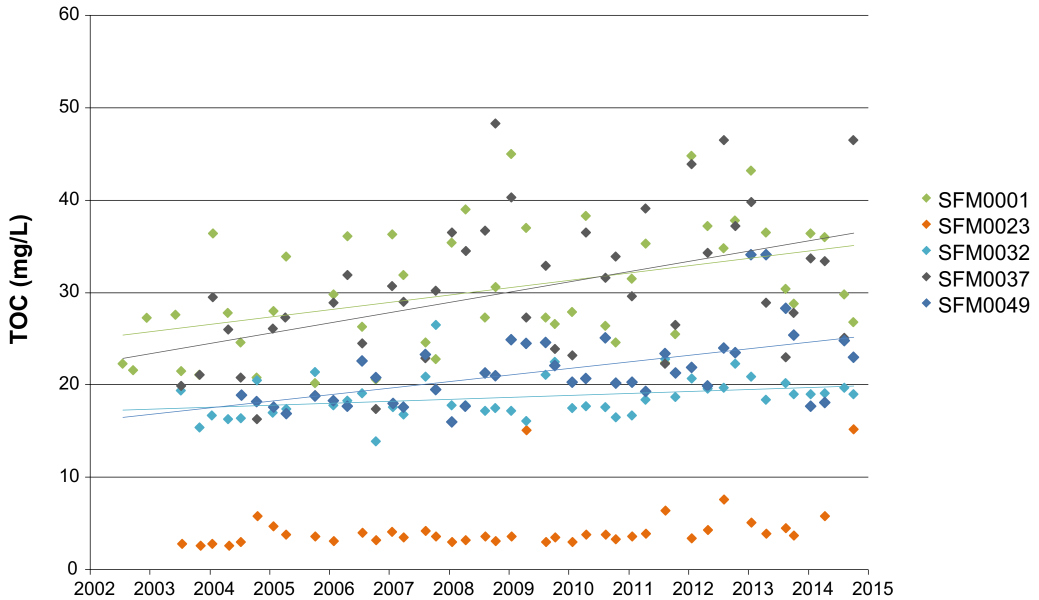

Figure 6-24. *Total organic carbon (TOC) versus date for shallow groundwater in the overburden. The possible stepwise shifts in 2006, which are also found for surface water, probably have methodological reasons. The lines mark the statistically significant trends according to the regression analysis ($p < 0.05$).*

The concentrations of REE in SFM0001 tend to increase together with the concentrations of Fe and organic carbon (Figure 6-25). REE are often associated with organic matter and Fe and Al oxy-hydroxides. Tritium shows decreasing trends for all studied monitoring wells except for SFM0023 (Figure 6-25). This pattern, which is also observed in surface waters, reflects the ongoing decay of the radionuclide ^{3}H in the atmosphere.

The general conclusion from the regression analysis is that most of the significant trends in near-surface groundwater are probably explained by methodological factors, rather than long-term changes of the natural conditions. Local seasonal differences could not be ruled out as underlying these patterns, but the low number of objects included in the monitoring programme makes it difficult to distinguish specific factors.

6.3.6 Reference data

Reference data might be important in order to put the measurements in a context. Regional reference data might contribute with longer time series that explain long-term temporal variations, whereas local reference data might serve as a reference during the construction and operational phases of the repositories.

Besides comparable data from sampling locations outside of the Forsmark area, there are monitoring wells with early data from 2002 to 2007 within the investigated site that will not be influenced by future construction and operation activities in the two repositories. Some of these locations are suitable as reference objects. It is proposed that additional sampling locations should be included for this purpose in the updated monitoring programme (cf. Section 8.3.3).

Regional reference data for near-surface ground water are available from a few stations with time series representing undisturbed conditions (SGU n d, a). The station, Gålarmora 1, which is located southwest of the Forsmark area and represents groundwater in till, is sampled four times per year. The parameters temperature, pH, PO_4, tot-P, EC, NH_4, NO_3, NO_2, tot-N, TOC, F, Cl, Alkalinity/Acidity, SO_4, Ca, Mg, K, Na, Fe, Mn, Si and Al are analysed at all sampling occasions, whereas Cu, Zn, Pb, Cd, Cr, Ni, Co, As, V and Hg are analysed less often. There is a similar sampling location near the municipality of Hallstavik, southeast of the Forsmark area, which is also sampled four times per year. A larger number of locations marked with green dots in the map (Figure 6-26) are sampled once every sixth year.

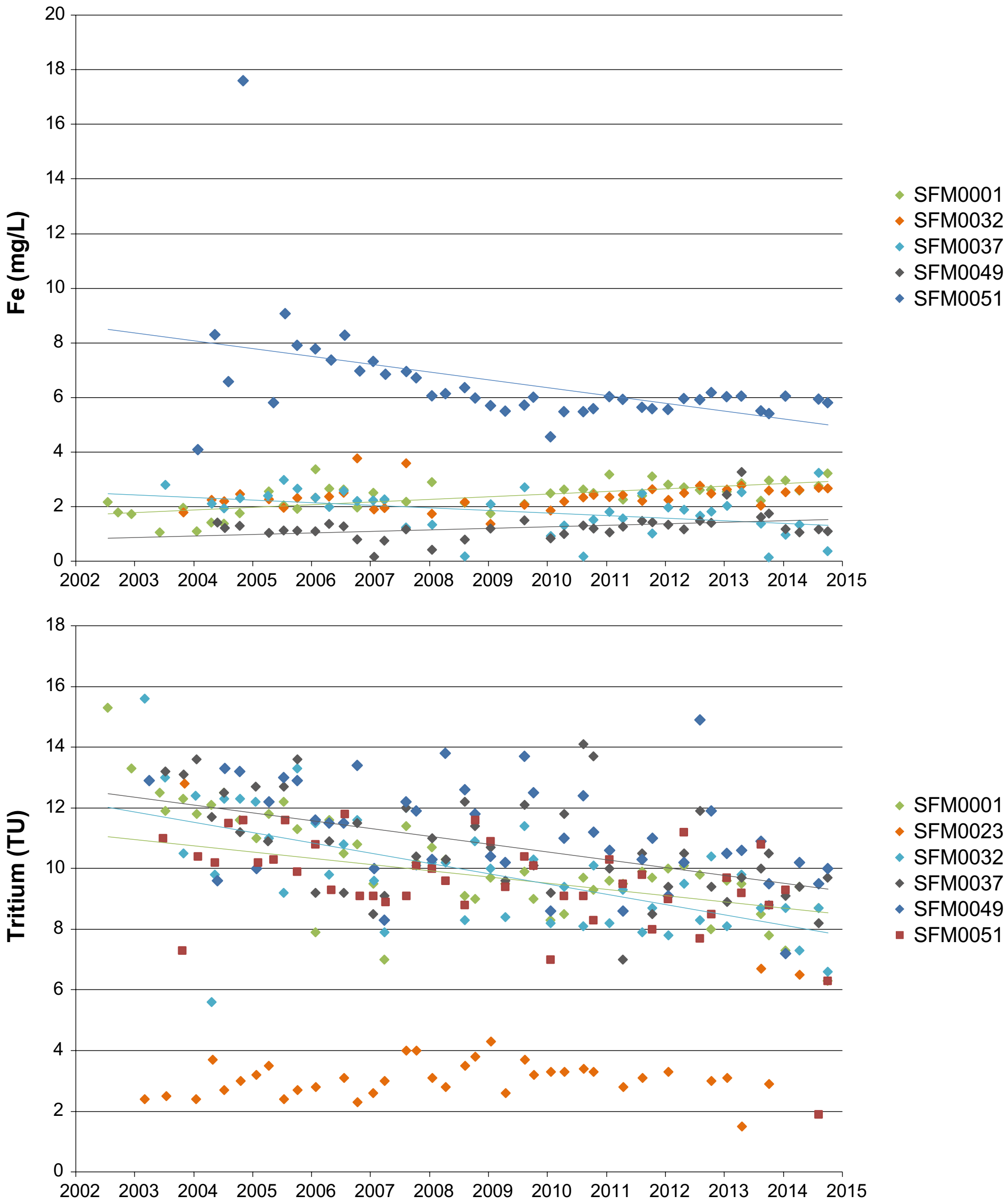

Figure 6-25. *Iron, Fe (upper) and tritium, ^{3}H (lower) versus date for shallow groundwater in the regolith. The decreasing trends for tritium in most monitoring wells reflect the ongoing decay of this radionuclide in the atmosphere. SFM0023 shows no trend and the variation patterns indicate varying influence from groundwater with different residence times. The lines mark the statistically significant trends according to the regression analysis ($p < 0.05$).*

Figure 6-26. Regional sampling locations for near-surface groundwater. The blue-coloured dots represent stations sampled four times per year (marked by arrows), and the green-coloured dots are locations sampled once every sixth year. The yellow dots mark villages in the area.

6.4 Hydrochemical monitoring of groundwater in bedrock

The long-term hydrochemical monitoring programme for groundwater in bedrock is focused on characterisation of temporal variations and long-term changes in groundwater sampled in percussion-drilled boreholes, usually in the range of 100–200 metres, and in core-drilled telescopic (cf. below) or conventional boreholes extending up to approximately 1 000 meters vertical depth. Generally, the core-drilled boreholes are of the so called telescopic type and comprise a percussion drilled first part (approximately 100 m) with a diameter of about 200–250 mm, followed subsequently by a core drilled hole (often to around 1 000 m depth) with a diameter of approximately 76 mm. This type of borehole can accommodate installation of borehole sections equipped with wide standpipes to facilitate the sampling of groundwater for hydrochemical monitoring (Figure 6-29). Furthermore, efficient air-lift pumping from the initial percussion drilled part of the borehole is conducted during and after core drilling to minimise the amount of contaminating flushing water and also drilling debris that otherwise would be forced into conductive bedrock fractures by the high pressure. The latter point is of importance for all subsequent hydrochemical sampling.

The hydrochemical data generated from the monitoring programme serve several purposes. Besides input to the general scientific understanding of the groundwater evolution and the processes forming the hydrochemical conditions in the bedrock, several specific objectives are recognised.

- For the repository for spent nuclear fuel, specific hydrochemical limits have been identified to ensure that favourable hydrochemical conditions prevail at deposition depth with respect to the requirements of the natural and the engineered barriers. Specific safety indicators have been identified (e.g. sulphide, Cl, pH) that should be maintained within defined ranges (Andersson et al. 2000). The monitoring data contributes to the understanding of the natural baselines of these parameters in order to evaluate whether the bedrock is suitable for the repository from a hydrochemical perspective.
- Relevant baseline data reflecting the temporal variation from the monitoring is crucial information in order to study the impacts from construction and operation of a facility at a later stage and understand the changes in the water composition and chemical conditions that will appear due to the progress of the excavation and the changed hydraulic conditions.
- Hydrochemical data are important input to hydrogeological models, for example via mixing calculations that give information on proportions of different water types defined based on the main origin of the groundwater, as well as parameters that give information on groundwater residence times. Hydrochemical data also define boundary conditions for the hydrogeological models needed for the interpretation of the disturbed conditions during construction and operation of the repository.

A challenge when interpreting hydrochemical data from boreholes in the crystalline bedrock is to evaluate the representativity of the samples. As further described in Section 6.4.4, several factors may influence the representativity such as the purged volume prior to sampling. The adequate volume to be exchanged depends on the number and transmissivity of the water-bearing fractures and their spatial distribution along the borehole section length. If too small a volume is exchanged, the samples will contain contributions from the water that was initially present in the borehole section.

This water is likely to be affected by, for example, increased microbial activity or corrosion on the installed equipment. Such processes, in turn, may lead to a complex series of reactions, causing, among others, the observed enhanced sulphide concentrations or high pH values. Also too much purging is unfavourable for representativity, since the sample water may have been withdrawn from a long distance from the borehole or a different vertical depth. Furthermore, other activities in the vicinity of the borehole like hydraulic interference tests etc. may influence the water composition and cause mixing of waters with different origin. All these factors together adversely affect interpretation of the groundwater sampling.

During the construction/operation phase of the repository, changes in the hydrochemistry will take place due to altered hydrogeological conditions. Expected changes are intrusion of shallow meteoric water to greater depth, up-coning of deeper more saline water and/or an increased degree of mixing of for example non-marine type groundwater with marine type groundwater. Experience from the SFR (Nilsson et al. 2011) and the Äspö HRL (Nilsson et al. 2013) show that all three effects occur, especially in the major deformation zones. Changed flow paths and drawdown effects during and after construction of the repository tunnel system will have different impacts on the groundwater composition in different parts of the bedrock volume depending on geometry and extent of geological structures and their hydraulic transmissivities.

Furthermore, bedrock volumes with stable and unaffected groundwater conditions will most certainly also be recognised in some of the low transmissive fracture domains. This groundwater will be of an older non-marine origin with extremely long residence time. Figure 6-27 illustrates some of the different conceptual models developed by different geoscientific disciplines as parts of the integrated Forsmark site description (cf. Table 6-11). The hydrogeochemical conditions in the bedrock correlate well with the fracture domain model (Olofsson et al. 2007) presented at the top of the figure.

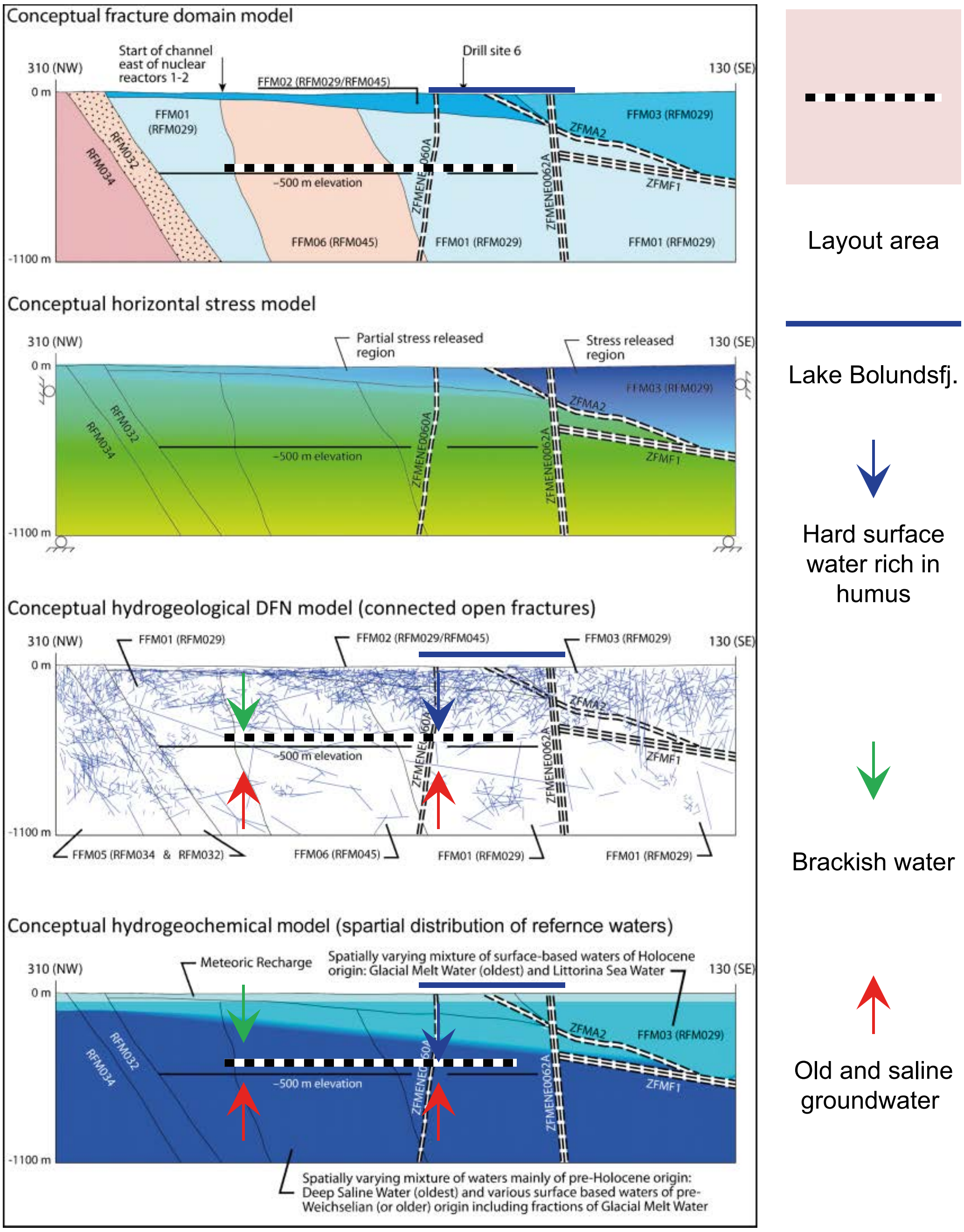

Figure 6-27. *Vertical cross section from NW to SE showing, from the top, conceptual fracture domain model, horizontal stress model, hydrogeological DFN model and hydrogeochemical model. The expected locations for introduction of surface waters of meteoric or brackish types into the bedrock and upconing of old saline groundwater are marked with blue, green and red arrows, respectively.*

The fracture system in the fracture-rich and very transmissive domain FFM02 (see Figure 6-27, fracture domain model at the top) contains a relatively young water of meteoric and/or Littorina origin. This is also more or less true for fracture domain FFM03 and its series of intersecting gently dipping minor deformation zones. These have allowed groundwater of Littorina origin to reach a larger depth than in the northwestern part of the site. Non-marine water with extremely long residence times are found in the low transmissive domains FFM01 and FFM06. The major vertical or gently dipping deformation zones lodge younger water originating mainly from Littorina Sea-water mixed with glacial melt-water. This distribution of the different groundwater types shows that the major deformation zones have served as important groundwater flow pathways over long periods of geological time, while single discrete fractures in rock volumes between zones generally contain older and more isolated groundwater.

The expected future impacts from the excavations and underground construction work are predicted from past to present-day observations and the proposed main pathways are illustrated by arrows in the lowermost two models (the conceptual hydrogeological and hydrogeochemical models in Figure 6-27, and the top view in Figure 6-28). As can be seen the zone ZFMENE0060A, which divides the repository area in two parts, plays an important role since it is likely to be subject to intrusion by brackish and meteoric water from above. The reason is that the bedrock volume (fracture domain FFM02) above the planned repository and down to maximum 300 m depth is very transmissive with lots of water in contrast to the bedrock below a depth of 400–500 m, which is almost fracture free and dry.

Impact is also expected adjacent to the large Eckarfjärden (upconing) and Singö deformation zones (intrusion from above). The directions of the water transport are determined by differences in altitude and the drawdown caused by SFR. Furthermore, upconing is expected close to the planned location for the main shaft and entrance tunnel were pumping of large volumes of water will take place during construction and operation.

In order to understand the changes in groundwater composition that will occur as an effect of up-coning, more knowledge concerning the groundwater composition at large depths (> 1 000 m) is desired. For the moment, there are insufficient data on this type of groundwater, since very few water yielding fractures were discovered at depth in the available boreholes in Forsmark of which none extends below 1 000 m vertical depth. There is also a need for surface-water data and especially data for shallow groundwater in the overburden in order to understand the impacts from this water when it intrudes into the bedrock. Isotopes that are useful tools in the interpretation of groundwater origin and residence times are especially important for this type of interpretation. By following the groundwater composition during long periods of time and interpreting the changes that occur, knowledge about the effects of the repository will be obtained, similar to the information gained from a large-scale hydraulic tracer test.

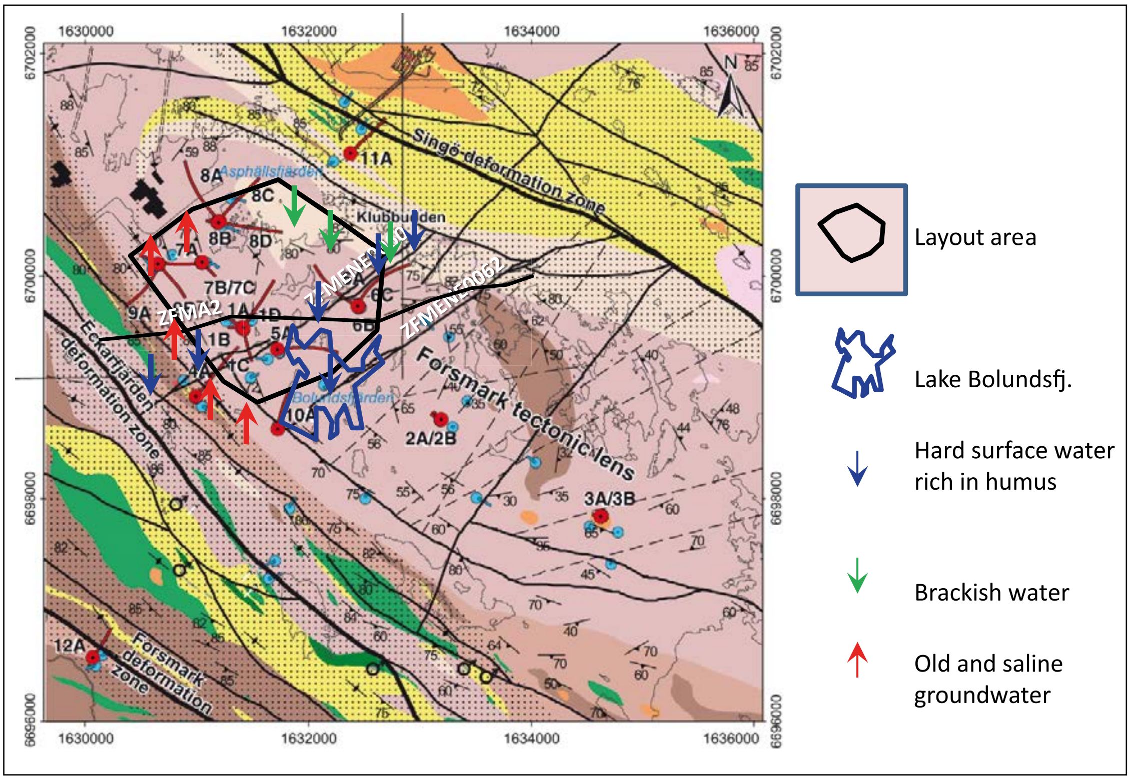

Figure 6-28. Top view of the Forsmark site with rock domains and deformation zones. The expected locations for introduction of surface waters of meteoric or brackish types into the bedrock as well as up coning of old saline groundwater is marked with blue, green and red arrows, respectively.

The monitoring programme for groundwater in the bedrock, and the data collected during the site investigations, as well as the extended monitoring period 2007–2009, are described in a number of SKB reports. From 2010, monitoring data are documented in internal SKB reports. In Table 6-11, reports and documents documenting the monitoring programme are listed in chronological order from 2002 until 2016. This compilation contains recent activity plans, yearly data reports, data evaluation reports, and site descriptive model reports dealing with groundwater in Forsmark.

Table 6-11. Compilation of reports and documents concerning monitoring of groundwater in the bedrock (percussion- and core-drilled boreholes). The list is sorted in chronological order based on the year when the data were obtained. The 7-digit numbers in the "document" column refers to SKBdoc IDs. This compilation contains recent activity plans, yearly data reports (P-reports), data evaluation reports (R- and TR-reports), and site descriptive model reports (TR-reports) dealing with hydrochemical data from Forsmark. Activity plans are documents controlling the monitoring activities.

Year	Document	Doc. type	Title (reference)
2001	TR-01-29	TR-report	Site investigations. Investigation methods and general execution programme (SKB 2001a).
2002	R-01-42	R-report	Program för platsundersökningar vid Forsmark (SKB 2001b).
2005	P-06-57	P-report	Hydrochemical monitoring of percussion- and core drilled boreholes. Result from water sampling and analyses during 2005. Forsmark site investigation (Berg and Nilsson 2006).
2005	R-05-14	R-report	Programme for further investigations of geosphere and biosphere. Forsmark site investigation (SKB 2005).
2006	P-07-47	P-report	Hydrochemical monitoring of percussion- and core drilled boreholes. Result from water sampling and analyses during 2006. Forsmark site investigation (Berg and Nilsson 2007).
2004	R-04-13	R-report	Monitoring during the stepwise implementation of the Swedish deep repository for spent fuel (Bäckblom and Almén 2004).
1984–2007	P-09-45	P-report	Presentation and evaluation of hydrogeochemical data from SFR-boreholes, 1984–2007. Site investigation SFR (Nilsson 2009).
2007	P-08-54	P-report	Hydrochemical monitoring of percussion- and core drilled boreholes. Result from water sampling and analyses during 2007. Forsmark site investigation (Berg and Nilsson 2008).
2008	P-09-51	P-report	Hydrochemical monitoring of groundwaters, surface waters and precipitation. Results from water sampling in the Forsmark area, January 2008–December 2008. Forsmark site investigation (Berg et al. 2009
1984–2009	R-10-38	R-report	Preliminary hydrogeochemical site description SFR (version 0.2) (Nilsson et al. 2010b).
2007–2009	R-07-34	R-report	Programme for long-term observations of geosphere and biosphere after completed site investigations. Forsmark site investigation (SKB 2007).
2009	P-10-40	P-report	Hydrochemical monitoring of groundwaters and surface waters. Results from water sampling in the Forsmark area, January–December 2009. Forsmark site investigation (Nilsson et al. 2010a).
2003–2009	TR-10-39	TR-report	SR-Site – sulphide content in the groundwater at Forsmark (Tullborg et al. 2010a).
2010	SKBdoc 1334697	Data report	Hydrochemical monitoring of groundwaters. Results from water sampling in the Forsmark area spring and autumn 2010 (Lindquist et al. 2012a).
2010	SKBdoc 1334698	Data report	Appendices to SKBdoc 1334697 (Lindquist et al. 2012b).
2010	P-11-14	P-report	Hydrochemical characterisation of groundwater in the SFR repository. Sampling and analysis during 2010. Extended investigations in KFR7A: 48.0 to 74.7 m, KFR08: 63.0 to 104.0 and KFR19: 95.6 to 110.0 m. Site investigation SFR (Nilsson 2011b).
2010	R-11-13	R-report	Bacterial sulphate reduction and mixing processes at the Äspö Hard Rock Laboratory indicated by groundwater $\delta^{34}S$ isotope signatures (Wallin 2011).
1984–2011	R-11-06	R-report	SFR site investigation. Bedrock Hydrogeochemistry (Nilsson et al. 2011).
2010–2011	SKBdoc 1225204	Activity plan	Hydrokemiskt övervakningsprogram för kärnborrhål under 2010–2011 (internal document).
2011	SKBdoc 1293502	Activity plan	Hydrokemiskt övervakningsprogram för kärnborrhål i Forsmark vår och höst 2011 (internal document).
2011	SKBdoc 1386270	Data report	Hydrochemical groundwater monitoring. Results from water sampling in the Forsmark area, spring and autumn 2011 (Lindquist and Harrström 2012a).
2011	SKBdoc 1386280	Data report	Appendices to SKBdoc 1386270 (Lindquist and Harrström 2012b).

Year	Document	Doc. type	Title (reference)
1984–2011	TR-11-04	TR-report	Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark (SKB 2013b).
2012	SKBdoc 1357756	Activity plan	Hydrogeokemiskt moniteringsprogram för kärn- och hammarborrhål 2012 (internal document).
2012	SKBdoc 1390369	Data report	Hydrochemical groundwater monitoring. Results from water sampling in the Forsmark area, spring and autumn 2012 (Lindquist and Nilsson 2013a).
2012	SKBdoc 1413845	Data report	Appendices to SKBdoc 1390369 (Lindquist and Nilsson 2013b).
2012	SKBdoc 1373688	Activity plan	Hydrokemiskt övervakningsprogram för grundvatten i borrhål borrade inom projekt SFR-Utbyggnad. Provtagning och analys under 2012 (internal document).
2012	SKBdoc 1413843	Data report	Hydrochemical groundwater monitoring. Results from water sampling at the SFR site, spring and autumn 2012 (Lindquist and Nilsson 2013c).
2012	SKBdoc 1413844	Data report	Appendices to SKBdoc 1413843 (Lindquist and Nilsson 2013d).
2013	SKBdoc 1391550	Activity plan	Hydrokemiskt moniteringsprogram för kärn- och hammarborrhål 2013 (internal document).
2013	SKBdoc 1385812	Data report	Hydrochemical groundwater monitoring. Results from water sampling in the Forsmark area and the SFR-site, spring and autumn 2013 (Ragvald et al. 2015).
2013	SKBdoc 1392590	Activity plan	Kemikarakterisering två sektioner i KFM08D hösten 2013 (internal document).
2014	SKBdoc 1420574	Activity plan	Hydrokemiskt moniteringsprogram för hammar- och kärnborrhål 2014 inklusive dockningstest (internal document).
2014	SKBdoc 1420576	Data report	Hydrochemical groundwater monitoring. Results from water sampling in the Forsmark area 2014 (Ragvald and Lindquist 2015).
2015	SKBdoc 1473527	Activity plan	Hydrokemiskt moniteringsprogram för hammar- och kärnborrhål 2015 (internal document).
2015	SKBdoc 1542091	Data report	Hydrochemical groundwater monitoring. Results from water sampling in the Forsmark area 2015 (Ragvald 2016).

6.4.1 Overview of borehole installations and sampling methods

Fixed monitoring equipment is installed in the boreholes after completion of general investigation activities in order to separate different borehole sections. The sections and type of installation in each section are selected upon summarised need for groundwater level/pressure, groundwater flow and groundwater chemistry monitoring. The sections are isolated by inflated rubber packers, which also prevent undesired short circuiting effects that will occur if boreholes are kept open. In telescopic core-drilled boreholes and percussion-drilled boreholes from the ground surface, the pressure is monitored on-line in standpipes hydraulically connected to each section (cf. Figure 6-29) and transmitted to SKB's hard and software data systems for processing and interim storage of hydrological, hydrogeological and meteorological data (HMS).

Groundwater sampling, as well as groundwater-flow measurements, are regularly conducted in selected, specially equipped, borehole sections that allow circulation of groundwater in the borehole section (circulation is needed for the groundwater flow measurements employing tracers). Figure 6-29 displays a simplified outline of the equipment in monitored boreholes drilled from the ground surface. The design of the equipment in tunnel boreholes is basically similar, although there are no standpipes since no pumping is needed to discharge the groundwater due to the pressure gradient between the section and the open tunnel.

For each borehole section included in the programme and at each recurrent sampling occasion, hydrochemical monitoring implies collection of sample series (minimum three samples) during continuous pumping/discharge (Figure 6-30). Individual plug-flow volumes are calculated for each sampled borehole section considering the water yielding fractures, their transmissivities and their positions in the borehole section. If possible, a minimum of five times the plug-flow volume is discharged when the last sample in the series is collected in order to ensure close to 100 % groundwater from the fracture/fractures, implying no contribution remaining from water initially present in the borehole section (Figure 6-31).

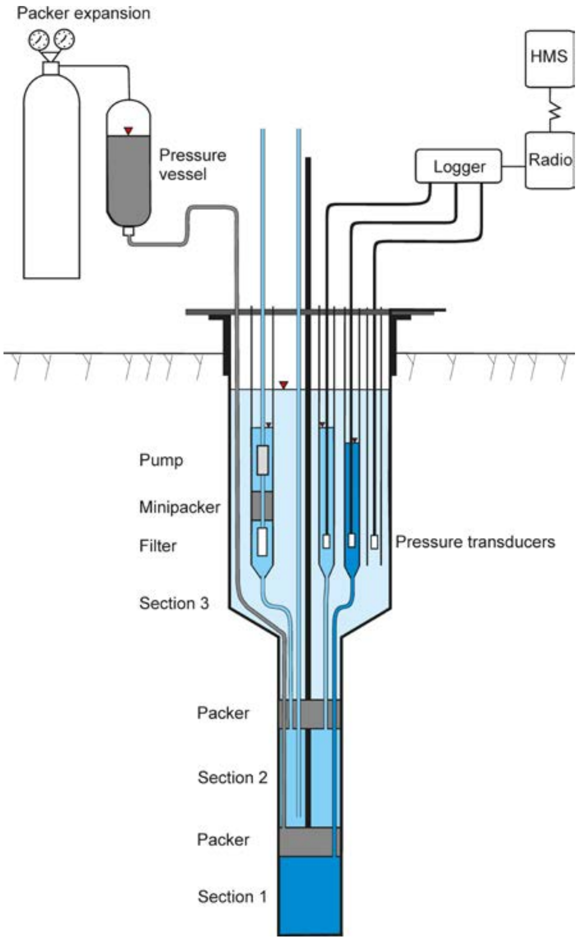

Figure 6-29. *Simplified outline of fixed equipment for pressure, groundwater composition, and groundwater-flow monitoring in a telescopic borehole from the surface. The sampling equipment (from the top pump, mini packer and filter) is lowered in the wider stand pipe connected to section 2. A maximum of ten pressure sections can be installed in a telescopic borehole, of which generally two are equipped for water sampling and circulation of tracers during flow measurements (ex. section 2). These circulation sections are connected to two stand pipes. The other sections are equipped solely for pressure measurements and connect to one narrow stand pipe each (ex. section 1). A few pressure sections are included in the current hydrochemical monitoring. These are sampled by gas-lift pumping using nitrogen.*

Figure 6-30. *The core-drilled boreholes drilled from the ground surface are sampled (left) by pumping in the stand pipe. The equipment which is lowered in the standpipe consists of, from the bottom, filter, mini packer and submersible pump. Boreholes drilled from tunnels (right) are sampled using the natural pressure gradient (here the orifice of KFR19 in the SFR facility with tubing from the different borehole sections).*

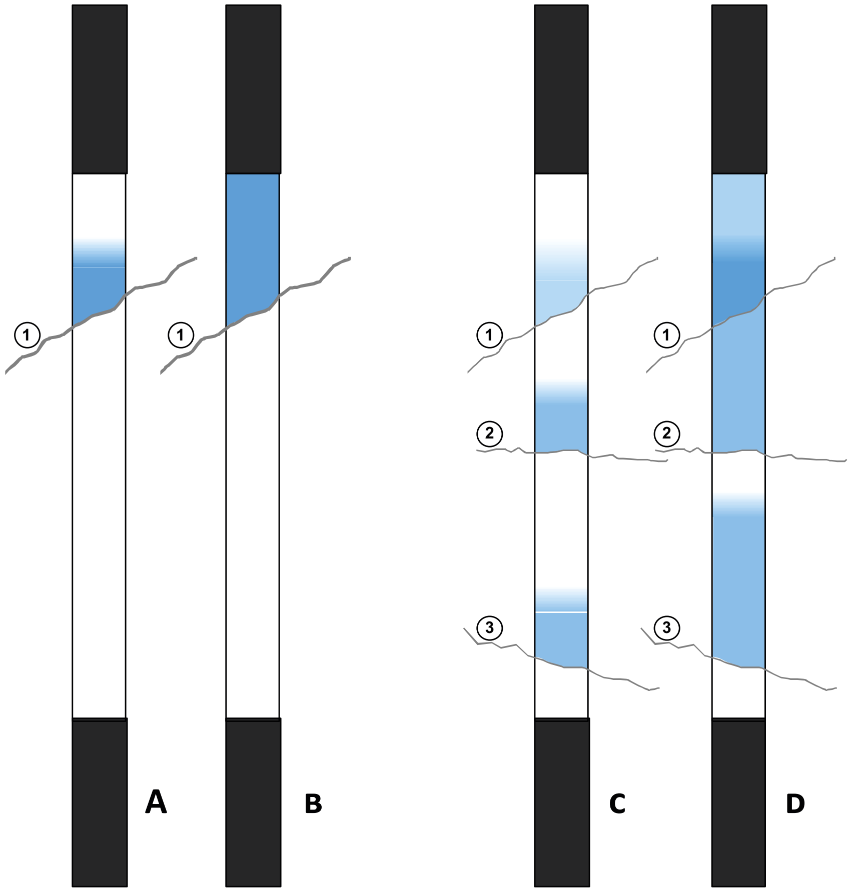

Figure 6-31. Estimation of initial section water contribution to the samples (Nilsson et al. 2010a). The colour strength illustrates the amount of new formation water in a borehole section during pumping. A and B show a situation with one water-yielding fracture. Shortly after pump start (A) the water from the only fracture has not reached the outlet from the section. After a certain time (B), all the water leaving the section is formation water. C and D show a situation with three fractures yielding similar contributions to the total flow. Shortly after pump start (C), no formation water has reached the outlet from the section. After a certain time (D), corresponding to the previous situation B, formation water from fracture 1) has reached the outlet, and formation water from fracture 2) has passed fracture 1). Formation water from fracture 3) has not yet reached fracture 2).

6.4.2 Current bedrock groundwater monitoring programme

The current hydrochemical monitoring programme for groundwater in the bedrock comprises ten percussion-drilled boreholes and 21 core-drilled boreholes. Sampling is performed in up to two sections per borehole, isolated by permanent packers. Since 2012, the bedrock monitoring activities for both the planned spent fuel repository and the planned extension of the existing SFR repository for low and intermediate activity nuclear waste have been coordinated in a common programme.

Sampling is performed once a year during spring, except in KFR101, KFR102A, KFR104 and KFR105, where sampling is performed on two occasions each year, in the spring and in the autumn. At each sampling occasion, a sample series of three samples is analysed in order to verify or refute the stability of the groundwater composition. The number of parameters analysed varies within the sample series, and a more complete characterisation is made for the last sample in each series. In Table 6-12, the number of analyses during 2014 is shown for each sampling location and component group (the number of individual samples in the sample series is reported). The parameters included in each component group are listed in Table 6-13. In previous reporting, these component groups were further aggregated into five "analysis classes" ranging from simple to complete chemical characterisation. The geographical locations of the sampled objects/boreholes are shown in Figure 6-32.

Table 6-12. The number of samples per borehole, section and component group in percussion-drilled and core-drilled boreholes during 2014. The component groups (compGrp) listed in the columns are explained in Table 6-13. At each sampling occasion, a sampling series of three individual samples is collected in order to assess the stability of the groundwater composition. SECUP and SECLOW denote upper and lower section limit, respectively.

				Component groups													
IDCODE	SECUP	SECLOW	SectionNo	Ammonium	Anions1	Anions2a	Carbon1	Carbon3	Cations1	EnvironIso1	EnvironIso2	FieldSonde1	HeavyIso2	IronSpecies	Nutrient1	Sulphide	Uranine
HFM01	33.5	45.5	2	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM02	38	48	2	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM04	58	66	2	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM13	159	173	1	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM15	85	95	1	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM16	54	67	2	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM19	168	182	1	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM21	22	32	3	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM27	46	58	2	3	3	3	3	3	3	1	1	3		3	3	3	3
HFM32	26	31	3	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM01A	109	130	5	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM01D	311	321	4	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM01D	429	438	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM02A	411	442	5	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM02A	491	518	3	3	3	3	3	3	3	1	1	3	1	3	3	3	3
KFM02B	410	431	4	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM02B	491	506	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM03A	633.5	650	4	3	3	3	3	3	3	1	1	3	1	3	3	3	3
KFM03A	969.5	994.5	1	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM04A	230	245	4	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM06A	341	362	5	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM06A	738	748	3	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM06C	531	540	5	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM06C	647	666	3	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM07A	962	972	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM08A	265	280	6	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM08A	684	694	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM08D	660	680	4	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM08D	825	835	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM10A	430	440	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM11A	446	456	4	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM11A	690	710	2	3	3	3	3	3	3	1	1	3		3	3	3	3
KFM12A	270	280	3	3	3	3	3	3	3	1	1	3		3	3	3	3
KFR101	279.5	341.8	1	6	6	6	6	6	6	6	6	6		6	6	6	6
KFR102A	214	219	5	6	6	6	6	6	6	6	6	6		6	6	6	6
KFR102A	423	443	2	6	6	6	6	6	6	6	6	6		6	6	6	6
KFR104	333	454.6	1	6	6	6	6	6	6	6	6	6		6	6	6	6
KFR105	265	306.8	1	6	6	6	6	6	6	6	6	6		6	6	6	6
KFR106	143	259	2	3	3	3	3	3	3	1	1	3	1	3	3	3	3
KFR106	260	300	1	3	3	3	3	3	3	1	1	3	1	3	3	3	3

Table 6-13. Definition of component groups for bedrock groundwater.

compGrp	Parameter group	Component Group	ComponentList
Ammonium	Nutrients and carbon	Ammonium	NH4
Anions1	Chemical environment	Anions1	Alkalinity (HCO3), pH, conductivity
Anions2a	Major constituents	Anions2a	Cl, F, SO4, Br
Carbon1	Nutrients and carbon	Dissolved organic carbon , dissolved inorganic carbon	DOC
Carbon3	Nutrients and carbon	Total organic carbon	TOC
Cations1	Major constituents	Cations, Si and S, class 3	Na, K, Ca, Mg, Li, Sr, Si-tot, S-tot
EnvironIso1	Environmental isotopes	Environmental isotopes	2H, 18O
EnvironIso2	Environmental isotopes	Tritium	3H
FieldSonde1	Field measurements	Field probe	pH, conductivity, temperature
HeavyIso2	Heavy isotopes	Uranium and thorium isotopes	234U, 238U
IronSpecies	Redox indicators	Iron species	Fetot, FeII
Nutrient1	Nutrients and carbon	Nutrient salt and silicate	NH4N, NO2N, NO3N, PO4P, NO2NO3N, SiO4Si
Sulphide	Redox indicators	Hydrogen sulphide	HS
Uranine	Flushing water tracer	Uranine	Uranine

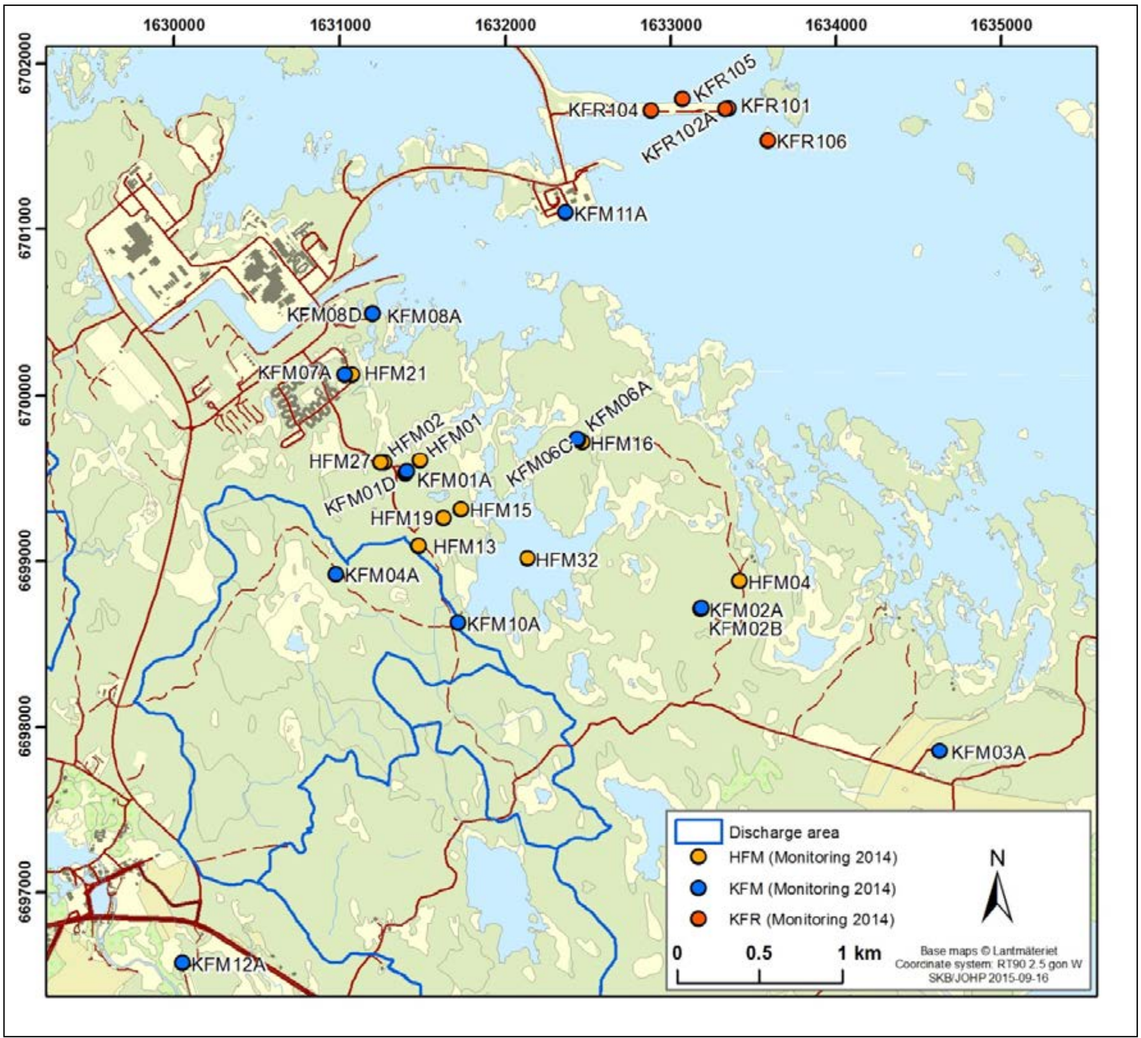

__Figure 6-32.__ The geographical locations of the boreholes included in the current monitoring programme (2014). HFM and KFM denote percussion and core drilled boreholes in Forsmark, respectively, while KFR denotes core drilled boreholes at the SFR site.

6.4.3 Hydrochemical monitoring of bedrock groundwater

Recurring investigations of hydrochemical parameters in groundwater in the Forsmark area have been performed in three different sets of boreholes drilled for three different purposes.

- The hydrochemical monitoring programme for the present SFR facility has been running since 1989 with the purpose of following changes caused by the presence of the tunnel system, especially the gradual intrusion of Baltic Sea water into the major vertical zones. The data produced are reported to the authorities (SSM and the County Administrative Board of Uppsala) and are also stored in Sicada (Nilsson et al. 2011).
- The hydrochemical monitoring programme during and after the site investigation for the spent fuel repository in Forsmark 2002–2007 (Laaksoharju et al. 2008).
- Hydrochemical monitoring for the SFR extension project 2007–2010 in boreholes drilled close to the present SFR facility (Nilsson et al. 2011).

The hydrochemical monitoring programme for boreholes drilled from the SFR facility in 1984–1986 implies yearly sampling of groundwaters in four boreholes (KFR01, KFR08, KFR7A and KFR10). The boreholes are selected to represent four different major deformation zones. More extensive sampling campaigns in all boreholes and borehole sections yielding water are conducted every fifth year. The latest occasions were in 2010 (Nilsson 2011b) and 2015 (Nilsson 2016). Single samples are collected from each sampling location and the analyses generally include major constituents, ^{3}H, $\delta^{2}H$ and $\delta^{18}O$. In some of the borehole sections, the extensive sampling campaigns include additional isotopes and trace elements.

When the site characterisation in Forsmark was finished in 2007, the long-term hydrochemical monitoring programme for groundwater was revised and extended without changes for two more years, until the site selection process for the spent fuel repository was completed in 2009. After 2009, the long-term monitoring programme in Forsmark has continued until today with only minor revisions. In 2010, the programme was slightly adjusted by decreasing the number of sampled objects, but increasing the extent of the analyses. Until 2012 the boreholes were sampled twice a year, during spring and autumn, but from 2013 sampling has been performed only once a year, during spring.

After the investigations for the planned SFR extension (2007–2009), hydrochemical monitoring was initiated in 2011 in five of the six new core-drilled boreholes drilled within the SFR extension project (KFR101, KFR102A, KFR104, KFR105 and KFR106). These boreholes are sampled twice a year. The boreholes drilled in the SFR extension project and the boreholes from the Forsmark site investigation for the deep repository have been included in a common monitoring programme since 2012.

The development of the monitoring programme for groundwater over time is shown in Table 6-14 (HFM and KFM boreholes) and Table 6-15 (KFR boreholes). The sampling locations included in the ongoing monitoring programme are denoted by "y" in the monitoring column. The leftmost columns show the number of samples per year for all monitored objects, whereas the rightmost columns show the percentage of analyses per component group, in relation to total number of samples during the entire monitoring period. The locations of all boreholes drilled in the Forsmark area are shown in Figure 6-33.

In Table 6-16, the same information is presented for a representative element per component group and for all objects summed together. The rightmost columns display the percentage of the samples each year that were analysed for each different component group. This table adds information on how the total number of samples per component group has changed over time, and emphasises any changes within the programme.

The revisions of the monitoring programme described above are depicted by the data in Table 6-14 and Table 6-15. After the revision 2007, sampling was temporarily interrupted in the percussion-drilled boreholes HFM14, HFM22, HFM33 and HFM36. In 2009, the sampling in KFM08D:2 was omitted temporarily due to observed leakage between borehole sections. The leaking equipment for isolation of borehole sections was raised in 2013 (see Figure 6-29), which allowed lowering of temporary mobile sampling equipment (for Complete Chemical Characterisation, cf. Tullborg et al.

2010a) for extensive sampling and measurements. Since 2010, the number of samples per year has increased due to introduction of sampling series (three samples collected at each sampling occasion twice a year). Prior to 2010, a single sample was collected at each sampling occasion. The change to sampling once per year has halved the number of samples since 2013 for most objects. The yearly sampling within the SFR monitoring programme, and the recurring extended campaigns every fourth to sixth year, are also evident as well as the addition of the SFR extension boreholes from 2009.

The changes in the extent of the analytical protocol over time are elucidated from Table 6-16. The number of analyses of iodide, environmental metals, trace elements and most isotopes was markedly reduced or ceased after the revision of the programme in 2010.

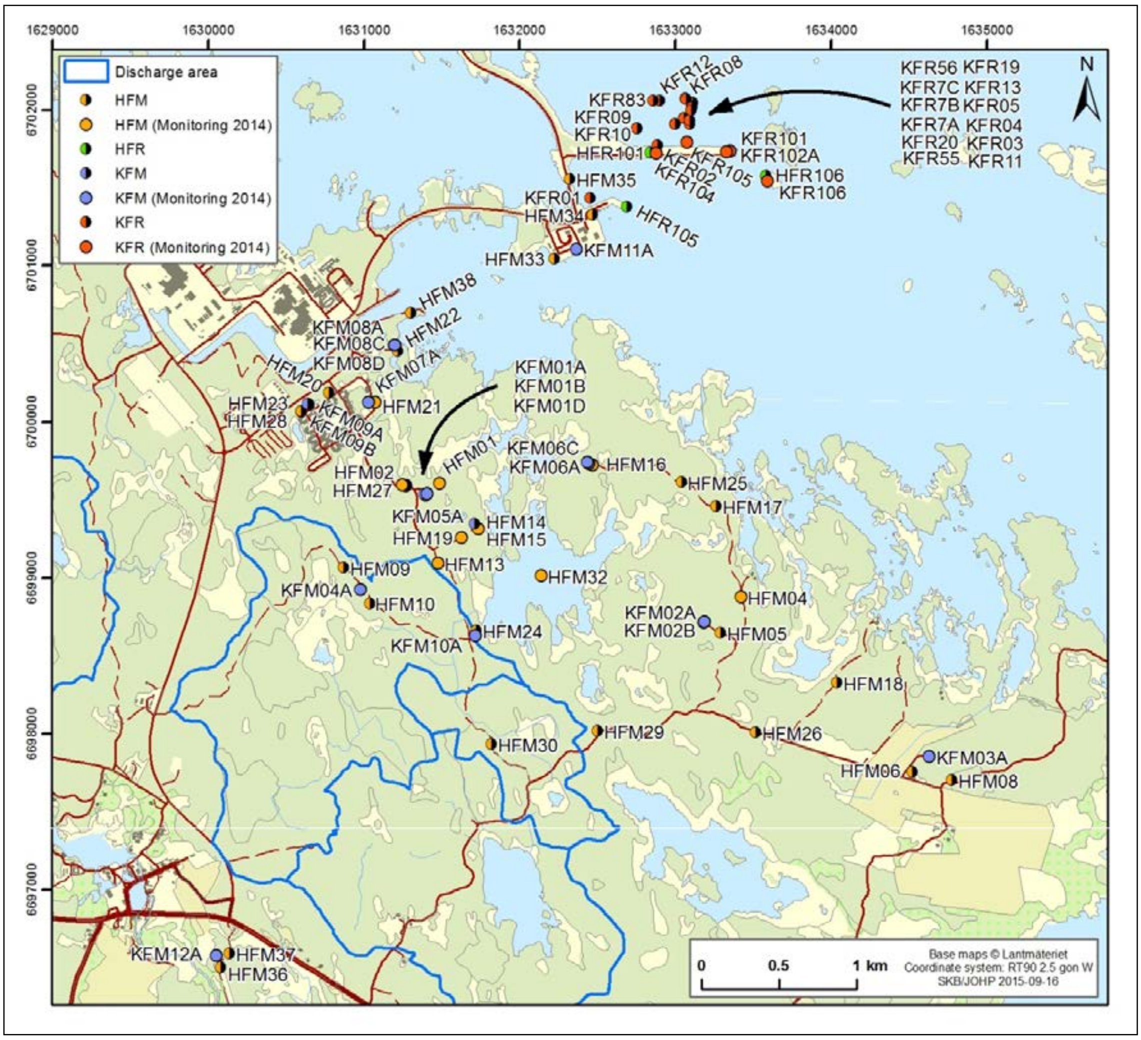

__Figure 6-33.__ Location of percussion-drilled and core-drilled boreholes within the SFR facility, the site investigation for the spent fuel repository and the SFR extension project. The full symbols represent boreholes that are included in the monitoring programme 2014 while the halved symbols are not included. HFM and HFR followed by an order number denote percussion-drilled boreholes in the Forsmark and the SFR sites, respectively, while KFM and KFR denote core-drilled boreholes.

Table 6-14. Overview of analysis extent per year at the Forsmark site (2002–2014): The leftmost columns give the number of samples per year and the sampled borehole section. The rightmost columns present the percentage of analyses per component group in relation to the total number of samples. The component groups are defined in Table 6-13. Only objects with time series of five samples or more have been included in the compilation. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

IDCODE	CorrSec*	CorrSECLOW** (m)	CorrSECUP** (m)	MonitProg***	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet1 (Al)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	HeavyIso1 (226Ra)	HeavyIso2 (234U)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	Oxygen (O2)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace1 (U)	Trace2 (Rb)
HFM01	b	200.2	31.93	n	4			4	2									10	80	100	90	50		60	40	100	20	40	70	70												30		30		
HFM01	2	45.5	33.5	y						2	2	2		6	6	3	3	24	100	100	100	13	75	75	13	92	79	13	50	50	13	13	13	100	8	8	8	25	33	29		13	75	13	13	13
HFM02	2	48	38	y				2	2	2	2	2		6	6	3	3	28	100	100	100	14	68	68	14	100	82	14	57	54	14	14	14	96	14	14	14	25	32	29		14	61	14	14	14
HFM04	2	65.9	57.9	y				2	2	2	2	2		6	6	3	3	28	100	100	100	18	68	68	14	100	82	14	57	54	14	14	14	96	14	14	14	25	32	29		14	68	14	18	14
HFM05	b	200.1	25	n	3	1	3	2										9	100	100	100	56		89	67	100	44	89	100	100												100		89		
HFM13	a	175.6	14.9	n		3	2											5	100	100	100	60		100	60	100		100	100	100												100		100		
HFM13	1	175.6	159	y				2	2	2	2	2		6	6	3	3	28	100	100	100	18	68	68	14	100	82	14	57	54	14	14	14	96	14	14	14	25	32	29		14	64	14	14	14
HFM14	a	150.5	0	n		3			6	3								12	100	100	92	25		50	8	100		25	33	33												25		25		
HFM15	1	99.5	85	y				2	2	2	2	2		6	6	3	3	28	100	100	100	14	68	68	14	96	79	14	57	54	14	14	14	96	14	14	14	25	32	29		14	68	14	14	14
HFM16	2	67	54	y					2	2	2	2		6	6	3	3	26	100	100	100	12	69	69	12	100	81	12	54	54	12	12	12	96	12	12	12	23	31	27		12	69	12	12	12
HFM19	1	185.2	168	y				2	2	2	2	2		6	6	3	3	28	100	100	100	18	68	64	14	100	82	14	57	54	14	14	14	96	14	14	14	25	32	29		14	68	14	14	14
HFM21	a	202	12.03	n			6											6	100	100	100	100	17	83	67	100	33	67	67	67												67		50		
HFM21	3	32	22	y						2	2	2		6	6	3	3	24	100	100	100	13	75	75	13	100	88	13	50	50	13	13	13	96	8	8	8	25	33	29		13	75	13	17	13
HFM22	a	221	12	n			2	2	2	1								7	100	100	71	57		100	71	100	29	86	86	86												86		86	29	
HFM24	a	151.35	0	n				1	4									5	100	100	100			100	20	100	20	20	40	40												20		20	20	
HFM27	2	58	46	y					2	2	2	2		6	6	3	3	26	100	100	100	12	69	69	12	100	81	12	54	50	12	12	12	100	12	12	12	23	31	27		12	69	12	15	12
HFM32	3	31	26	y					3	2	2	2		6	6	6	3	30	100	100	100	13	70	70	10	100	80	10	53	50	10	10	10	97	10	10	10	20	30	23		10	70	10	10	10
HFM33	a	140.2	0	n					5	3								8	100	100	100			63	25	100	13	25	38	38												25		25		
HFM36	a	152.55	0	n					3	2								5	100	100	100			100	40	100		40	60	60												40		40		
KFM01A	5	130	109	y				2	2	2	3	6	8	6	6	3	3	41	98	98	98	24	71	71	15	98	90	10	61	61	20	20	20	83	7	7	7	29	44	44		10	78	10	34	20
KFM01A	b	120.77	110.1	n		8												8	88	100	100		63		13	88	88	38	75	75						38	38	75				38	88	38	13	13
KFM01A	d	183.9	176.8	n		10												10	100	90	90	60	90		40	90	90	50	90	90						40	40	90	40	40	10	40	90	40	50	50
KFM01D	4	321	311	y						2	2	6	8	6	6	3		33	100	100	100	24	79	79	9	100	97	12	64	64	24	24	24	85	6	9	9	30	48	48		12	82	15	42	24
KFM01D	f	435.64	428.5	n					6									6	100	100	100	50	100	17	17	100	100	33	100	100	50	50	50		17	17	17	100	50	50	17	50	100	50	50	50
KFM01D	2	438	429	y						2	5	10	8	6	6	3		40	90	90	85	20	65	65	8	90	88	10	53	53	20	20	20	70	5	8	8	25	40	40		10	85	13	35	20
KFM01D	g	575.14	568	n					6									6	100	100	67	67	67	17		67	67	67	67	67	67	67	67		17	17	17	67	67	67	17	67	67	67	67	67
KFM02A	5	442	411	y				1	2	2	2	6	8	6	6	3	3	39	100	100	100	23	77	77	15	100	92	13	64	64	23	23	23	85	15	21	21	31	46	44		13	79	18	44	23
KFM02A	3	518	490	y				1	3	2	2	6	13	6	6	3	6	48	98	96	98	23	73	73	21	100	98	15	54	56	38	38	38	85	17	35	35	31	52	52		15	85	21	50	25
KFM02A	j	516.08	509	n		16												16	100	69	69		50		6	69	69	19	56	69					13			63			6	31	50	31	31	31
KFM02B	4	431	410	y						1	2	2		6	6	3	3	23	100	100	100	13	78	78	9	100	96	9	48	48	13	13	13	100	9	9	9	26	35	30		9	83	9	13	13

IDCODE	CorrSec*	CorrSECLOW** (m)	CorrSECUP** (m)	MonitProg***	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet1 (Al)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	HeavyIso1 (226Ra)	HeavyIso2 (234U)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	Oxygen (O2)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace1 (U)	Trace2 (Rb)
KFM02B	2	506	491	y						1	2	2		9	6	3	3	26	100	100	100	12	69	69	8	100	96	8	42	42	12	12	12	100	8	8	8	27	31	27		8	85	8	12	12
KFM03A	5	650	633.5	y				2	2	2	2	6	8	6	6		3	37	100	100	100	27	76	76	8	100	89	19	68	65	27	27	27	86	22	43	43	35	49	46		19	76	27	57	27
KFM03A	j	646.12	639	n			6											6	100	83	83		67			100	100	50	83	83								83			17	50	67	50	50	50
KFM03A	o	946.62	939.5	n			8											8	100	88	88	38	88			88	88	38	88	88					13	13	13	88			13	38	88	38	38	38
KFM03A	2	994.5	969	y				2	2	2	2	6	8	6	6	3	3	40	100	100	100	25	75	75	5	100	90	13	65	63	23	23	23	85	15	13	13	30	45	43		15	75	15	38	23
KFM03A	p	1001.19	980	n		8												8	100	100	100		100			100	100	13	100	100						38	25	100			13	38	100	38	38	38
KFM04A	4	245	230	y						2	2	2		6	6	3	3	24	100	100	100	13	75	75	13	96	83	13	50	50	13	13	13	100	8	8	8	25	33	29		13	75	13	13	13
KFM04A	c	237.64	230.5	n			7											7	100	86	86		57			86	86	29	86	86								86				29	86	29	29	
KFM05A	a	722.02	712.55	n			6											6	100	100	50	50	83	17		100	100								17			83			17		100		50	50
KFM06A	5	362	341	y					2	1	2	2		6	6	3	3	25	100	100	100	4	68	68	4	100	80	4	52	48	4	4	4	100	4			20	28	24		4	68	4	8	4
KFM06A	g	360.62	353.5	n				8										8	100	100	50	50	88		13	100	100	50	88	75					13	13	13	88			13	50	88	50	50	50
KFM06A	3	748	738	y					2		2	2	9	6	6	3	3	33	100	100	97	12	67	67	3	100	88	3	55	55	12	12	12	82	3			21	30	30		3	76	6	18	12
KFM06A	k	775.12	768	n			9											9	100	100	56	56	100		11	100	100	56	100	100						11	11	100			11	56	100	56		
KFM06C	5	540	531	y					1		2	2		6	6	3	3	23	100	100	100	4	70	70	4	100	87	4	30	30	4	4	4	100	4			22	30	26		4	74	4	4	4
KFM06C	3	666	647	y					1		2	2		6	6	3	2	22	100	100	100		64	64		100	77		27	9				86					23	18			64			
KFM07A	i	1001.55	848	n				10										10	100	100		50	100			100	100	50	100	80	10	10	10		10	10	10	100			10	50	100	50	50	50
KFM07A	j	972	962	n						2	1	5	5	3				16	94	100	100	50	100	100	25	100	100	31	75	75	50	50	50	50	19	19	19	38	75	75		31	100	38	81	50
KFM07A	2	972	963	y								1	3	3	6	3		16	100	100	100		63	63		100	94		50	50				100				6	25	25			63		6	
KFM08A	6	280	265	y							5	6		6	6	3	3	29	100	100	100	7	72	72	7	100	93	7	52	52	7	7	7	90				21	38	34		7	83	7	21	7
KFM08A	m	690.79	683.5	n				13										13	100	100	100	54	100	8		100	100	54	100	100	54	54	54		8	8	8	100	8	8	8	54	92	54	54	54
KFM08A	2	694	684	y							5	6	8	6	6	3	3	37	100	100	100	19	76	76	8	100	95	11	57	54	19	19	19	81	11	16	16	24	43	43		11	78	16	38	19
KFM08D	4	680	660	y							3	6	9	6	3			27	100	100	96	19	81	81	7	100	93	7	59	59	19	19	19	74		4	4	30	48	48		7	81	11	41	19
KFM08D	a	676.84	669.7	n						8						9		17	100	100	94	71	94	41	29	94	94	41	94	94	47	47	47		12	12	12	41	41	41	6	41	94	41	47	47
KFM08D	2	835	825	y							2	5						7	100	100	100	29	71	71	14	100	71	29	100	100	29	29	29	86	14	14	14	43	71	71		29	71	29	57	29
KFM08D	b	835.54	828.4	n						8								8	100	100	88	50	88	13		88	88	50	88	88	50	50	50		13	13	13	88	50	50	13	50	88	50	50	50
KFM09A	q	792.24	785.1	n					5									5	100	100	80	40	80			80	80	40	80	80	40	40	40					80	40	40	20	40	80	40	40	40
KFM10A	a	305.14	298	n					6									6	100	100	83	67	83	17		83	83	50	83	83	50	50	50		17	17	17	83	50	50	17	50	83	50	50	50
KFM10A	2	440	430	y						2	2	6	8	6	6	3	3	36	100	100	100	22	81	81	11	100	94	14	61	61	22	22	22	86	8	8	8	31	47	47		14	81	14	39	22
KFM10A	b	487.49	478	n					6									6	100	100	83	50	83	17	17	83	83	50	83	83	50	50	50		17	17	17	83	50	50	17	50	83	50	50	50
KFM11A	4	456	446	y						11	2	2		6	6	3	3	33	94	100	91	15	73	55	6	91	82	15	55	55	15	15	15	70	6	9	9	36	30	27	3	15	73	15	18	15
KFM11A	2	710	690	y						4	2	2		6	6	3	3	26	100	100	100	12	69	69	8	100	81	12	54	54	12	12	12	88	12	12	12	23	31	27		12	69	12	12	12
KFM12A	3	280	270	y							2	2		6	6	3	3	22	100	100	100	5	73	73	5	100	86	5	45	45	5	5	5	100	5	5	5	18	27	23		5	73	5	9	5

* Section number (from bottom).

** corrSECUP=upper section limit, corrSECLOW=lower section limit.

*** Included in the current monitoring programme (Y=yes, N=no).

Table 6-15. Overview of analysis extent per year in the SFR boreholes (1984–2014): The leftmost columns give the number of samples per year and sampled borehole section. The rightmost columns presents the percentage of analyses per component group in relation to the total number of samples, (see Table 6-13). The compilation includes objects with five samples or more. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

IDCODE	CorrSec*	CorrSECLOW** (m)	CorrSECUP** (m)	MonitProg***	1984	1985	1986	1987	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet1 (Al)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	HeavyIso1 (226Ra)	HeavyIso2 (234U)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace1 (U)	Trace2 (Rb)
KFR01	2	43.65	11	n	1	1						1		1					1						1				1	3				10	80	100	60		10			90	60		50	40				40				20				50			
KFR01	1	62.3	44.5	n	3	5	9	12	2	2	1	3	2	3	2	1	1	1	5	1	1	1	1	1	1	1	1	1	1	3	1	1		67	54	97	39	9	15	3	4	97	58	4	55	37	3	3	3	7	6	6	4	25	48	3	3	54	3	7	6
KFR02	4	80.24	43	n		3	1					1		1					1						1				1	3				12	100	100	58	8	17	8	8	92	58	8	42	33	8	8	8	33	8	8	8	25	50	17	8	67	8	8	8
KFR02	3	118	81	n		4	4					1		1					1						1				1					13	46	100	31	8	15	8	8	92	54	8	38	31	8	8	8	8	8	8	8	31	69	8	8	69	8	8	8
KFR02	2	136	119	n			1					1		1					1						1			1	1					7	100	100	71	14	29	14	14	86	29	14	71	57	14	14	14	14	14	14	14	43	29	14	14	29	14	14	14
KFR02	1	170.33	137	n			2					1		1					1						1				1	3				10	100	100	80	10	20	10	10	90	50	10	50	30	10	10	10	40		10	10	30	30	10	10	60	10	10	10
KFR03	4	44.16	5	n		1						1		1					1						1				1					6	100	100	50		17			83	50		83	67				17				17	17			33			
KFR03	3	56.16	45	n		1						1		1					1						1				1					6	100	100	50		17			83	50		83	67				17				17	17			33			
KFR03	2	80.16	57	n		1		2				1		1					1										1					7	100	100	57		14			86	43		57	29				14				43	43			57			
KFR03	a	101.6	81	n		1	1	1				1		1					1															6	100	100	33		17			83	33		50	33								33	50			50			
KFR04	3	43	28	n		1		2				1		1					1						1				1					8	88	100	63		13			88	38		63	38				13				38	38			50			
KFR04	2	83	44	n								1		1					1						1				1					5	100	100	60		20			80	40		100	80				20				20				40			
KFR04	a	100.5	84	n								1		1					1						1				1					5	100	100	60		20			80	40		100	80				20				20				40			
KFR08	3	35	6	n								1		1					1						1				1					5	80	100	60		20			80	40		100	80				20				20				40			
KFR08	2	62	36	n								1		1					1						1			1	1					6	83	100	67		17			83	33		83	67				17				17				33			
KFR08	1	104.4	62.95	n					2	2	1	3	2	3	2	1	1	2	2	1	1	1	1	1	1	1	1	2	3	3	1	1		39	85	95	41	5	13	10	5	95	64	5	85	59	5	5	5	10	3	5	5	8	5	5	5	21	5	10	5
KFR09	c	80.24	63	n			2	1				2	2	3	2	1	1	1																15	87	93	13					93	67		67	20								13	20			13			
KFR10	a	107.28	0	n															5	1	1	1	1	1	1	1	1	1	1	1	1	1		18	94	100	72	6	11	6	11	94	56	11	94	94	6	6	6	17	11	11	11	28	11	11	6	22	6	6	6
KFR10	b	107.28	87	n		1	20	1	2	2	1	1		1				2																31	65	94	26	10	10			90	52		39	26					3	3		26	65			71		3	
KFR101	1	341.76	279.5	y																							1	7	1		6	6	6	27	100	100	100	22	52	52	11	100	89	11	48	48	15	15	15	85	7	4	4	19	26	22	11	22	15	15	15
KFR102A	5	219	214	y																								5		1	6	6	6	24	100	100	100	25	63	63	8	100	100	8	50	46	8	8	8	100	4	4	4	25	33	29	8	63	13	8	8
KFR102A	2	443	423	y																								5		1	6	6	6	24	100	100	100	25	63	63	8	100	100	8	50	46	8	8	8	100	4	4	4	25	33	29	8	63	13	8	8
KFR104	1	454.57	333	y																										3	6	3	3	15	100	100	100	20	60	60		100	80		40	47				80					20	13					

IDCODE	CorrSec*	CorrSECLOW** (m)	CorrSECUP** (m)	MonitProg***	1984	1985	1986	1987	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total	Anions1 (pH)	Anions2a (Cl)	Anions2b_Br (Br)	Anions2b_I (I)	Carbon1 (DOC)	Carbon3 (TOC)	CarbonIso (14C)	Cations1 (Na)	Cations2 (Fe)	ChlorineIso (37Cl)	EnvironIso1 (2H)	EnvironIso2 (3H)	EnvironMet1 (Al)	EnvironMet2 (Zn)	EnvironMet3 (Ni)	FieldSonde1 (pH_field)	HeavyIso1 (226Ra)	HeavyIso2 (234U)	HeavyIso3 (230Th)	IronSpecies (Fe_tot)	Nutrient2 (PO4P)	Nutrient4 (NO23N)	StrontiumIso (87Sr)	Sulphide (S_2-)	SulphurIso (34S)	Trace1 (U)	Trace2 (Rb)
KFR105	b	134	120	n																								5						5	100	100	100	80	80	80	20	100	100	20	60	60	60	60	60		20	20	20	80	80	80	60	80	60	60	60
KFR105	1	306.81	265	y																								6	4		6	3	3	22	100	100	100	23	77	77	5	100	100	5	41	41	14	14	14	59	5	5	5	27	36	32	14	82	14	27	14
KFR106	2	259	143	y																								3			6	3	3	15	100	100	100	20	60	60		100	100		33	33				87		27	27		20	20				47	
KFR106	1	300.13	260	y																								3			6	3	3	15	100	100	100	20	60	60		100	100		33	33				87		27	20		20	20				47	
KFR11	d	98.07	56	n			11	1																										12	100	100	17	8	8			100	83		25									17	100			92			
KFR13	2	53	34	n								1		1					1						1				1					5	80	100	60		20			80	40		100	80				20				20	20	20		20			
KFR13	1	76.6	54	n								1		1					1						1				1					5	80	100	60		20			80	40		100	80				20				20	20	20		20			
KFR19	2	94.57	77	n								1		1					1						1				1					5	80	100	60		20			80	40		100	80				20				20				40			
KFR19	b	110.17	95	n										1					1										3					5	80	100	80	20	80	60	20	100	80	20	100	60	20	20	20		20	20	20	40	20	20	20	80	20	60	20
KFR55	4	21	8	n								1		1					1						1				1					5	80	100	60				20	80	40		100	80				20				20				20			
KFR55	3	39	22	n								1		1					1						1				1					5	80	100	60				20	80	40		100	80				20				20				20			
KFR56	1	81.73	9	n								1		1					1						1			1	1					6	83	100	67		17			83	33		83	67				17				17				33			
KFR7A	3	19	2	n								1		1					1						1				1					5	80	100	60		20			80	40		100	80				20				20				40			
KFR7A	1	74.7	48	n		4	10	5	2	2	1	3	2	2	2	1	1	1	5	1	1	1	1	1	1	1	1	2	3	3	1	1		59	88	97	39	8	17	7	5	97	68	3	66	46	3	3	3	7	7	7	5	19	36	3	3	47	3	10	5
KFR7B	a	7.6	4	n								1		1					1						1				1					5	80	100	60					60	20		100	80				20								20			
KFR7B	b	21.1	8	n			1	1				1		1					1						1				1					7	86	100	71	14	14			71	14		71	57				14				14	29			43			

* Section number (from bottom).

** corrSECUP=upper section limit, corrSECLOW=lower section limit.

*** Included in the current monitoring programme (Y=yes, N=no).

Table 6-16. Overview of analysis extent per year. The upper table denote the number of samples per year and component group (represented by a typical component). The lower table denote the percentage of analyses per component group in relation to the total number of samples. The component groups are defined in Table 6-13. The colour coding added to facilitate interpretations of major patterns ranges from green (many obs.) to red (few obs.), and from red (0 %) to blue (100 %).

compGrp	Typical MetaAbb	1984	1985	1986	1987	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Anions1	pH	1	17	48	23	4	8		34	8	20	8	4	4	3	44	4	20	102	90	81	171	97	86	178	146	219	235	139	116	1910
Anions2a	Cl	4	26	66	35	8	8		38	4	44	8	4	4	7	45	4	24	101	87	80	172	99	86	178	145	219	235	139	116	1986
Anions2a_I	I			4	9														43	52	56	46	41	35	73	44	3		13		419
Anions2b_Br	Br			17	31	4										41		18	101	74	60	163	90	86	178	142	219	235	139	116	1714
Anions2b_BrI	I			4	9														43	52	56	46	41	35	73	44	3		13		419
Anions2b_I	I			4	9														43	52	56	46	41	35	73	44	3		13		419
Carbon1	DOC			4	9											32			39	38	41	46	51	38	104	91	194	117	126	107	1037
Carbon3	TOC																	13	23	31	18	80	35	44	104	91	194	117	123	107	980
CarbonIso	14C															3		10	30	15	19	28	29	25	31	20			5	3	218
Cations1	Na	4	26	64	35	8	8	4	8	8	44	8	4	4	7	39	4	25	100	87	80	166	90	86	178	146	219	235	135	116	1938
Cations2	Fe	3	23	43		4	4		8	8	8	8	4	4	7	37	4		47	57	72	57	52	50	120	146	216	235	135	116	1468
ChlorineIso	37Cl															3		12	40	36	41	43	44	27	38	7			4		295
EnvironIso1	2H			16	3	4	8	4	43	8	44	8	4		5	42	4	16	75	58	69	120	80	69	155	113	73	81	54	39	1195
EnvironIso2	3H			1	4	4	8	4	43						2	41	4	16	77	58	66	110	80	69	155	108	70	79	54	40	1093
EnvironMet1	Al																			2	19	39	40	34	53	45			5	6	243
EnvironMet2	Zn																			2	19	39	40	34	53	45			5	6	243
EnvironMet3	Ni																			2	19	39	40	34	53	45			5	6	243
FieldSonde1	pH_field																				9	31	43	64	134	73	216	225	130	116	1041
HeavyIso1	226Ra				3											3			2	4	14	25	24	27	25	10			1		138
HeavyIso2	234U				3											3			11	4	14	22	25	26	26	25	4	6	5	4	178
HeavyIso3	230Th															3			10	4	14	22	25	26	26	25	4	5	5	4	173
IronSpecies	Fe_tot	1		18	33											39			41	41	41	45	51	39	66	40	63			31	549
Nutrient2	PO4P	3	25	65	34											7			4		12	36	40	40	104	56	64	39	43	40	612
Nutrient4	NO23N															5			4		12	36	40	40	102	56	64	39	42	12	452
Oxygen	O2																		5	6	3	5	3								22
StrontiumIso	87Sr																	8	45	37	41	44	44	27	53	8			4		311
Sulphide	S_2-	3	19	58	34											29			39	41	40	46	51	51	116	121	216	101	114	95	1174
SulphurIso	34S																	8	42	35	35	44	44	27	53	24	2		4		318
Trace1	U				3											3			17	13	30	44	42	34	97	83	4	23	9	5	407
Trace2	Rb															3			17	11	27	39	40	34	53	45			5		274
uranine	uranine																							72	169	100	198	231	131	116	1017
Anions1	pH	25	65	70	66	50	100		79	100	45	100	100	100	43	96	100	77	78	100	89	91	98	98	98	99	100	100	97	100	1910
Anions2a	Cl	100	100	96	100	100	100		88	50	100	100	100	100	100	98	100	92	77	97	88	92	100	98	98	99	100	100	97	100	1986
Anions2a_I	I			6	26														33	58	62	25	41	40	40	30	1		9		419
Anions2b_Br	Br			25	89	50										89		69	77	82	66	87	91	98	98	97	100	100	97	100	1714
Anions2b_BrI	I			6	26														33	58	62	25	41	40	40	30	1		9		419
Anions2b_I	I			6	26														33	58	62	25	41	40	40	30	1		9		419
Carbon1	DOC			6	26											70			30	42	45	25	52	43	57	62	89	50	88	92	1037
Carbon3	TOC																	50	18	34	20	43	35	50	57	62	89	50	86	92	980
CarbonIso	14C															7		38	23	17	21	15	29	28	17	14			3	3	218
Cations1	Na	100	100	93	100	100	100	100	19	100	100	100	100	100	100	85	100	96	76	97	88	89	91	98	98	99	100	100	94	100	1938
Cations2	Fe	75	88	62		50	50		19	100	18	100	100	100	100	80	100		36	63	79	30	53	57	66	99	99	100	94	100	1468
ChlorineIso	37Cl															7		46	31	40	45	23	44	31	21	5			3		295
EnvironIso1	2H			23	9	50	100	100	100	100	100	100	100		71	91	100	62	57	64	76	64	81	78	85	77	33	34	38	34	1195
EnvironIso2	3H			1	11	50	100	100	100						29	89	100	62	59	64	73	59	81	78	85	73	32	34	38	34	1093
EnvironMet1	Al																			2	21	21	40	39	29	31			3	5	243
EnvironMet2	Zn																			2	21	21	40	39	29	31			3	5	243
EnvironMet3	Ni																			2	21	21	40	39	29	31			3	5	243
FieldSonde1	pH_field																				10	17	43	73	74	50	99	96	91	100	1041
HeavyIso1	226Ra				9											7			2	4	15	13	24	31	14	7			1		138

compGrp	Typical MetaAbb	1984	1985	1986	1987	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
HeavyIso2	234U				9											7			8	4	15	12	25	30	14	17	2	3	3	3	178
HeavyIso3	230Th															7			8	4	15	12	25	30	14	17	2	2	3	3	173
IronSpecies	Fe_tot	25		26	94											85			31	46	45	24	52	44	36	27	29			27	549
Nutrient2	PO4P	75	96	94	97											15			3		13	19	40	45	57	38	29	17	30	34	612
Nutrient4	NO23N															11			3		13	19	40	45	56	38	29	17	29	10	452
Oxygen	O2																		4	7	3	3	3								22
StrontiumIso	87Sr																	31	34	41	45	24	44	31	29	5			3		311
Sulphide	S_2-	75	73	84	97											63			30	46	44	25	52	58	64	82	99	43	80	82	1174
SulphurIso	34S																	31	32	39	38	24	44	31	29	16	1		3		318
Trace1	U				9											7			13	14	33	24	42	39	53	56	2	10	6	4	407
Trace2	Rb															7			13	12	30	21	40	39	29	31			3		274
uranine	uranine																							82	93	68	90	98	92	100	1017

6.4.4 Conditions and aspects of importance when interpreting hydrochemical data from the bedrock

Identified practical problems and other conditions of varying importance that might have had an impact on the bedrock groundwater samples, analyses and measurements are described below.

The spatial representativity of the samples could be severely compromised due to specific hydraulic conditions in the sampled section and beyond.

- Hydraulic contact between sections in a borehole, or with another borehole (Figure 6-34) may affect the spatial representativity of the sample. Pressure responses indicate if there is deficient isolation by packers along the boreholes, or if the packers are short circuited by the rock fracture system itself. A delay between the impacting pressure signal and the response generally indicates hydraulic contact via the fracture system (e.g. KFM01D).
- Decreasing hydraulic pressure gradients, naturally or artificially created, for example due to the presence of a tunnel system in the vicinity of a sampled borehole, may have impact on the sample representativity. An example is borehole KFM11A that was drilled in the direction towards SFR (Figure 5-11). Large volumes of shallow water reached the bottom of the open borehole and intruded into the intersecting fracture systems along the borehole during and after the drilling. Therefore, the first chemical investigations and the subsequent hydrochemical monitoring period in isolated borehole sections show an ongoing slow recovery with a trend towards more saline conditions (Figure 6-37 at the top). In areas with vertical pressure gradients, the length of the time delay between drilling and chemical sampling is an especially important factor when assessing the representativity of groundwater samples. The problem could be serious if boreholes are kept open for a long time, with no packers separating different hydraulically conductive fractures. In a groundwater recharge area, large volumes of shallow water are likely to intrude along the boreholes to greater depths and penetrate into deeper fractures while the borehole is open. In such situations, it may be justified to question the representativity of the groundwater samples.
- The need to remove large volumes of water (purging) from the borehole section in order to prevent influence from stagnant water initially present in the borehole section, or in the standpipe, may affect a larger bedrock volume including several sources of groundwater from different water bodies. This may result in questionable representativity of the sampled water due to mixing which, in turn, may impact for example the sulphide concentrations.
- Sampling close in time to the drilling may result in groundwater samples still impacted from the drilling (flushing water in combination with the pressure impact during drilling).
- The lowering and raising of equipment in the two standpipes connected to each circulation section creates pressure differences and water movements that probably propagate down to the borehole section being sampled. The sounding of the groundwater level each month in the narrow standpipe for pressure measurements is a frequently repeated activity that in the long run may impact on conditions in the borehole section.

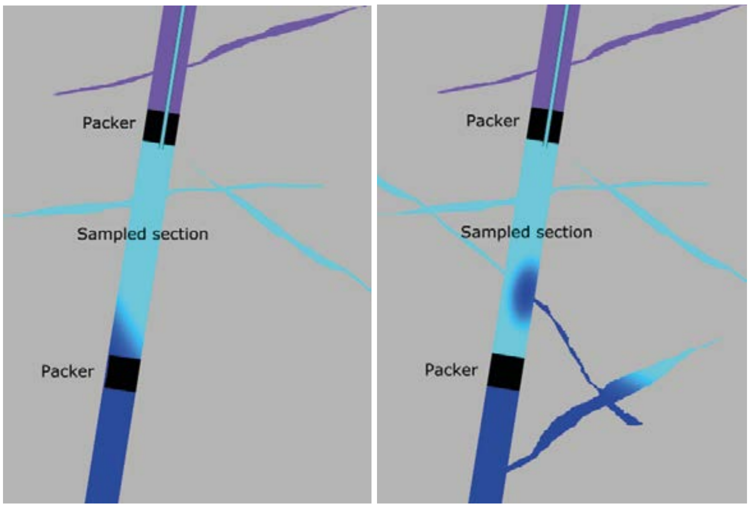

Figure 6-34. Illustration of how the hydraulic contact between different borehole sections may be due to insufficient (or deficient) isolation by the packers (left picture), or contact via the rock fracture system (right). In these examples groundwater from the deeper section (dark blue) reaches the sampled section (light blue) and the sample will be influenced by contaminated borehole section water (see text below) from another depth, meaning that the sample will not contain solely water from the bedrock formation adjacent to the borehole section as desired.

There are several sources for **contamination** of the groundwater samples. Several aspects of these sources are discussed below.

- The long contact time between the groundwater isolated in the section and the stationary/fixed borehole equipment may promote corrosion, contamination, microbial activity and enhanced sulphide production (Tullborg et al. 2010a, b). The equipment constitutes a complex system and the contribution from trapped stagnant water to the samples from the borehole section or from tubing may be difficult to avoid, despite long pumping periods and removal of large water volumes before sampling.
- Corrosion problems have been observed on equipment in boreholes and on equipment in standpipes connected to boreholes (Figure 6-35), see also Sections 4.3.2 and 5.7.6. This has impacted the hydrochemical data in different ways. Elevated pH values (as high as 11.5) have been measured in a few borehole sections. The elevated pH in turn, causes additional changes in the water composition. Hydrogen gas generation has also been observed (Nilsson and Sandberg 2017).
- The standpipes, the tubing connecting each standpipe to the corresponding borehole section, and probably also the sections themselves, contain after some time a turbid, smelling, stagnant water with a high microbe content and high TOC and sulphide concentrations (Nilsson et al. 2010a, Rosdahl et al. 2011), all of which may contaminate the samples. Remains from dead insects and vegetation and even mice are sometimes present on top of the packers sealing off the standpipes. It is not unreasonable to believe that some of these materials reach the water in the standpipes when the packers are released and lifted to the surface. Furthermore, transport of this material further down the borehole section by gravity is likely to occur. For the implications, see the next bullet.
- Contamination by organic compounds and other energy sources may increase the microbial activity in the groundwater. The occasionally high concentrations of sulphide observed probably reflect disturbed conditions in the circulation sections due to contamination by organic substances from the surface via the standpipe and the tubing and/or from the sampling equipment (Tullborg 2010a, Drake et al. 2014).
- A pump connected to a 50 µm filter must be lowered through the dirty water to the bottom of the standpipe in order to sample the connected borehole section (Figure 6-36). However, the pump is first rinsed with this water to avoid contamination from the previously sampled borehole. Therefore, during sampling, therefore, the filter will most probably catch solid dirt that may contaminate subsequently collected samples.

- In order to reduce the influence from stagnant section water, plug-flow calculations have been used since spring 2010 to estimate the water volumes to be exchanged prior to sampling. The previous procedure was to exchange 3 to 5 section volumes. The first plug-flow calculations in 2009 showed that these volumes, generally, are too small for most borehole sections (cf. Figure 6-31).
- Gas lift pumping with nitrogen gas is used for the sampling in sections where only pressure is measured (one line, circulation is not possible) (KFR101, KFR104, and KFR106). The sampling conditions created by such pumping are different from the conventional pumping generally used in the hydrogeochemical monitoring programme. The more effective (intermittent) pump action might affect the borehole walls (microbe coating, mineral particles etc.), and thus have an impact on the water composition (for example TOC, DOC and trace metals). Also the fact that nitrogen gas is used may be of importance. Especially, constituents such as hydrogen sulphide and radon may be affected.

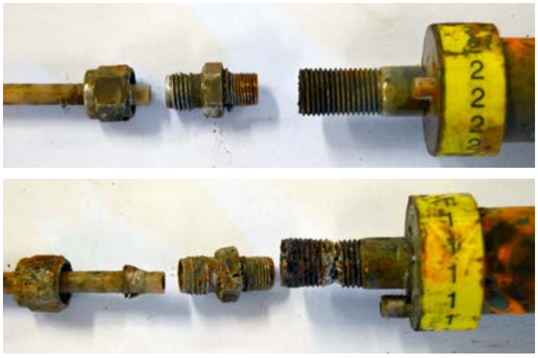

Figure 6-35. *Connections between tubing to the section and standpipe belonging to the raised equipment from KFM08D in Forsmark. Examples of corroded connections to the bottom section (1) and the next section from the bottom of the borehole (2). The corrosion is more severe on the connection to section no. 1.*

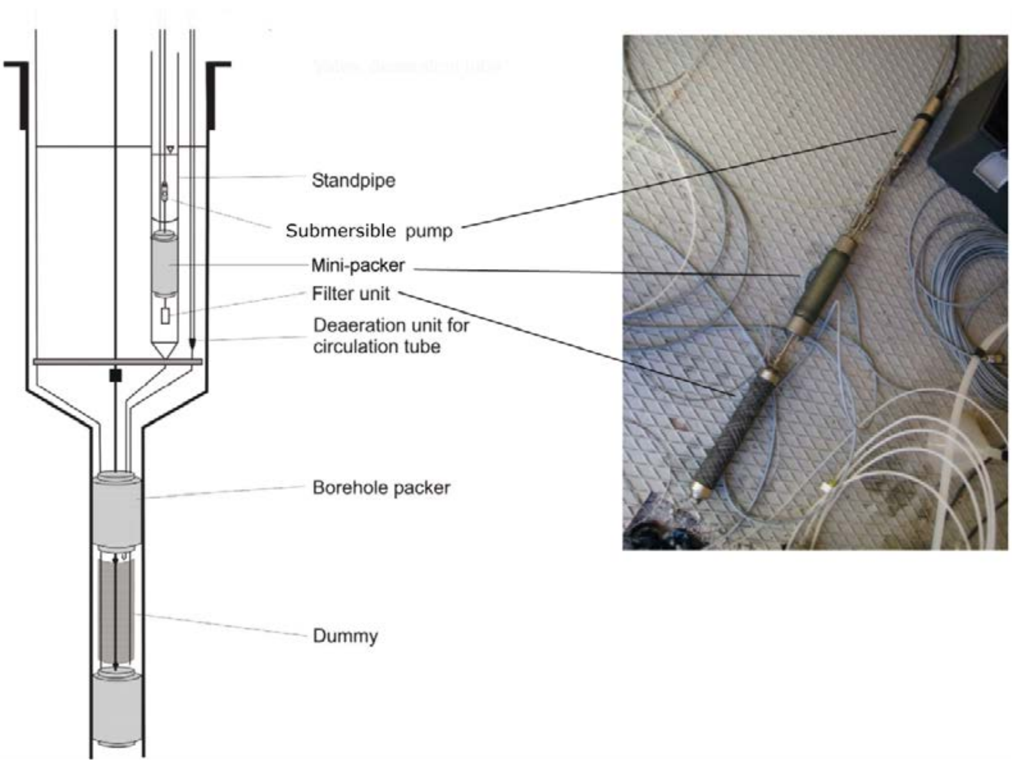

Figure 6-36. *Picture showing the filter, the inflatable mini packer and the submersible pump that is lowered into the standpipe for sampling of groundwater. The "Deaeration unit for circulation tube" connected to the borehole section is not used during the hydrochemical sampling. The circulation circuit is only used in groundwater flow tests when the dilution of an added tracer is monitored during circulation via the stand-pipe and this smaller tube.*

6.4.5 Statistical evaluation of hydrochemical data from the bedrock

This section summarises the results from the statistical evaluation of hydrochemical data for groundwater from percussion-drilled boreholes and core-drilled boreholes. The comprehensive statistical overviews of the data in Appendix 3 reflect different aspects of data quality, general patterns of variability, representativity of chemical data and long-term temporal changes with the main purpose of evaluating data quality and inconsistencies amongst sampled objects and analysed parameters. All data from SFR and the site investigation and the monitoring for the spent fuel repository are included in the statistical analysis.

In contrast to the analysis and modelling underpinning most site descriptive models, the current evaluation comprises all quality controlled data in Sicada, in order to objectively describe the total dataset rather than adding new interpretations of the data. Many of the findings from the statistical analysis are well known by modellers and personnel handling data and they are already described in the site description reports pertaining to the Forsmark area (Laaksoharju et al. 2008, Nilsson et al. 2011).). The purpose of this evaluation is, however, to systematically go through and compile the data in order to judge if the current monitoring programme is sufficient regarding sampling frequency, temporal and spatial representativity, and if it is suitable for answering the general questions at issue, see the introduction to Section 6.4.

The evaluation is based on five major data compilations briefly described in the list below. These compilations contribute to different complementary evaluations of the extensive (both concerning number of records/samples and measured parameters) hydrochemical dataset from the Forsmark area. The results from each of these analyses are summarised below and the tables are found in Appendix 3.

1. The total number of observations per parameter and object combination (sampling location).
2. The fraction of observations per parameter and object combination that fall below reporting limits.
3. The coefficient of variation (CV) for all parameter and object combinations. This compilation show the relative variance among parameters and objects, and this information could be used to identify objects with, for some reason, increased variation compared with other objects. For parameters or objects with high inherent variation, longer time series and/or more frequent sampling is needed in order to detect significant deviations. Low inherent variation could, conversely, imply the possibility of lower sampling frequency.
4. Normalised means based on all data from similar objects (percussion-drilled and core-drilled boreholes in bedrock). Independent of the absolute parameter values, this compilation shows where the mean values of individual objects are located on the total range for each parameter and all similar objects. This information could be used to identify specific objects with deviating chemistry and also to show common patterns among several parameters.
5. The results from a regression analysis with the purpose to identify time trends in the data. Significant trends over time could be an indication of methodological, climatic or anthropogenic factors that influence data over time.

Total number of observations (Appendix 3, Table A3-11): The overview of the total number of data for all parameters and groundwater objects during the period 1984–2014 reflects the changes of the monitoring and site characterisation programmes over time. Among the objects sampled (HFM and KFM boreholes), the total numbers of samples differ mainly depending on when the borehole was drilled. The boreholes KFM06A (sampling sections 3 and 5) and KFM06C (sections 3 and 5) deviate and have fewer data due to discarded sampling because of the occasionally high flushing-water content. Among the boreholes associated with SFR, KFR01, KFR08, KFR7A and to some extent also KFR10 stand out by showing a large number of samples due to yearly sampling in the monitoring programme that started in 1989. KFR09 was sampled instead of KFR10 by mistake during a four-year period (1992–1995) due to a mix up of valves at a control panel. Therefore, the number of samples from KFR10 is somewhat smaller. No data are available from 1993 (cf. Table 6-14).

The total number of data differs significantly among the parameters, due to changes in the hydrochemical characterisation and monitoring programmes over time. The major constituents (Na, K, Ca, Mg, Si, Li, Sr, Cl, SO_4, Br, HCO_3, pH) have been analysed at all sampling occasions. Environmental isotopes (^2H, ^3H and ^{18}O) and minor constituents such as Fe, Mn, TOC and sulphide are analysed only in the final sample in the sample series and thus have a lower frequency in the table. Most other isotopes and trace metals occur at even lower numbers due to the exclusion of these parameters from the monitoring programme after 2010 (cf. Table 6-10).

Analyses below reporting limits (Appendix 3, Table A3-12): If a large fraction of the analyses fall below the reporting limit, this could be an indication that the analytical method is inappropriate. No groundwater sampling locations stands out by showing an elevated proportion of analyses below reporting limits compared with the general pattern. On the other hand, there are large differences among the parameters, and in a few cases the majority of the analyses are below the reporting limits.

Only a minor fraction of the samples has ^3H activities below the reporting limit. Values below this limit are expected in undisturbed groundwater with a long residence time due to the short half- life of this isotope. There are a large number of samples with measurable tritium contents that are difficult to explain and different sources of contamination are considered.

Most analyses of trace metals (As, Cu, Cd, Hg, Pb, Sb, Th, and Zn) are below the reporting limits, and they were therefore excluded from the monitoring programme from 2010. Furthermore the few measurable values were probably due to contamination. The REEs (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and Hf, Sc, Zr and Tl also fall below the reporting limits in most cases. Among the most abundant REE elements, the first drilled boreholes differ with most analyses above the reporting limits, compared with the boreholes drilled later (KFM08-KF12), where almost all analyses are below reporting limits.

The subsurface boreholes drilled from SFR often show sulphide concentrations below the reporting limit. This is not the case for the boreholes drilled from the ground surface in the lens area. Generally, the sulphide concentrations increase in the water column in the borehole when boreholes ”become of age”. This is especially true for boreholes drilled from the surface, and it may be a consequence of the installed equipment and/or contamination from the surface via standpipes and tubing (cf. Section 6.4.4).

The concentrations of oxidised forms of nitrogen and phosphorus (NO_2, NO_3 and PO_4) are in most cases below reporting limits due to the prevailing reducing conditions in the groundwater; therefore it is difficult to measure these low levels of the oxidised forms in routine analyses. NH_4 is the most abundant nitrogen species.

Comparisons of variance (Appendix 3, Table A3-13): The coefficient of variation, which is defined as the ratio between the arithmetic standard deviation and the arithmetic mean, represents the relative variance among parameters and objects (CV is calculated for each object and parameter combination). This information can be used to identify objects and parameters with, for some reason, increased inherent variation.

From the CV analysis, it is concluded that many parameters show similar variance both among parameters and among objects. Some parameters deviate by showing significantly higher variance in almost all objects, whereas other parameters deviate in only a single object.

The major constituents show stable concentrations in most objects and have very low CV (e.g. Ca, Cl, Na, EC). For example, borehole HFM15 deviates from this pattern by showing a large variance for several marine ions (e.g. Br, Cl, Na, SO_4), which is mainly explained by a decreasing marine trend in this borehole. Na often shows lower variance than K and Li, due to different factors affecting the origin of these ions. HCO_3 (alkalinity) show larger variance than, for example, Cl in several objects, probably because of additional influence from other processes besides mixing.

Dissolved and total organic carbon (DOC, TOC) show significantly larger variation than most major constituents, even at great depths (e.g. KFM03A:2 at almost 1 000 m depth). Contamination by organic matter from the ground surface or leaching of the plastic material in the installed equipment are possible sources of dissolved carbon and may cause these variations. At the more shallow depths the DOC concentrations are often around 10 mg/L, whereas concentrations at depth are usually around 2 mg/L. For comparison, 1 000 L of water with an average DOC concentration of 2 mg/L contains 2 g carbon, which corresponds to the carbon contents of 5 000 ants, or 40 g of moist organic soil, or 4 mL of ethanol, or 2 cubic centimetres of HDPE.

The oxidised forms of nitrogen, NO_2 and NO_3, show very high variance compared to for example NH_4 and all other parameters. In this compilation, values below reporting limits have been excluded, which means that the CV could be even higher. The high variability probably reflects the influence from varying redox conditions, which in turn might be effects of disturbances during sampling. Redox sensitive parameters such as NH_4/NO_3, Fe, Mn and S^{2-} show generally high variance, indicating varying redox conditions during sampling. Mn and Fe show high variance, but not as high as NO_3. The variance of sulphide is very large since the concentration depends on the exchanged water volume prior to sampling and varying contributions from stagnant section water with high sulphide concentrations.

The general conclusion is that the CV shows consistent patterns for most parameters and objects, including the boreholes at SFR. Some parameters, for example the major constituents (e.g. Cl, Na and Ca) show consistently lower variance than for example the redox sensitive parameters (e.g. Mn, NO_3, and sulphide). The variance of organic carbon is relatively high indicating varying sources of carbon, probably due to contamination by carbon species in the standpipes housed in the wide part of boreholes and connected to each borehole section (see Section 6.4.4).

Comparisons among normalised means (Appendix 3, Table A3-14): The major purpose with the comparisons of normalised means is to relate the individual objects, for example the objects included in the current monitoring programme, to all data from similar objects in order to identify objects with generally deviating chemistry. This gives information on whether the selected sampling locations reflect the relevant spatial variation in the Forsmark area, and if there are previously sampled objects with deviating chemistry that are not included in the current monitoring programme.

The generally low values of the environmental isotopes ^{2}H and ^{18}O observed at SFR have almost no correspondence inland, except for borehole KFM12A at a depth of 300 m. These cold climate signatures are due to a large contribution of glacial melt-water to the groundwater in the low transmissive bedrock fractures. This is in contrast to the major deformation zones, which contain more of a younger Littorina-influenced groundwater. ^{3}H show higher values in the groundwater samples from the KFR boreholes than the KFM boreholes. This is due to generally shallower sampling locations in the SFR and gradual intrusion of modern sea water into the bedrock caused by drawdown.

Ca and Cl show the highest concentrations at depth in the deep saline groundwater. Concentrations of Mg and Mn are highly correlated especially among the KFM and HFM boreholes. This is due to two different causes that coincide. The concentration of Mg increases with the proportion of water of marine origin (present Baltic Sea or the Littorina Sea) in the groundwater while the concentration of Mn is higher under moderate reducing conditions than under strongly reducing ones. Most KFR boreholes show intermediate, to slightly elevated concentrations of Mg and Mn within the context of the Forsmark range, with the exception of borehole KFR07A with significantly enhanced concentrations at relatively shallow depth (< 100 m) due to the strong Littorina signature.

The highest concentrations of DOC and HCO_3^- are observed in a number of percussion-drilled boreholes (HFM) at relatively shallow depths, where the meteoric contribution to the groundwater is more pronounced.

Deviating pH values are observed in the boreholes KFM07A, KFM08A and KFM08D at approximately 600 to 800 m depth. Elevated pH could be an effect of corrosion on equipment in the borehole (cf. Section 6.4.4).

In borehole KFM01D at approximately 400 m depth, the sulphide concentrations show a significant spread between the samples in the same sample series collected during continuous purging as well as between different sampling occasions. The concentrations are elevated compared with all other groundwater sampling locations. This object also shows deviating and high concentrations of Si and REE, high values of ^{34}S and low values of ^{13}C. The total concentration of SO_4 is relatively low in the context of the Forsmark groundwater range. Pressure responses indicate that contributions from water from other borehole sections in the same borehole cause contamination. The rather stagnant water present in boreholes has generally high sulphide concentrations and usually the composition differs also in other aspects (cf. Tullborg et al. 2010a, Drake et al. 2014).

The uranium concentrations are unusually high in boreholes KFM02A and KFM06C at approximately 500 m depth. This is also the case in borehole KFR101 at 300 m depth. The concentrations are higher than expected under reducing conditions and this is being further investigated within an ongoing project dealing with "Uranium and redox conditions in Forsmark".

The general conclusion from the evaluation of normalised means is that the groundwater sampling locations included in the current monitoring programme are representative for most parameters and for the whole range of groundwater data from the Forsmark area. This conclusion is based on the fact that the range of the monitored objects covers the whole range for all investigated objects and most parameters.

There is a general difference between the observations at SFR facility compared with HFM and KFM boreholes further inland, in the respect that the former show significantly fewer extreme values. The groundwaters in the SFR dataset represent a relatively limited salinity range, whereas $\delta^{18}O$ values show a wide variation similar to that reported from the inland boreholes and marine indicators such as Mg/Cl, K/Cl and Br/Cl also show relatively large variations considering the limited salinity range. This last situation is reflected in the larger variance of Mg, K and Br compared to Cl since the groundwaters at the SFR are less influenced by meteoric water and deep saline groundwater. A number of objects show deviating chemistry compared to the Forsmark range, for example regarding pH, S^{2-} and U. These objects are subjected to special investigations.

Evaluation of time series (cf. Appendix 3, Table A3-15): The evaluation of time series by a linear, parametric regression analysis is a screening method with the purpose to find trends in data not explained by chance. It is expected that most of the time series show no trends if they reflect baselines at undisturbed conditions. This, since superimposed effects of yearly (seasonal) and especially diurnal variations in the meteorological/hydrogeological situation is believed to be of minor importance at the relevant sampling depths in the bedrock boreholes. On the contrary, a significant trend or variation could be an indication of such effects, disturbed conditions or methodological bias. As this analysis catches stepwise shifts, gradual trends and influences from individual outliers, the results must be checked by time-series plots. It should also be kept in mind that an evaluation of a large number of relationships implies that a portion of these are falsely recognised as significant. The regression analysis has been applied to all time series comprising of at least 10 observations ranging over a time period of four years, or longer. The statistics given in Table A3-15 in Appendix 3, represent the probabilities for the hypothesis that there is no time-trend in data, i.e. values between –0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign of the probabilities represent the direction of the trends based on the sign of the correlation coefficients.

Several major constituents, e.g. Ca, Cl, Conductivity, Na and Sr, show significant increasing and decreasing trends. These trends usually represent a gradual return from disturbed to primordial conditions. Many of these time-series show gradual increments in Cl concentration over the whole period according to the examples of Cl in the upper panel of Figure 6-37. These trends indicate that slow mixing processes change the composition of the groundwater over time towards a more mixed composition and the occurrence of groundwaters of clearly non-marine or marine origins decrease.

A special case is borehole KFM08A, in which the groundwater is changing character from saline non-marine towards more diluted water with a strong glacial signature similar to some of the groundwaters in the SFR boreholes and in borehole KFM12A. In the longer time series from SFR, the lower panel in Figure 6-37, the trends are scattered but usually slightly increasing, except for boreholes with very saline signatures like KFR01 and KFR7A. These show clear decreasing trends due to increasing contribution of young meteoric or marine water with a lower salinity than the initial Littorina type groundwater.

The organic carbon (DOC, TOC) shows predominantly decreasing trends in the cored boreholes, and both increasing and decreasing trends among the percussion drilled boreholes. According to Figure 6-38, the decreasing trends are mainly explained by deviating initial conditions, after which the concentrations stabilise around 2010 due to new routines for exchange of water prior to sampling. In the percussion drilled boreholes on the other hand, DOC contents tend to increase gradually, which might be explained by ongoing contamination by naturally occurring organic matter.

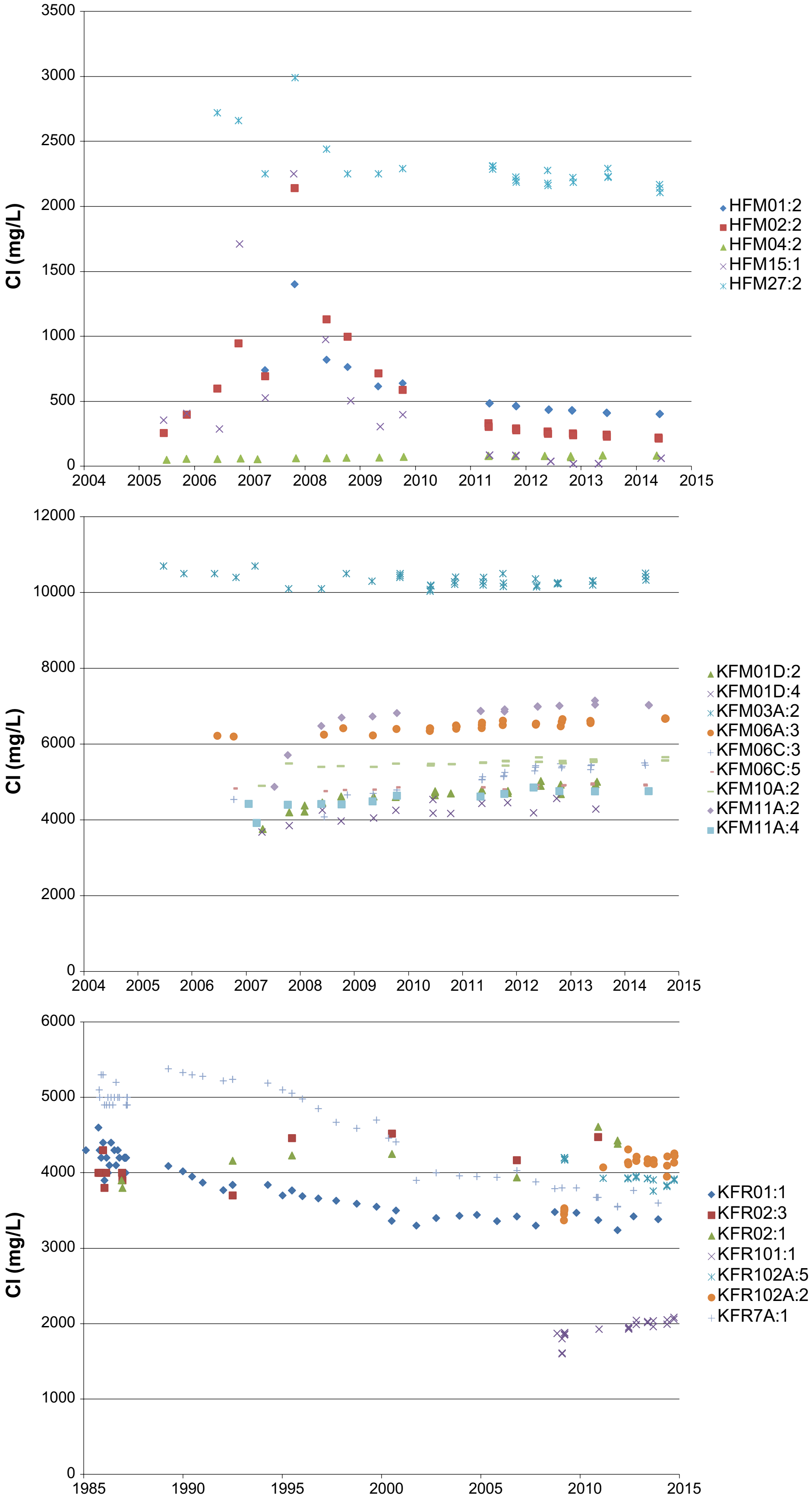

Figure 6-37. *Examples of time series for Cl that show statistically significant time trends ($p < 0.05$). These trends may reflect the return to primordial conditions (top) or influence from modern meteoric or sea water (bottom). The intrusion of shallower water (KFM11A, middle) or the use of flushing water during drilling have most probably influenced the early samples in the top diagram.*

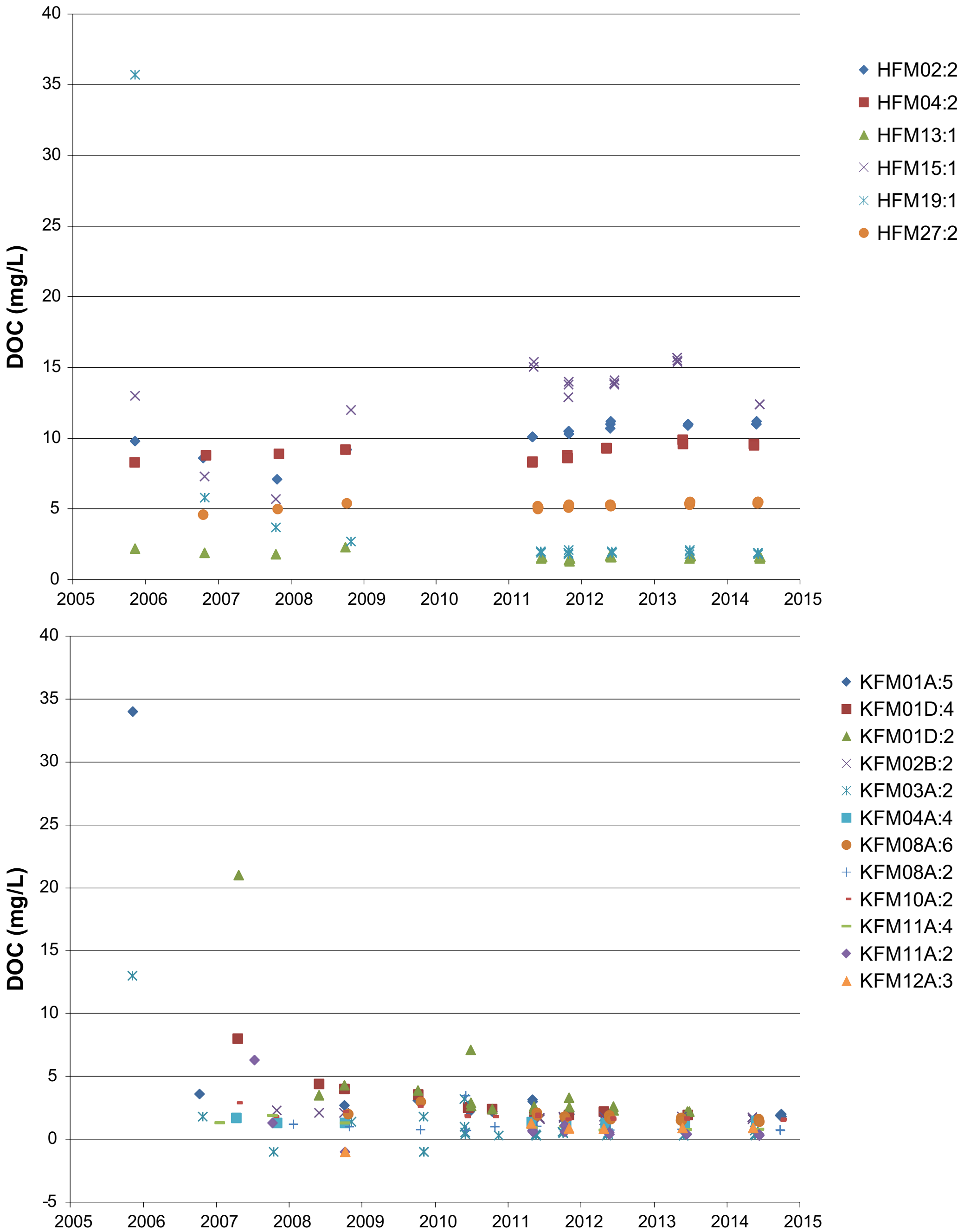

Figure 6-38. *Examples of time series for DOC that show statistically significant ($p < 0.05$) time trends. These time trends could reflect real trends or artefacts due to methodological reasons.*

The pH values generally show somewhat increasing trends. According to the time series in Figure 6-39, many of these trends might be explained by a stepwise increase around 2010, and it is probable that this increase has a methodological basis. Corrosion processes in the borehole could also contribute to increasing pH. In contrast to the pH trend, HCO_3^- decreases over time in most boreholes.

The variability of the time series for S^{2-} in Figure 6-40 decreases around 2010, when a new routine for exchange of water prior to sampling was introduced. However, the borehole that shows the highest sulphide contents, KFM01D:2, showed similar S^{2-} concentrations after the new sampling routine was applied due to leakage and contamination of water from other sections of the borehole i.e. the samples do not represent formation groundwater directly from the fracture system.

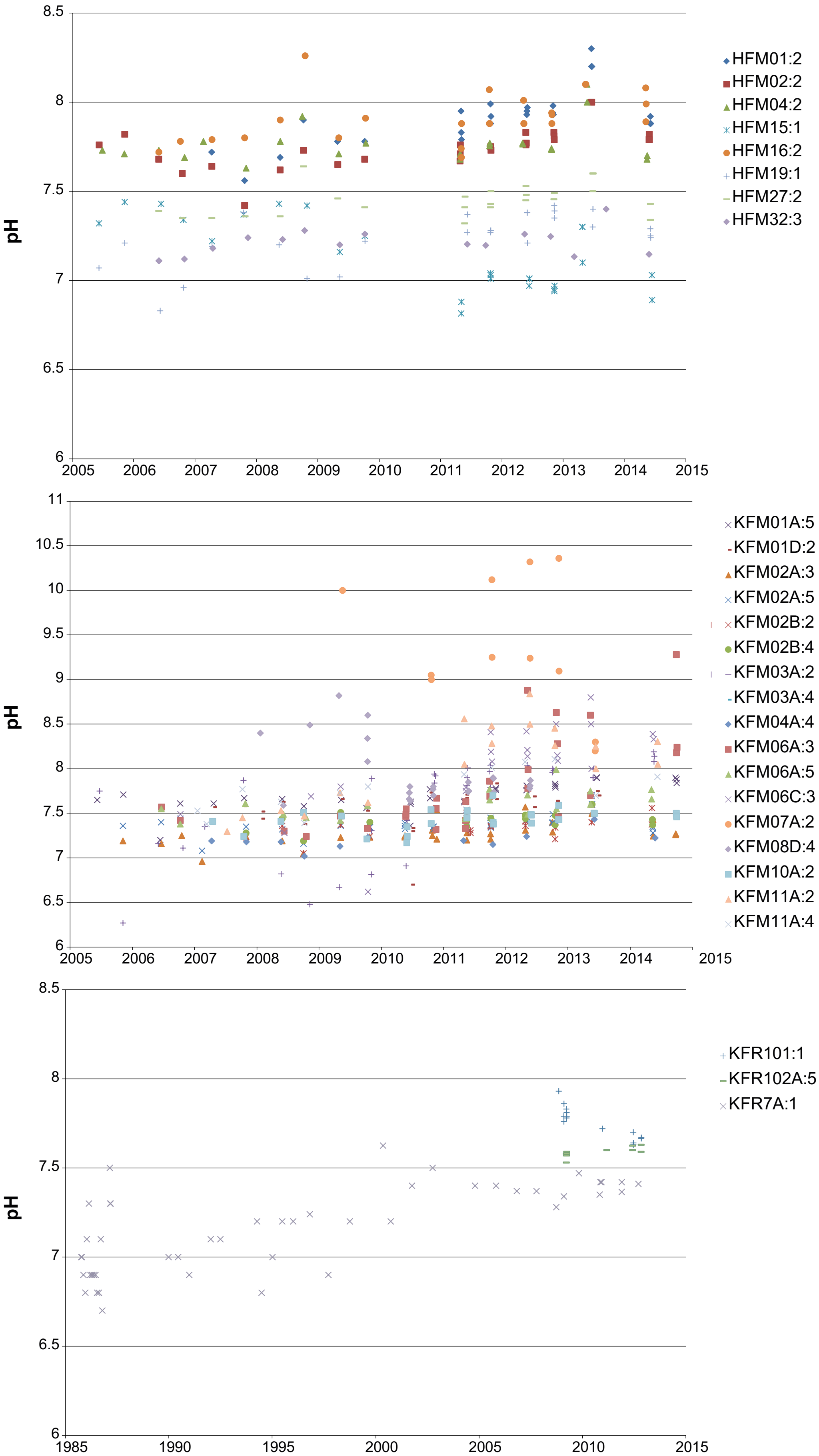

Figure 6-39. Examples of time series for pH (lab) that show statistically significant ($p < 0.05$) trends. These time trends could reflect real trends or artefacts due to methodological reasons.

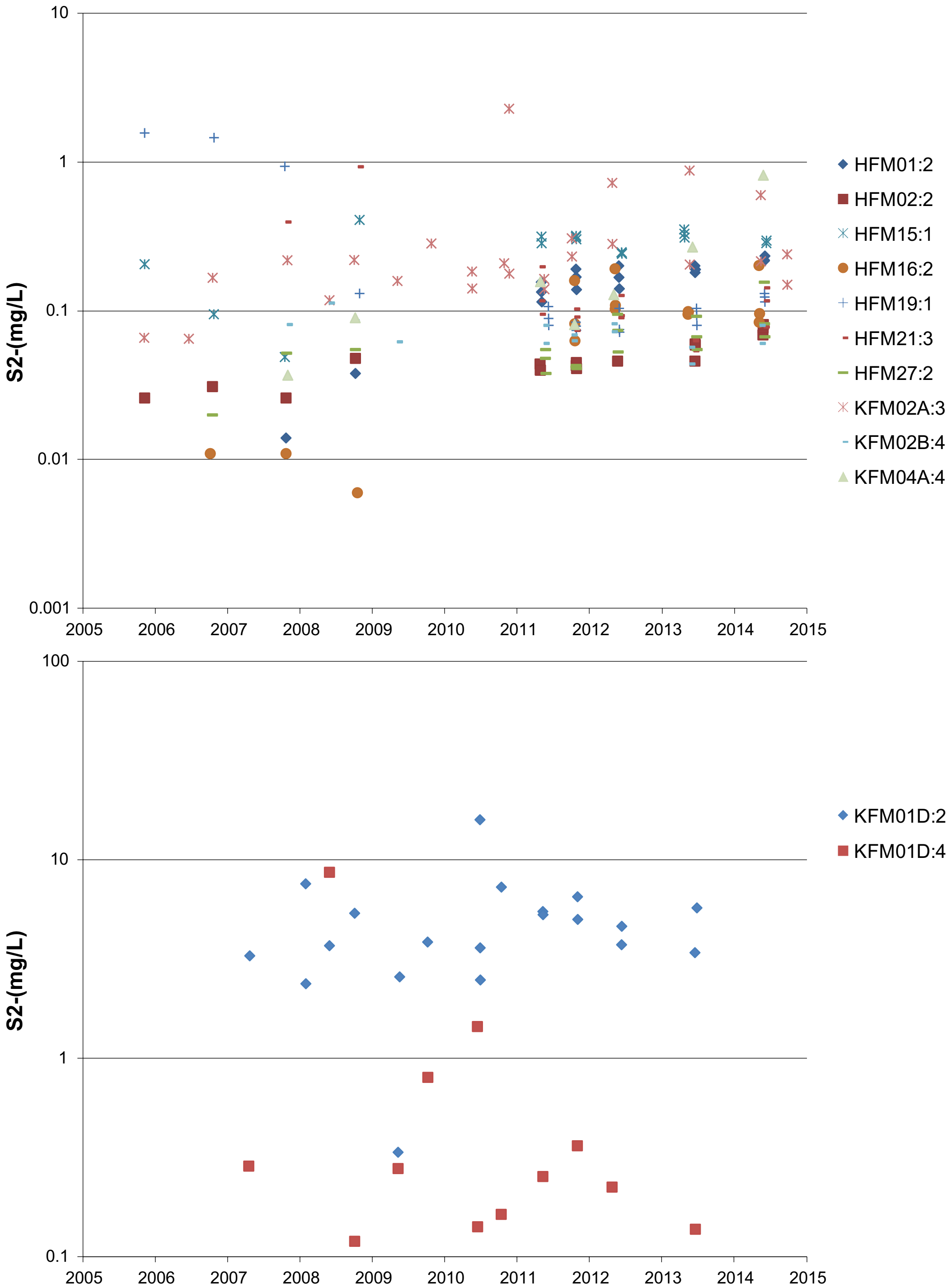

Figure 6-40. *The upper panel shows examples of time series for sulphide that show statistically significant trends ($p < 0.05$). Note that these trends could reflect either methodological changes or real trends. More stable values occur from 2011 after introduction of plug flow volume exchange/purging before sampling. The lower panel shows time series for the borehole KFM01D, where high sulphide concentrations have been observed.*

According to the regression analysis, a few time series of tritium (^3H) show decreasing trends. However, borehole HFM15:1 shows an increasing trend. All time series with significantly decreasing trends descend with similar slopes that could be explained by radioactive decay (half-life 12.3 years) of the radionuclide (Figure 6-41).

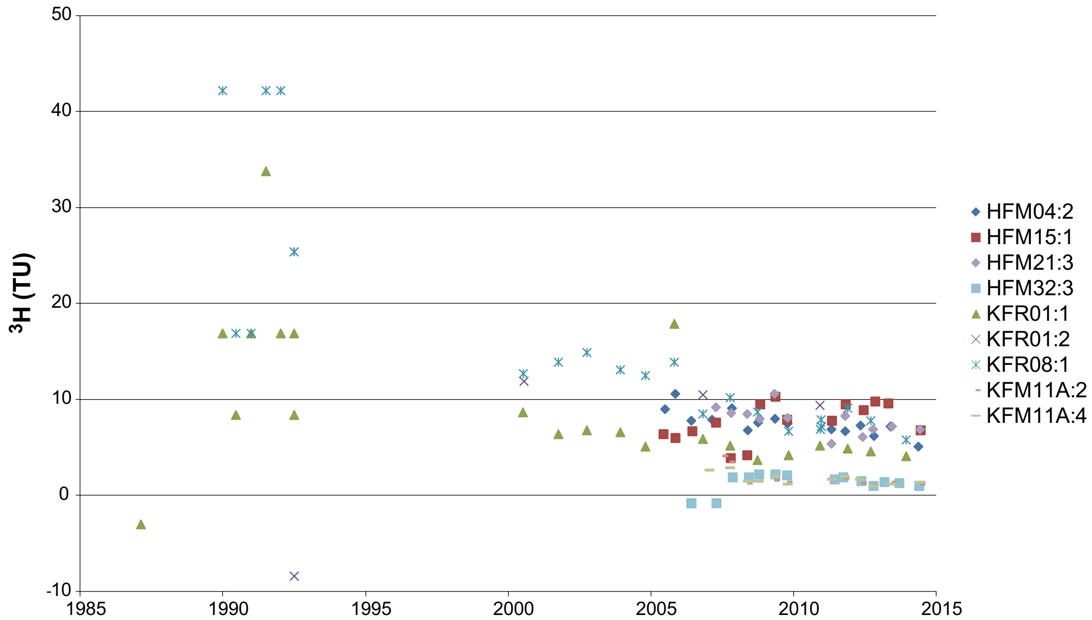

Figure 6-41. *Examples of time series for ^3H that show statistically significant trends ($p < 0.05$).*

The general conclusion from the regression analysis and the examination of the underlying time trends is that most of the apparent trends could be explained as methodological artefacts, e.g. DOC and pH. Tritium, however, shows decreasing trends that are readily explained by radioactive decay. The concentrations of several major constituents, for example Cl, seem to gradually increase over the period in many objects, which might be an indication of a gradual return to primordial conditions. This is especially true for KFM11A, in which both borehole sections were contaminated by shallow water prior to packer installations due to a decreasing hydraulic pressure gradient created by the presence of the SFR tunnel system. The implication for the future monitoring of bedrock groundwater is the insight that at all present sampling locations are necessary in the programme and that long time series are important in order to reveal temporary trends and recurrent variation patterns in order to secure a relevant base-line level.

6.4.6 Reference data

There are few relevant regional reference data available for the sectioned boreholes. The previous SKB investigations at the study site Finnsjön west of Forsmark might be useful, but this monitoring has ceased and the available time-series are short. Within the investigated Forsmark area, some of the currently monitored boreholes/borehole sections will most probably not be influenced by the construction and operation of the two repositories. These locations are suitable as reference objects and are presented in Section 8.3.4.

Regional groundwater data from private wells are available in the national SGU database (SGU n d, b). These data have good spatial coverage, but no time-series are available. The representative vertical depth is also unclear in these open boreholes, although the total drilled depth is usually recorded in the database. These data are probably of minor value for comparisons with the sectioned deep boreholes in the Forsmark area. An example from this database is shown in Figure 6-42 where chloride concentrations in private wells are shown for northeastern Uppland. The scatter of chloride concentration values in this region mostly reflects the variation in representative depth and other well specific factors, rather than the regional pattern in chloride abundance.

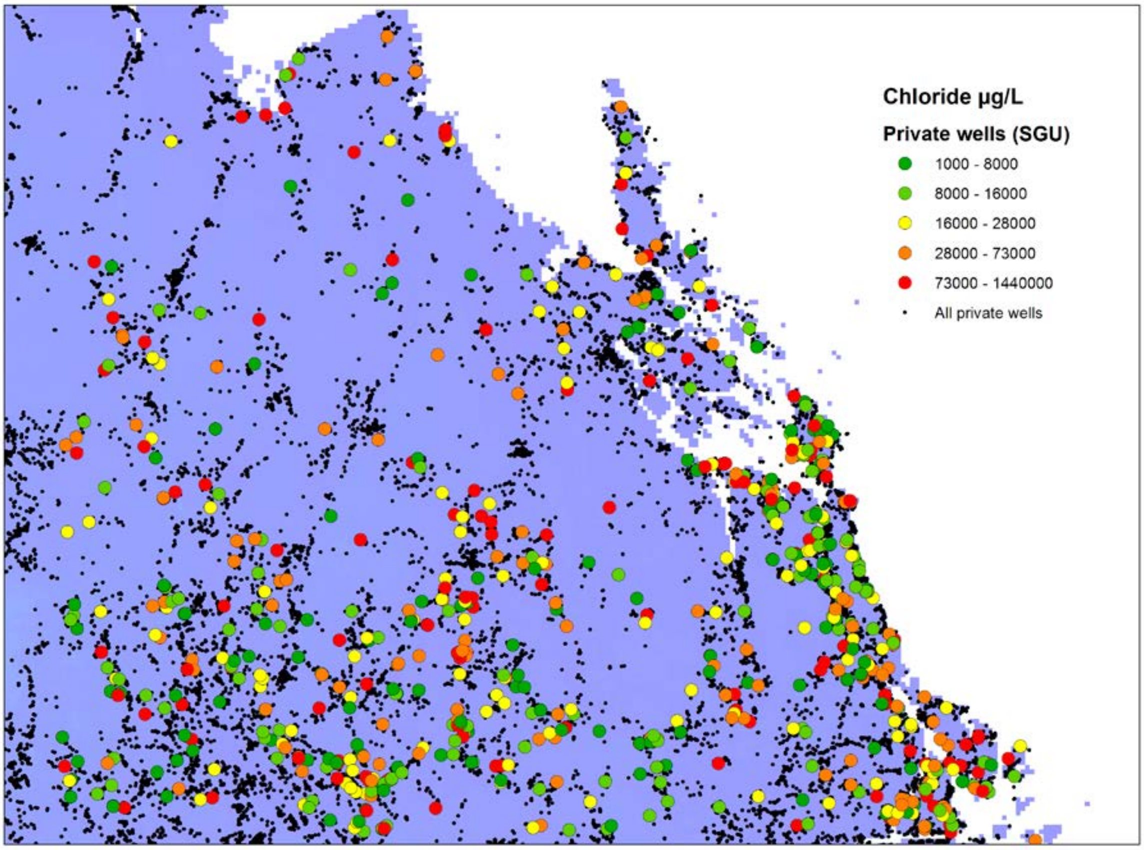

Figure 6-42. *Chloride concentrations (µg/L) in private drilled wells from the SGU national database (SGU n d, b). The private wells usually represent depths in the range of 50 to 200 meters.*

6.5 Routines for data handling and quality control

The routines for handling of hydrochemical data are the same independent of type of sampling object (e.g. surface waters, near-surface groundwater or bedrock groundwater). The samples are analysed by SKB's laboratories at Forsmark and Äspö, and by different external laboratories in Sweden and abroad, depending on the required analyses. The analytical protocol and the laboratories involved are stated in an Activity Plan for the monitoring activity in question (cf. references to the most recent activity plans in Tables 6-1, 6-6 and 6-11).

The laboratories report the results in their own formats as pdf files, in paper reports sent by regular mail or as Excel spread sheets. The received results are then transferred manually into a special Excel sheet, formatted to facilitate the import to the different data tables in Sicada. This is not an ideal procedure, since it is time consuming and a possible source of manual errors. Therefore, this transfer of data from laboratory reports to the Sicada import sheets is being reviewed in an ongoing project in order to improve the procedure and minimise the possibilities to make mistakes.

Each water sample corresponds to several records/rows in this Excel data sheet, one record/row for each laboratory. Some components may have data from more than one laboratory, resulting in the full data entry divided into several rows. A first evaluation of the data to obtain one value for each analysed component and marking of erroneous values is performed at this stage before the import to the database. The selected data for each sample is marked with "Y" and the rejected values are marked with "N" in special columns. The charge imbalance is then calculated for the selected set of concentration values. This error estimation provides an indication of the quality and uncertainty of the analyses of major constituents. In general, an error of ± 5 % is accepted. A larger error, up to ± 10 %, might be accepted if the chloride concentration is lower than 60 mg/L. The Excel sheets are imported to Sicada by database administrators and also the rejected results are stored with a comment as to why they have been rejected. Data deliveries from Sicada to different users, on the other hand, will only contain the selected values that are marked with "Y" if not otherwise requested. Only data marked with "Y" are evaluated in this report.

In summary, the chemical data (analytical results and field-measured values) from different sources are checked in several steps before they are used in interpretations and modelling work. The first screening at the investigation site is important since it is conducted close in time to the sampling and analyses by personnel familiar with the sampling and analytical performance. This screening involves charge-balance calculations, simple consistency checks and judgments based on experience and previous results. In the case of questionable data, there is still the possibility of repeating analyses at this stage.

A further check is performed when the data are entered into Sicada, mainly to confirm correct entries by signing the quality check for each sample record. Further control is added by plotting large amounts of data in x-y scatter plots to check for trends and outliers when the data reports are compiled. The final data quality assessment with respect to analytical performance/quality and sample representativity will be performed within the explorative analyses in connection to the hydrochemical modelling work (e.g. Laaksoharju et al. 2008). In the case of erroneous data at this stage, modellers report comments back to Sicada for further evaluation and correction (data error function). The documentation and data handling process prior to storage in Sicada is summarised in Figure 6-43.

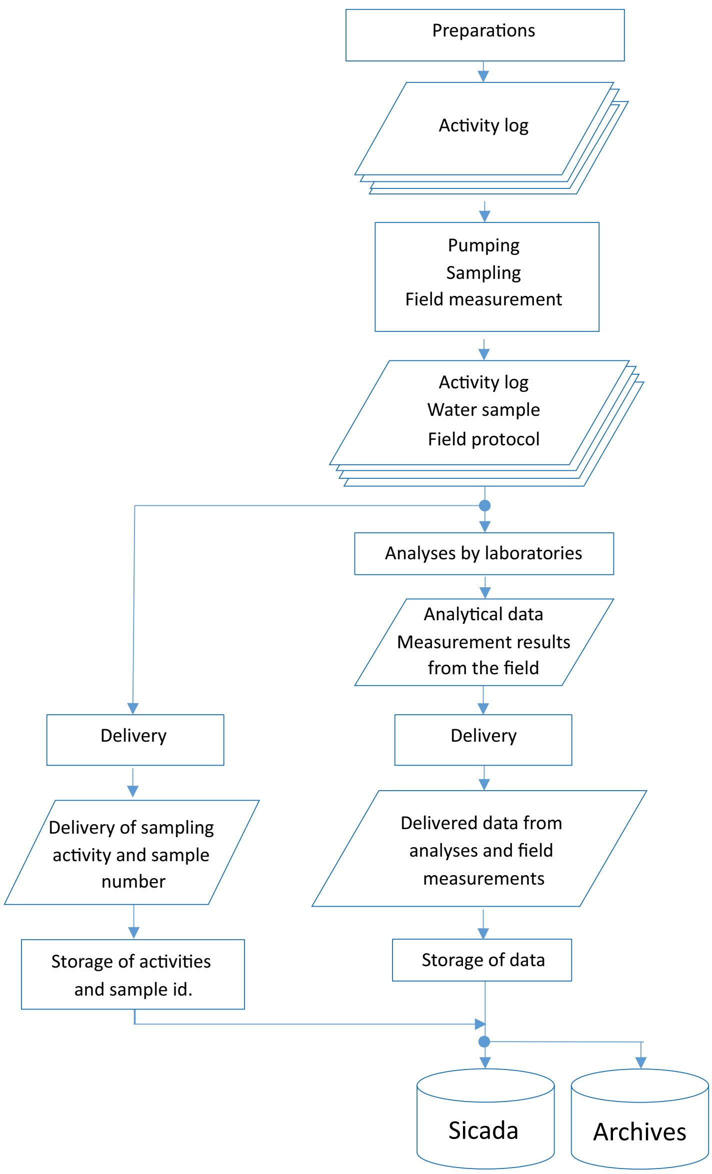

Figure 6-43. *Flow chart describing the documentation and data-handling process from sampling to data storage in Sicada.*

7 Monitoring of ecology and nature values

7.1 The present monitoring programme

Several of the present monitoring activities that are coordinated by SKB at Forsmark were initiated in 2002 as a part of the site investigation related to the siting of a repository for spent nuclear fuel (Table 7-1). The aims at that time were to increase the knowledge of the site and also to be able to detect whether the forthcoming increased activity at the site would affect the environment.

Table 7-1. Overview of the present ecological monitoring activities in the Forsmark area. Activities not coordinated by SKB and where data can be accessed from an external source are marked with an asterisk. The second column describes the target species or functional group, the third when the monitoring activity started. The fourth column describes the number of objects monitored (if applicable). The fifth column shows the number of years monitored through 2015 and the sixth column shows at what interval the monitoring has been performed so far. The last column shows recent references in which further information can be found. "na" means "not applicable". Regarding wildlife monitoring (the first activity in the table), it may be noted that a fifth inventory was performed during 2016; it is reported in Truvé et al. (2016), but not further discussed in the present report.

Activity	Target species/ functional group	Start	Number of monitored objects	Number of monitored years (through 2015)	Frequency	Recent references
Wildlife monitoring	Large mammals	2002	na	4	Every 5th year	P-12-20 (Truvé 2012)
Hunting statistics	Moose	2002	na	14	Annually	P-12-16, P-12-17 (Cederlund et al. 2012a, b)
General bird monitoring	Breeding birds	2002	na	5	Every 3rd year	R-14-16 (Green 2014)
Threatened bird species	11 species	2002	na	12–14	Annually	R-14-16, P-16-04 (Green 2014, 2016)
Aquatic birds*	7 species	2002	7	14	Every second month	Adill et al. 2014, 2016, Adill and Heimbrand 2015
Threatened plant species	Fen orchid	2012		4	Annually	P-14-02, P-15-02, P-16-01 (Collinder 2014, 2015, Collinder and Zachariassen 2016)
Reptiles and amphibians	Pool frog, great crested newt and common newt	2011–13	15	3–5	Annually	P-14-02, P-15-02, P-16-01 (Collinder 2014, 2015, Collinder and Zachariassen 2016)
Artificial ponds	Chlorophyll, turbidity	2012	4	4	Monthly	P-14-01, SKBdoc 1422519 (Qvarfordt et al. 2014a, Wallin et al. 2017)
	Vegetation and invertebrate fauna	2012	2	4	Annually	P-14-03, R-15-07, R-16-03 (Qvarfordt et al. 2014b, 2015, Wallin et al. 2016b)
Ponds	Chlorophyll, turbidity	2010	4	4	Annually	P-14-01, SKBdoc 1422519 (Qvarfordt et al. 2014a, Wallin et al. 2017)
	Vegetation and invertebrate fauna	2012	2	4	Annually	P-14-03, R-15-07, R-16-03 (Qvarfordt et al. 2014b, 2015, Wallin et al. 2016b)
Lake	Chlorophyll, turbidity	2002	4	14	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)
	Fish	1991, 2001, 2004	2	3	na	P-04-06 (Borgiel 2004a)
Sea	Chlorophyll, turbidity	2002	3	14	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)
	Macrofauna*	1985	2 + 4 (ref. area)	31	Annually	Adill et al. 2014, 2016, Adill and Heimbrand 2015
	Fish*	2003	1 + 1 (ref. area)	13	Annually	Adill et al. 2014, 2016, Adill and Heimbrand 2015
Stream	Chlorophyll	2005	4	11	Monthly – 4/year	P-10-40, SKBdoc 1459924 (Nilsson et al. 2010a, Wallin et al. 2016a)

Since then further needs have been identified, such as increasing the knowledge of habitats that potentially may be affected by the construction and operation of repositories at the site. The different activities are presented according to their spatial extent and habitat specificity, where for example wildlife monitoring is performed across the whole landscape. Other activities are more related to a specific habitat of special interest e.g. wetlands (fens and ponds), which are habitats for several threatened species. Moreover, some activities have also been identified as important baseline descriptions that can be used for follow-up investigations at a later stage, if necessary (Table 7-2). These are presented in Section 7.2.

The description of the activities includes monitoring objectives, parameters monitored, areal extent, the number of inventories made so far, an overview of methods, and important results and conclusions. In addition, difficulties encountered during the monitoring, and errors and precision related to parameter estimates are discussed. Generally, data are reported in connection with the monitoring effort in separate reports, and Tables 7-1 and 7-2 show the most recent report for each activity. Another important aspect is to provide information on other similar monitoring activities that can provide data for comparison.

Table 7-2. Overview of other activities coordinated by SKB in the Forsmark area that can be used as a baseline for potential forthcoming monitoring activities. NMP indicates that the method used is compatible with the method of a national monitoring programme. "na" is not applicable, "Y" is yes and "N" is no.

Activity/ habitat	Parameter	Year	Number of monitored objects	Method compatible with NMP	SKB report (reference)
Wild-life	Bat inventory	2004	na	Y	P-05-61 (de Jong and Gylje 2005)
Vegetation distribution	Vegetation types	2002	na	Y	P-03-83 (Boresjö Bronge and Wester 2003)
Sea	Invertebrate community	1998, 2003, 2004, 2012	5 + 3	Y	R-99-69 (Kautsky et al. 1999), P-04-82 (Borgiel 2004b), P-05-135 (Borgiel 2005), SKBdoc 1370543 (Qvarfordt et al. 2012b)
	Plant	1998, 2003, 2004, 2011, 2012	5 + 3	Y	R-99-69 (Kautsky et al. 1999), P-04-82 (Borgiel 2004b), P-05-135 (Borgiel 2005), P-11-10 (Aquilonius et al. 2011), SKBdoc 1370543 (Qvarfordt et al. 2012b)
	Fish	2003, 2004	2	Y	P-05-116 (Abrahamsson and Karås 2005), P-05-117 (Axenrot and Hansson 2005), P-05-148 (Heibo and Karås 2005)
Lake	Benthic vegetation	2005, 2006	2	Y	P-05-136 (Huononen 2005), Karlsson and Andersson 2006
	Macrofauna	2005	2	Y	P-05-136 (Huononen 2005), R-03-27 (Andersson et al. 2003)
Stream	Vegetation	2005	8	N	P-05-150 (Carlsson et al. 2005), P-11-18 (Andersson et al. 2011)
	Fish migration	2005, 2013	3	N	Loreth 2005, SKBdoc 1422348 (Olsson et al. 2014)
Forest/wetland	Vegetation	2001, 2002	8	N	P-03-81 (Abrahamsson 2003)
	Vegetation	2006	4 + 14	Y	TR-06-29 (Tagesson 2006)
	Vegetation	2004	6	N	P-05-80 (Löfgren 2005)
Swedish Forest Soil Inventory	Vegetation	2003	2x8	Y	R-04-08 (Lundin et al. 2004)
Nature values of conservational interest	General description of nature values	2007–2010	na	Y and N	R-10-16 (Hamrén and Collinder, 2010)
	Compilation of sensitive species and environments expected to be affected	2012	na	N	R-10-17 (Hamrén et al. 2010) SKBdoc 1368801 (Allmér and Collinder 2014)

7.1.1 Wildlife monitoring and hunting statistics

Monitoring of wildlife in the Forsmark area has been performed based on two different activities, field estimates and collecting information from local hunters.

Wildlife monitoring

Wildlife monitoring has been performed since 2002 both in the area of Forsmark and in a reference area close by (Hållnäs) at four occasions (2002, 2003, 2007 and 2012, Truvé 2012) (Figure 7-1). The reason for using a reference area is to be able to interpret whether changes would be specific for the Forsmark area or for the region as a whole. The results are put together from a combination of different methods: aerial survey, snow tracking along water, snow tracking along transects and faecal pellet counts (Table 7-3). The reason for combining these different methods is that they are more or less effective depending on different species. A combination of methods will also give support to a single estimate for particular species.

The aerial survey is most efficient for large mammals (moose) resulting in density estimates, whereas the snow tracking will give more specific results depending on the habitats. In 2004, an aerial survey of moose covering the whole of Northern Uppland and trapping of fox and badger was made (Cederlund et al. 2004). However, the trapping did not provide any useful results, because of a low trapping frequency in comparison with animal densities. A comparison of the monitoring result for 2002, 2003, 2007 and 2012 was made by Truvé (2012), but did not include the moose densities from 2004. This comparison was not put into any larger context, other than in a very general sense for some of the species (included species are listed in Table 7-3).

The most abundant species of the larger mammals in the area is the roe deer that has declined between the two later inventories. This seems to be an effect of the increased abundance of red fox and the appearance of lynx in the region. The moose has so far showed a relatively stable population, whereas the wild boar has increased in number during the whole period. Another species that has increased in number is the otter that seems to be becoming more common in the whole area at the same time as the mink is declining, probably as an effect of increasing otter and red fox populations. Lately, signs of both brown bear and wolf have been observed in the region, and these will probably become more regular features of the fauna of northern Uppland, if their population sizes are allowed to increase in the future.

Generally, there are large sources of error in the estimates of abundances, especially those that are used as an index (Table 7-3). Indices are difficult to compare with other data and are therefore mainly comparable for the same site between years. This makes the conclusions drawn from index data highly dependent upon the number of earlier inventories from the area.

A general problem with this monitoring is to relate the results to actual events in the landscape. Many of the monitored mammals have large territories using different types of habitats and move over large areas during different seasons. Otter is perhaps the exception of the species listed in Table 7-3, which is mainly restricted to a very specific habitat, i.e. streams. A reference area makes it possible to detect changing trends in the monitored areas, although such changes could be difficult to interpret in terms of e.g. disturbances.

On the national scale, the results may be compared with data sampled by the Swedish Association for Hunting and Wildlife Management (Svenska Jägareförbundet), whose estimates are based on culled animals reported by hunters (see also below). Another reference-data source is monitoring done since the early 1970s at the Grimsö Research Station in southcentral Sweden. Moreover, the same monitoring effort was done in Simpevarp and an adjacent reference area in 2003 and 2007 (Truvé 2007). However, suitable datasets need to have fairly long time series to be of any value in a comparison where the aim is to disentangle responses by wildlife to disturbances.

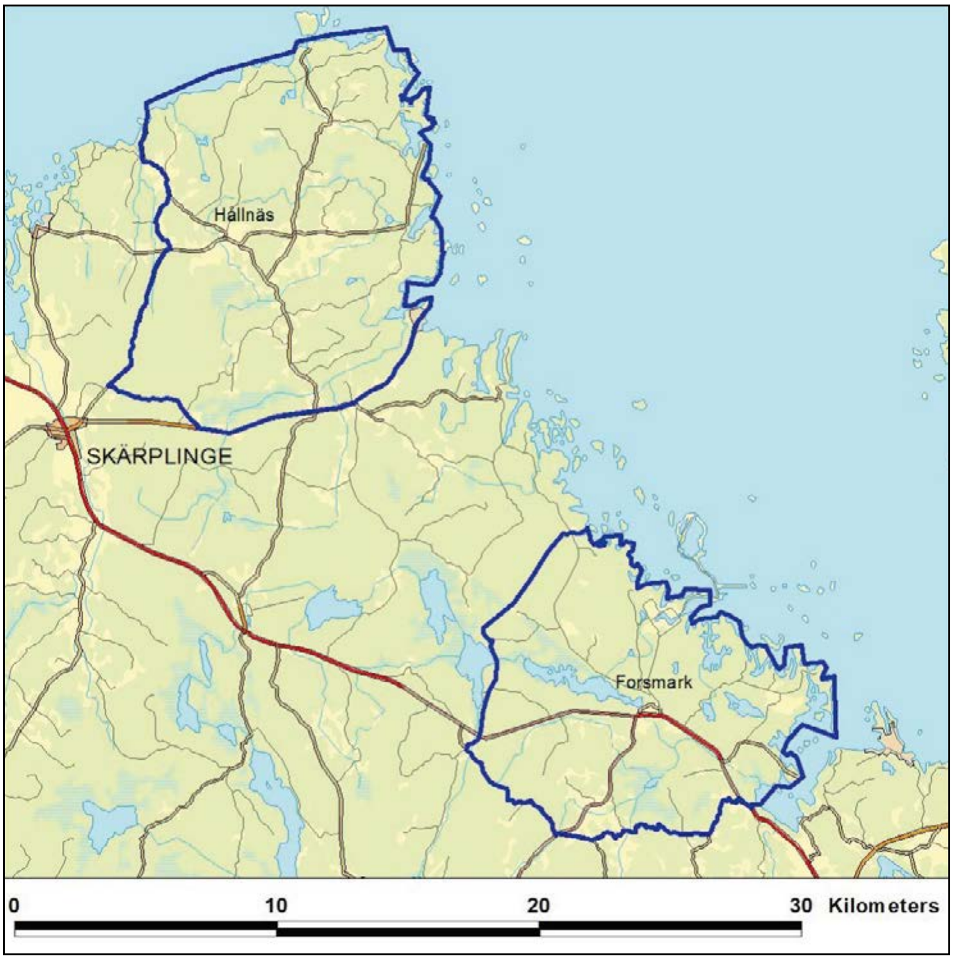

Figure 7-1. *The two monitored areas within the wildlife monitoring programme (from Truvé 2012).*

Table 7-3. The species found during monitoring and the methods by which population sizes have been estimated. The last column shows if the results are expressed as a density estimate or an index value.

Species English (Swedish)	Latin	Surveys in the Forsmark area	Density (D) or index (I)
Moose (Sw. Älg)	Alces alces	Pellet, aerial	D
Roe deer (Sw. Rådjur)	Capreolus capreolus	Pellet	D
European (common) hare (Sw. Fälthare)	Lepus europaeus	Pellet	D
Mountain hare (Sw. Skogshare)	Lepus timidus	Pellet	D
Lynx (Sw. Lodjur)	Lynx lynx	Snow tracking	
Marten (Sw. Mård)	Martes martes	Snow tracking	D, I
Red fox (Sw. Rödräv)	Vulpes vulpes	Snow tracking	I
Squirrel (Sw.Ekorre)	Sciurus vulgaris	Snow tracking	I
Wild boar (Sw. Vildsvin)	Sus scrofa	Pellet	D, I
American mink (Sw. Mink)	Mustela vison	Snow tracking	I
Badger (Sw. Grävling)	Meles meles	Snow tracking	I
Weasel (Sw. Vessla)	Mustela nivalis	Snow tracking	I
Otter (Sw. Utter)	Lutra lutra	Snow tracking	I

Hunting statistics

The moose (*Alces alces*) is an important game species in Forsmark, as well as in the rest of Sweden. Since 2002 hunting statistics have been analysed annually from the Vällen and Östhammar culling districts (85 000 ha, including Forsmark) in order to estimate age distribution, reproduction and slaughter weights. These data are important for the description and management of culling areas in order to plan future culling.

Results show that the present culling scheme has led to a moose population in Forsmark with a biased sex ratio with fewer adult males than females and furthermore a low average age in the population (Cederlund et al. 2012a). This type of data is biased by the hunting intensity, the degree of reporting and the recommendation by the culling programme in regard to what individuals should be culled and will therefore only be a rough index corresponding to the actual densities. The activity generates data needed for management of the moose population and is a way for SKB to keep contact with an important group of the local community. This type of data is collected and stored on a nationwide basis making comparisons possible between different culling districts.

7.1.2 Bird monitoring

Monitoring of birds in Forsmark has been performed annually since 2002, where one aim has been to investigate whether changes in numbers of breeding birds can be related to disturbances from the site investigations (e.g. Green 2008). Monitoring of breeding birds in general, using line transects and point counts, has been performed 2002–2004, 2007 and 2013 covering the whole regional model area (in 2004 only the candidate area (Green 2014), Figure 7-2). So far only the data from the line transects have been used in the analysis, mainly because this approach results in more observations. The results from both methods are however available in the database Sicada. This monitoring method gives both a good estimate of the number of species and the number of individuals within the area. However, it may be difficult to get an exact estimate of the number of breeding birds, because in some species young birds may spend their time in the area without breeding.

An additional approach was to focus monitoring on selected species listed in the Swedish Red List and the EU Birds Directive Annex 1 (Table 7-4). This selection has been monitored annually since 2004. A species was included in the selection if one or more of the following criteria was met: 1) Forsmark is a vital area for the species in a regional or national perspective; 2) The species in question is suspected to be sensitive to disturbances and thus possibly affected in a negative way by the then ongoing site investigations; 3) The species shows a negative population trend at the national level (but not necessarily in Forsmark); 4) Forsmark holds high densities of the species (Green 2006). The choice of areas to be investigated was based on earlier monitoring results 2002–2003 (Green 2003, 2004) and limited to known territories and/or suitable habitats (e.g. Green 2006, 2007, 2009, 2011, 2015). Identified territories were visited several times at appropriate occasions during the breeding season. The species included in this comparison were not only counted, but also analysed using a measure of reproductive success e.g. number of juvenile birds and/or successful breedings out of the total number of breeding pairs.

The monitoring methodology used is the same as the one used within the Swedish Bird Survey (Green and Lindström 2014), which is a part of the National Monitoring Programme of the Swedish Environmental Protection Agency (Sw: Naturvårdsverket). This means that the results from Forsmark are easily put into the context of national or regional trends (e.g. Green 2014). In the last presentation of the general bird monitoring in Forsmark 2013, the results were presented using the method TRIM (TRends and Indices for Monitoring data, van Strien et al. 2004), where time series are converted to an index and analysed with a log-linear method. This method is now widely used and is also used for Pan-European comparisons. However, all bird monitoring raw data from Forsmark are also delivered separately and stored in Sicada, making other types of comparisons and discretisations of data possible.

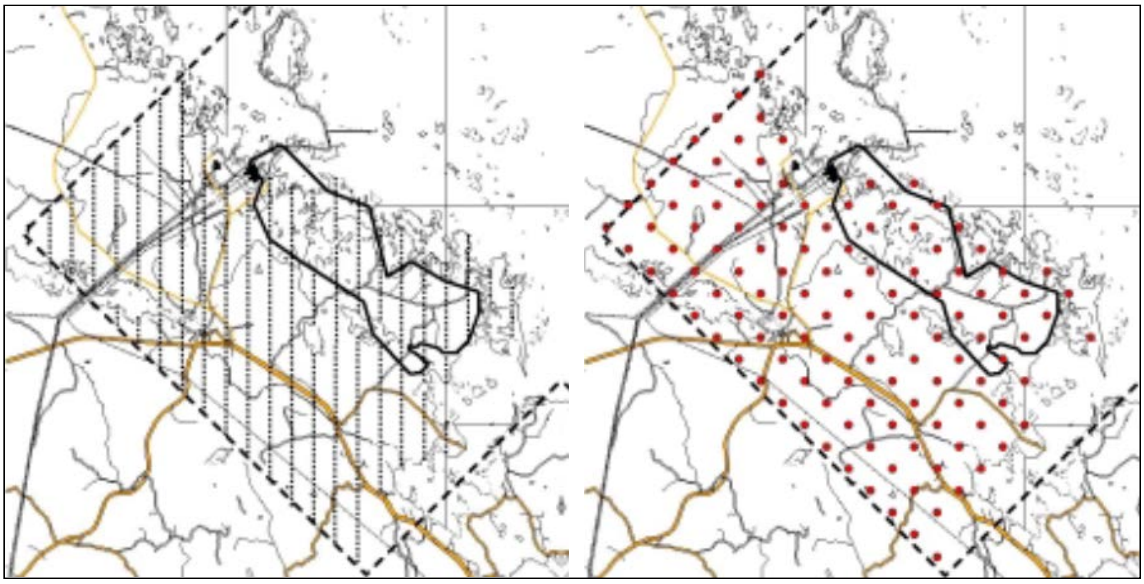

Figure 7-2. Maps showing the regional model area (hatched line) and the candidate area (black line) with the line transects in the first map and the point counts in red in the second map (from Green 2003).

Table 7-4. Selected bird species that were specifically monitored in Forsmark during 2004–2013 (Green 2014). The selected species are on the Swedish Red List (ArtDatabanken 2015) and/or are included in the EU Birds Directive Annex 1. Those marked with * were added during 2005–2006.

English name	Swedish name	Latin name
Black-throated Diver	Storlom	Gavia arctica
Honey Buzzard	Bivråk	Pernis apivorus
White-tailed Eagle	Havsörn	Haliaeetus albicilla
Osprey	Fiskgjuse	Pandion haliaetus
Black Grouse	Orre*	Tetrao tetrix
Capercaillie	Tjäder*	Tetrao urogallus
Hazelhen	Järpe*	Bonasia bonasia
Ural Owl	Slaguggla	Strix uralensis
Wryneck	Göktyta	Jynx torquila
Lesser spotted Woodpecker	Mindre hackspett	Dendrocopus minor
Red-backed shrike	Törnskata	Lanius collurio

Based on the results from bird monitoring in Forsmark, the effects of increased human presence in the area due to the site investigations was analysed together with data on forestry actions (or no actions). This analysis showed no significant effects from people working (with the site investigations) in the area on bird numbers during the breeding period (Green 2008). However, there were significant effects on some groups of birds from forestry actions. Clear cutting was, not surprisingly, positively associated with population development of birds connected to clear-cuts or forest edges as well as, perhaps more surprising, generalist species. It was also possible to explain the disappearance of black grouse from the candidate area where no forestry activity had occurred during the period. The black grouse generally needs a suitable patchwork of successional forests, but this decline was also a part of a national decrease.

Consequently, it is possible to partly explain changes in the distribution pattern using a combination of data from the national context and local knowledge. Depending on the distribution of the different species within the monitored area, it would be important to make appropriate discretisations in the data depending on the question that has to be answered. So far, data analysed from line transects have revealed trends based on discretisations among habitats or species for the whole monitored area. To be able to answer more specific questions about certain areas, it may be necessary to make areal distinctions, and such areal distinctions would be restricted to where the actual transects or the point counts are located within the landscape. The general conclusion from both the repeated surveys of all breeding birds using transects and from the more detailed monitoring of selected listed species is that the site investigations, associated potentially disturbing activities and increased human presence in the area, have had very little impact on the breeding birds of the area (Green 2014).

In the site monitoring programme at Forsmark (Sw: "baskontrollprogrammet") there is monitoring of how biotic communities are affected by the power-plant use of cooling water i.e. the release of heated water (e.g. Adill et al. 2014). The abundance of a specific set of bird species, based on their dietary choice (Table 7-5) has been followed twice a month during the year according to the previously mentioned point counts. The area and its subareas (see Figure 7-3) have been monitored since 2002.

Table 7-5. The monitored species in the site monitoring programme at Forsmark and their dietary choice.

Species	Latin name	Diet
Mallard (Sw. Gräsand)	Anas platyrhynchos	Plants/algae
Mute swan (Sw. Knölsvan)	Cygnus olor	Plants/algae
Common goldeneye (Sw: Knipa)	Bucephala clangula	Bottom fauna
Tufted duck (Sw. Vigg)	Aythya fuligula	Bottom fauna
Common merganser (Sw. Storskrake)	Mergus merganser	Fish
Great cormorant (Sw. Storskarv)	Phalacrocorax carbo	Fish
Grey heron (Sw. Häger)	Ardea cinerea	Fish

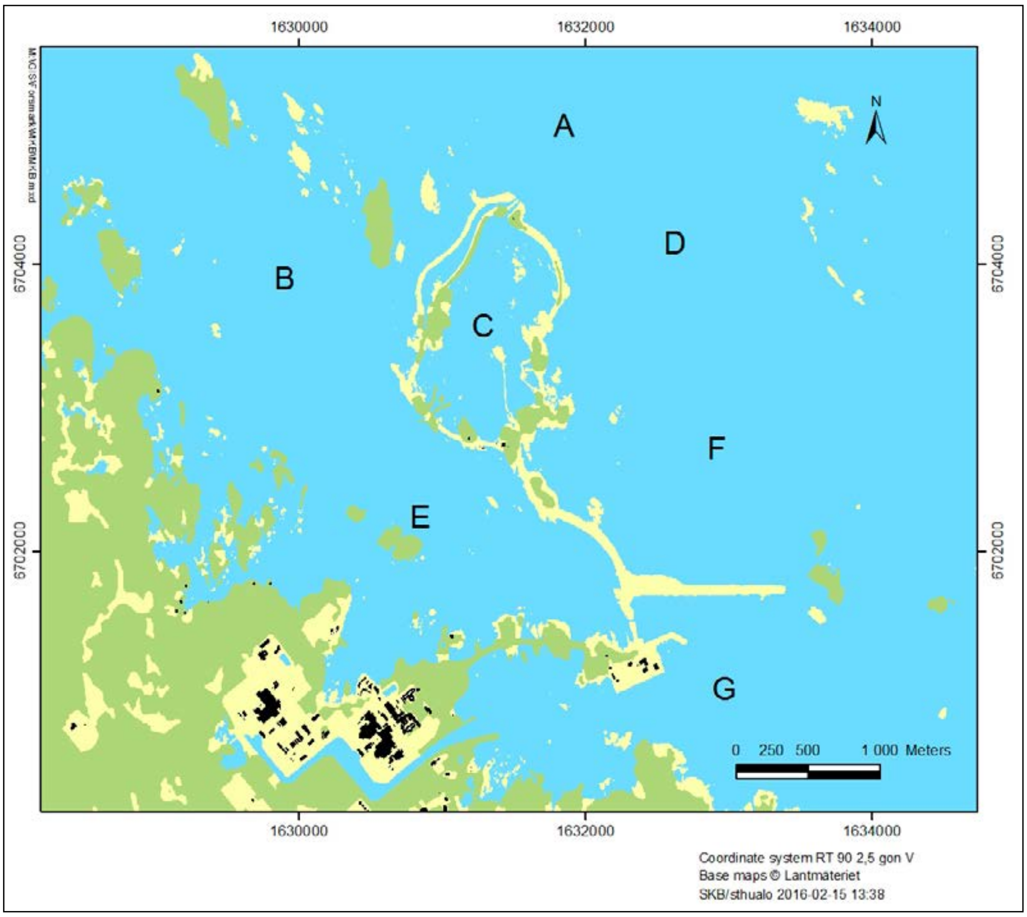

Figure 7-3. *Map showing the approximate area (surrounding the letters A–G) that is monitored for a specific set of bird species. This area is further discretised (indicated by letters) based on the potential impacts of the cooling-water use in this area (Adill et al. 2014). Areas B, E and F are assumed to be less effected and would serve as references. Area G is affected by the intake, whereas A, C and D are affected by the outlet.*

7.1.3 The Sea

The coastal area offshore of Forsmark contains many different habitats, ranging from shallow and narrow bays with slow water turnover to deeper basins with faster water turnover. In the hydrochemical monitoring programme (see also Chapter 6), samples have been taken monthly at two coastal locations (Figure 7-9) between 2002 (Nilsson et al. 2003) and 2008. Since 2009, one of these locations has been sampled four times a year. Chlorophyll a, c, pheophytin, turbidity and water transparency have been measured at these locations.

Apart from chemistry variables, such as nitrogen, phosphorous and temperature (see Chapter 6), Svealands Kustvattenvårdsförbund (SKVVF) has also regularly made measurements of water transparency and chlorophyll a along the Svealand coast at 175 locations since 2006. These measurements are done twice a year during the summer (SKVVF 2015). One location is in Kallrigafjärden and three locations are in Öregrundsgrepen. Data from this monitoring are available at the SKVVF website (SKVVF n d).

In the biological monitoring programme of the Forsmark nuclear power plant, coordinated by Forsmarks Kraftgrupp AB (FKA, the operator of the nuclear power plant), there is monitoring of how biotic communities are affected by the power plant's use of cooling water, i.e. the release of warm water into the sea (e.g. Adill et al. 2014). Besides sampling of the area affected by the cooling-water release (Lake Biotestsjön), two reference areas are also sampled, one in Öregrundsgrepen and one in the Finbo archipelago at Åland. The latter areas have been sampled since 2003. Fish species composition and catch per effort are compared using gill nets at 45 stations at both localities. The age structure for perch (*Perca fluviatilis*) is described for both Forsmark and Finbo. In Forsmark, also the presence of injuries, parasites, health condition and reproductive condition (gonad status) are documented. Moreover, spawn and abundance of younger fish are estimated using detonations in Forsmark. The fish populations have turned out to be fairly stable during the monitoring period.

In the biological monitoring programme by FKA, the macrofauna at soft bottoms are monitored at depths of 16 and 41 m at two stations in Forsmark and at four stations in Finbo. Five grabs are taken using a van Veen collector at each station in Forsmark and three grabs are taken per station in Finbo. Presence of species, abundance and biomass data are collected. Data are available since the mid-1980s. It is noticeable that the shallower station in Forsmark is somewhat affected by the cooling-water plume and a recent collapse of the macrofauna community was possibly caused by the work with the Fenno-Skan 2 cable (Adill et al. 2014). SKVVF has at least one station for collecting macrofauna at a soft bottom in Öregrundsgrepen (SKVVF 2015). However, their soft-bottom sampling programme is under revision.

7.1.4 Lakes

Lakes have been monitored as a part of the hydrochemical monitoring programme since the start of the site investigations in 2002, and four lakes have a continuous time series since then (see Figure 6-4 and Nilsson et al. 2003). The number of included localities has gradually decreased during the course of the monitoring programme. Four lakes were monitored on a monthly basis until 2008, but have since 2009 been monitored four times a year. As for ponds, variables related to vegetation in this programme are 1) concentration of chlorophyll a, c and pheophytin in the water (an indirect measure of the amount of photosynthesising phytoplankton, related to biomass), 2) turbidity, which is a measure of the concentration of particulate matter (plankton and organic matter) in the water, 3) water transparency, which also includes effects of dissolved matter, 4) photographs on each monitoring occasion.

The chlorophyll measurements have been problematic, possibly due to the fact that humic substances and chlorophyll have similar fluorescence at the wavelength used by the sonde. Since the inland waters show high concentrations of humic substances, the amount of chlorophyll tends to be overestimated. The turbidity measurements performed in the sea and in lakes often display negative values. This may be due to poor probe sensitivity in clear waters (i.e. waters with little turbidity) (Nilsson et al. 2010). However, both these problems are noted in the database along with the data.

In Sweden, there is a national monitoring programme for lakes mainly, focused on chemistry. Two lakes in the Forsmark area are included in this programme. Lake Vambörsfjärden was included in 2012 and Lake Bruksdammen has been visited regularly. However, there are also programmes monitoring benthic fauna (1986–), zooplankton (1990–), phytoplankton (biomass and species, 1975–) and macrophytes (2007–) on a national level (Havs- och vattenmyndigheten 2014).

Borgiel (2004a) undertook standardised sampling of fish in the four lakes Bolundsfjärden, Fiskarfjärden, Eckarfjärden and Gunnarsbo-Lillfjärden (Figure 7-4), using benthic multi-mesh gillnets based on methods recommended by the Swedish Environmental Protection Agency (Naturvårdsverket 1999, 2000a) and the National Board of Fisheries (Fiskeriverket 2001). The lakes were classified according to the Swedish fish index (FIX), which is based on nine variables. The data were also stored in the national database at the National Board of Fisheries. This database serves as a reference for local, regional and national investigations. Moreover, archive samples for future analysis were stored according to the report. Two of the lakes (Lake Eckarfjärden and Lake Bolundsfjärden) in the area have been investigated earlier by the University of Uppsala and Upplandsstiftelsen (1991 and 2001, respectively), in addition to 80 other lakes in the County of Uppsala (Nyberg 1999). A comparison with these results was made by Borgiel (2004a). The used inventory sampling technique is a simplified method for fish sampling, mainly providing a rough estimate of the occurrence and abundance of dominating fish species in the lake and is an index describing the "catch by unit effort".

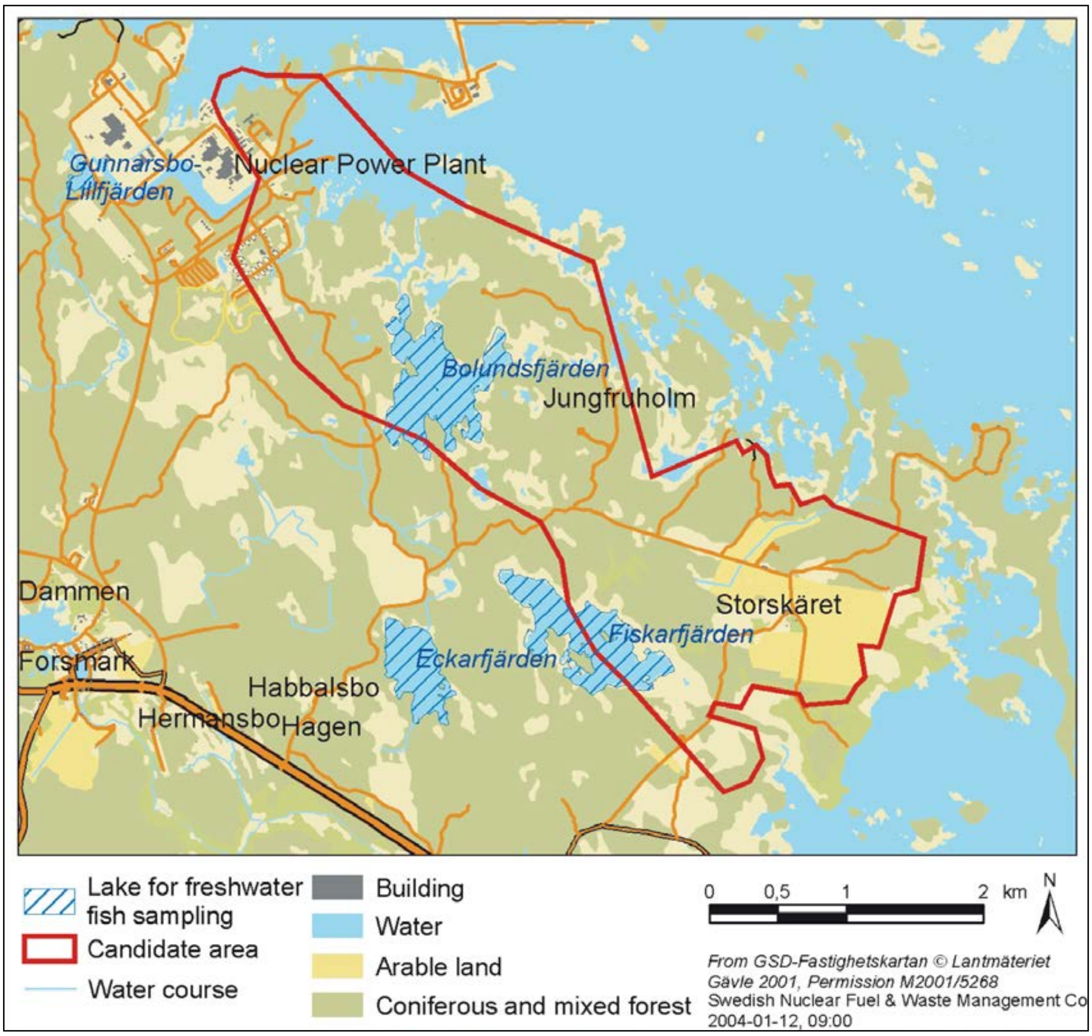

__Figure 7-4.__ The location of the four lakes in which standardised sampling of fish was made using benthic multi-mesh gillnets (Borgiel 2004a).

In 2013 and 2014, Lake Eckarfjärden and Lake Fiskarfjärden were again studied with regard to fish abundance using an echo sounder and gillnets (see Kaljuste 2013). The aim of this study is to establish a baseline for the echo sounder methodology in estimating biomass and also to estimate the fish production by a modelling approach.

7.1.5 Ponds and wetlands

Ponds are small shallow surface waters that are surrounded by wetland areas. Wetlands are characterised by land where water, during a large part of the year or all year round, is close to, under, at or just above the ground surface. The difference between a pond and a lake is not strict and here they are distinguished by the fact that ponds are somewhat smaller but perhaps more importantly they are assumed to be potential habitats for the pool frog and the great crested newt (see below). One important feature of ponds inhabited by these species is that they most often lack predatory fish species that are more commonly found in larger surface waters. The low-relief landscape and the fast shoreline regression make these habitats common in the area. Succession will gradually transform ponds into wetlands (in 100 to 1 000 years). Wetlands in the area were early shown to be of importance in a national conservation value perspective (e.g. Gunnarsson and Löfroth 2009).

The low-relief landscape affected by a fairly fast shoreline regression with calcite-rich soils and abundant wetlands are factors contributing to the uniqueness of the area. Several Red-Listed species had earlier been recorded and were also found during the site investigation. Examples include species among molluscs and fungi, and the fen orchid. Several early projects during the site investigations were aimed at describing the flora and fauna, and were never intended to be of a regularly monitoring character e.g. classification of fens according to indicator species of vascular plants (Göthberg and Wahlman 2006), inventory of amphibians and reptiles (Andrén 2004), nature-value classifications of different habitats such as wetlands/ponds, terrestrial molluscs and snails, and dragonflies (Hamrén and Collinder, 2010) (see Section 7.2.7 for further information). According to current plans for the construction of surface facilities for the spent fuel repository, two ponds where the pool frog has been observed will be filled. Therefore, a project was performed to construct six new artificial ponds in suitable locations in the area (four were constructed in 2012 and two in 2014). Four of these ponds along with two existing ponds have been followed since their construction to describe a number of different aspects.

Amphibian monitoring

Pool frog (*Rana lessonae*) and great crested newt (*Triturus cristatus*) are both protected according to the EU Habitat Directive and are found in similar, shallow surface-water habitats. The pool frog has been monitored annually since 2011 in the Forsmark area. The great crested newt has been monitored since 2012 and the common newt (*Lissotriton vulgaris*) was also included in the 2013 inventory (Collinder 2014, see Figure 7-5). These species have been found close to the planned spent fuel repository and some localities will be directly affected by the planned surface excavations (SKB 2011a, 2014c). Moreover, one potential effect of the deep repository excavations is drawdown of the groundwater table (Werner et al. 2010) that could adversely affect the habitats for these species.

The aim of the monitoring activities has been to describe the distribution and abundance of these species in the area, thereby providing information relevant to avoiding negative effects on their populations during construction and operation of the spent fuel repository. Another aim has been to describe how many occupied (and also some non-occupied) ponds potentially could be affected by long-term groundwater-table drawdown. In the winter of 2012 and 2014, six new ponds were constructed in order to investigate the possibilities to replace two ponds that will disappear due to surface excavations. These six new ponds were localised based on the data from the ongoing monitoring, i.e. reasonably connected with present populations to increase the possibility for colonisation of the constructed ponds and to potentially increase the number of suitable habitats for the metapopulation.

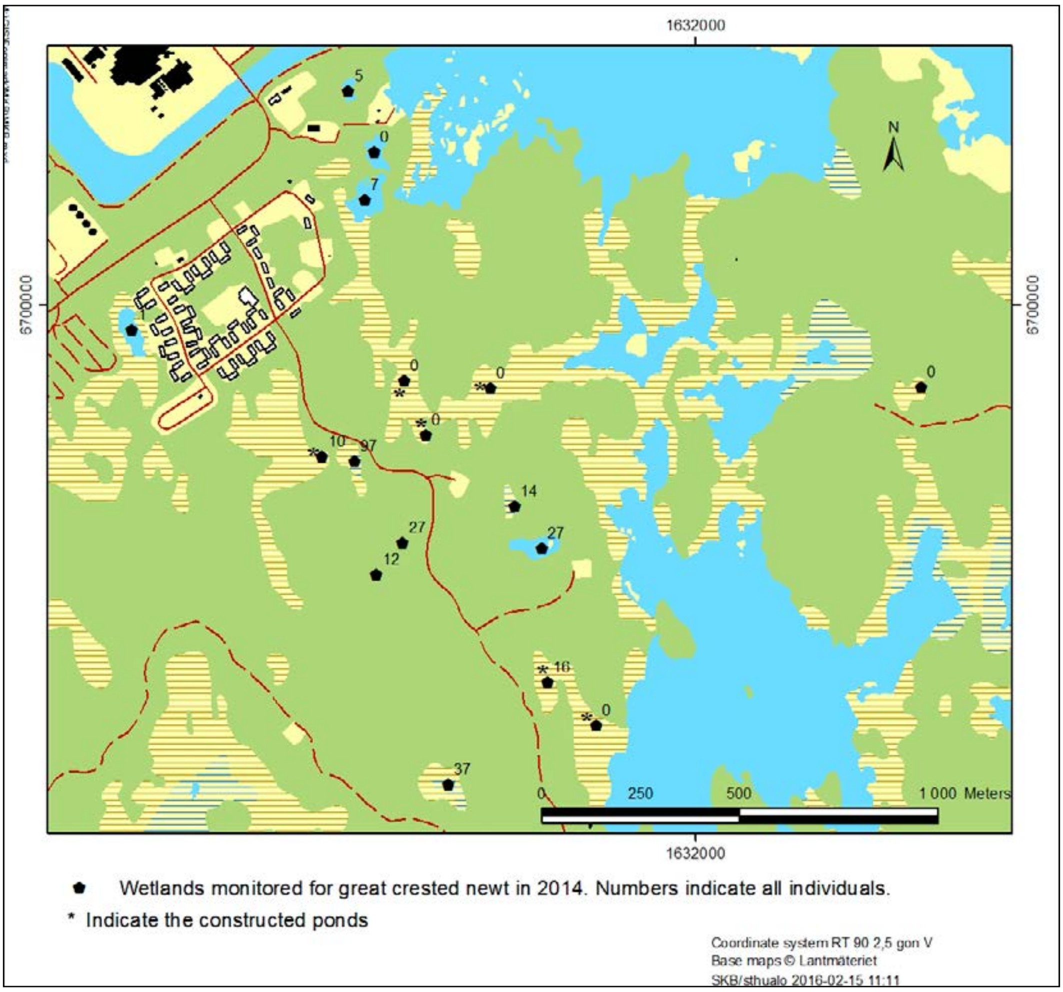

Figure 7-5. *Map showing the ponds included in the inventories of great crested newt (Triturus cristatus) and common newt (Lissotriton vulgaris) (after Collinder 2014).*

In the inventory of pool frog in 2013 (Figure 7-6), six localities with known populations were visited, and five other ponds were also visited as they were assumed to be potentially suitable pool-frog localities. Moreover, the four recently constructed ponds were also included in the inventory (see above, Collinder 2014). Each pond is visited twice during the breeding season and the visit must be done under suitable weather conditions to maximise the effectiveness. The result of frog monitoring is sensitive to sun exposure and the temperature of the pond water, and it is therefore important to monitor under as good conditions for mating as possible. Otherwise, it would be expected that large errors are introduced into the results, which are based on the number of mating males. In 2013 a supplementary measure, reproductive success, was included by further visits in late summer to count juvenile frogs. In 2013, seven ponds had calling males and juvenile frogs were also found in one of the four constructed ponds, suggesting at least one successful colonisation. This was also the pond that had the largest number of calling males among the four newly created ponds.

The pool frog has been monitored also by the County Administrative Board of Uppsala on three occasions (2001, 2005 and 2009, Nilsson 2013) and 574 different localities were visited in 2009 (Figure 7-7). This inventory covers the coastline of the northern part of Uppland and includes all known localities of pool frog occurrence since 1980 (Nilsson 2013). Moreover, all potentially suitable ponds within an area of 5 km in radius from each known locality were also visited. They visited each pond at least once and further visits were made if the presence of pool frogs was not noted at the first visit. This monitoring also included a measure of reproduction by a visit in late summer and also collected information on other environmental variables. However, at the time of writing these results were not yet published.

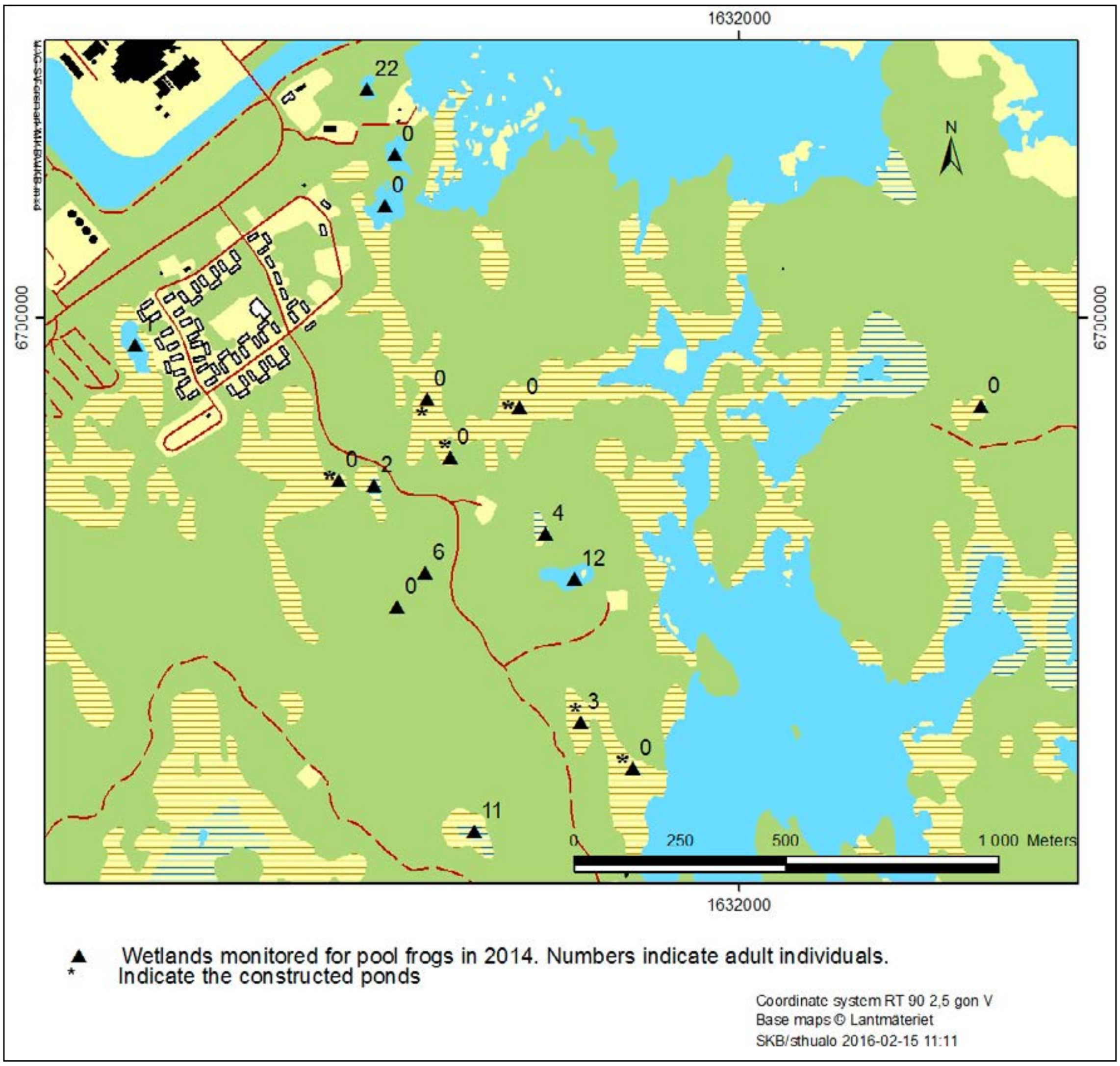

Figure 7-6. *Map showing the ponds that were visited in the search for the pool frog (Rana lessonae) in 2014. Figures show the number of individuals found in each pond (after Collinder 2014) and the asterisk indicate the six constructed ponds.*

Earlier inventories were done in 1983, 1987, 1990 and 1994 as a part of research projects (Gylje 2004a), but these inventories included fewer localities than the later efforts. Generally, it can be said that the population sizes are difficult to estimate based on the number of calling males. It has been observed that the weather and environmental conditions greatly influence the number of calling males, such that few or no males will call unless conditions are sunny and not too windy and that the water has a certain temperature. Based on these observations, it is likely that the number of calling males varies greatly during the breeding period.

The monitoring of great crested newt has so far comprised 15 different ponds during four years (Collinder 2014). These 15 ponds are suitable for the species and are within or close to areas that might be affected by repository construction and operation. Individuals are located by torch at night. In 2013, five of the 15 investigated ponds were occupied by the great crested newt. Moreover, they were found in three of four constructed ponds in 2012 (Collinder 2013). A number of Swedish County Boards (e.g. those of Östergötland and Örebro) are regularly doing monitoring of this species, and their surveys can serve as bases for comparison with those made in Forsmark.

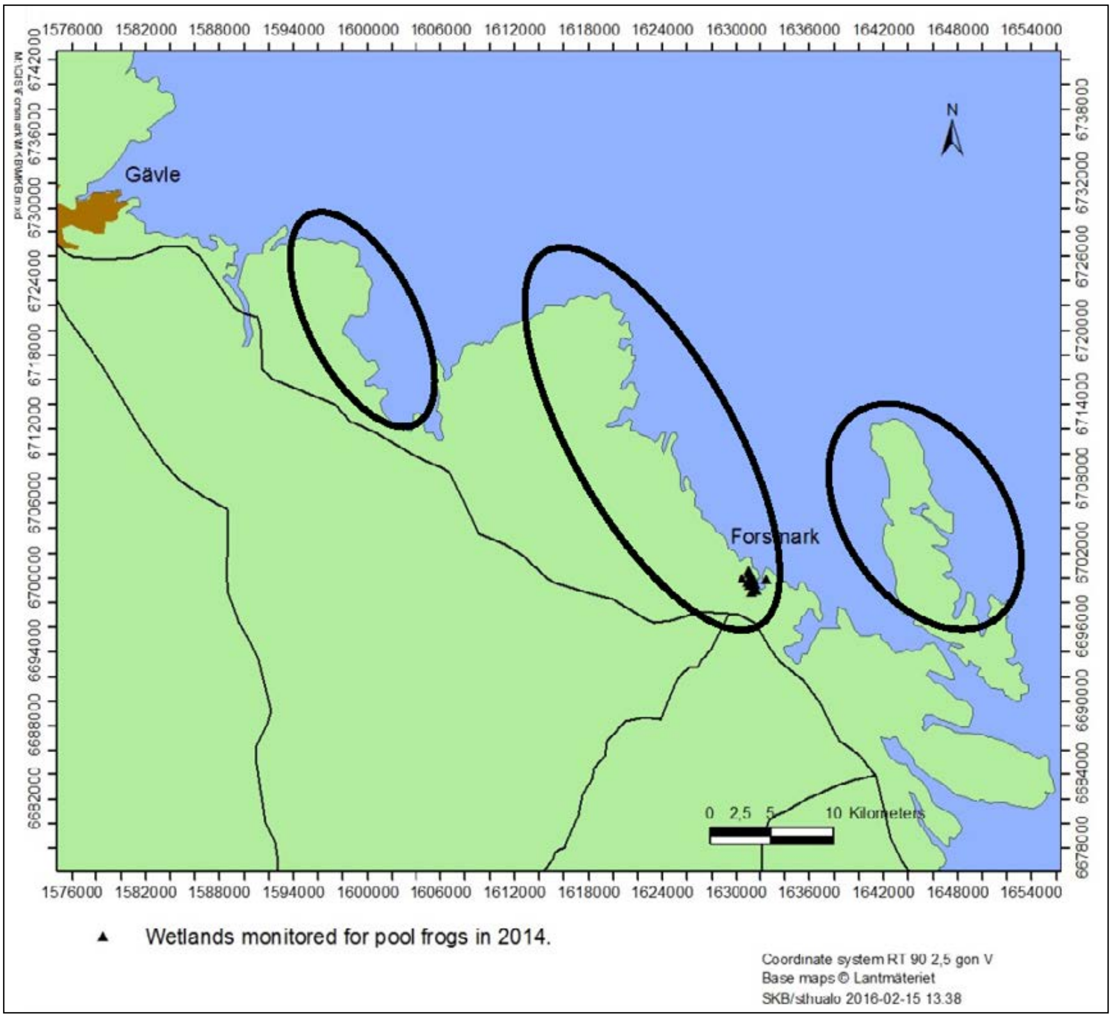

Figure 7-7. *The three regions in northern Uppland with localities where the pool frog was found during the latest inventory by the County Administrative Board of Uppsala in 2009 (after Nilsson 2013). Triangles indicate the localities that are monitored by SKB.*

Wetland vegetation

The fen orchid (*Liparis loeselii*) is protected according to the EU Habitat Directive Annex 2 and has been monitored in Forsmark since 2012 (Collinder 2014). It has in total been found in nine fens in the Forsmark area during these activities. Five of these fens could potentially be affected by the potential groundwater-table drawdown due to repository construction and operation. Hence, the aims for this monitoring are similar to the monitoring of amphibians mentioned above. In 2013, 27 localities were visited to investigate to what extent new localities could be identified (Figure 7-8). A number of different parameters are included in the current monitoring (Table 7-6). Habitats for fen orchid sub-populations are characterised in terms of peat depth, coverage of brown mosses and the ground coverage of reed, bushes and litter. One aim of including these parameters is to be able to characterise suitable wetlands for the fen orchid. This knowledge can be used for optimising the search for new localities and also to identify non-occupied suitable wetlands. During 2014 a study was initiated to monitor effects of fluctuations of the groundwater level on the population size and fecundity of five wetlands with fen-orchid populations.

The present monitoring can be compared with work coordinated by the Swedish Species Information Centre (ArtDatabanken) that performs monitoring of species found on the Swedish Red List, so called "floraväkteriverksamhet". However, this work does not contain many examples of localities with long time-series for the fen orchid. One example is from northern Uppland, where a part of a population at Kista hav was followed 1997–2001 and 2009 (Ericsson 2010). This locality and Maran, which is also located in northern Uppland, have longer records from the 1980s and 1990s, respectively, with observations reported to the Swedish Species Information Centre. Both of these localities are however areas with a management programme, which today is not present in the fens around Forsmark. Generally, the work with "floraväkteri" has become increasingly popular and it might be reasonable to believe that more time-series will be available in the future.

Table 7-6. Variables measured as part of yearly fen-orchid monitoring.

Variables measured for each identified subpopulation	Comment
Number of flowering individuals	
Number of rosettes	
Number of leaves of each rosette (size)	
Reed coverage	
Bryales coverage	In comparison to e.g. *Sphagnum* and *Carex* in the field and bottom layer.
Bush coverage	
Litter coverage on the ground	
Peat depth	For each subpopulation.
Distance to groundwater table for each individual	Measured in 2014 and 2015.

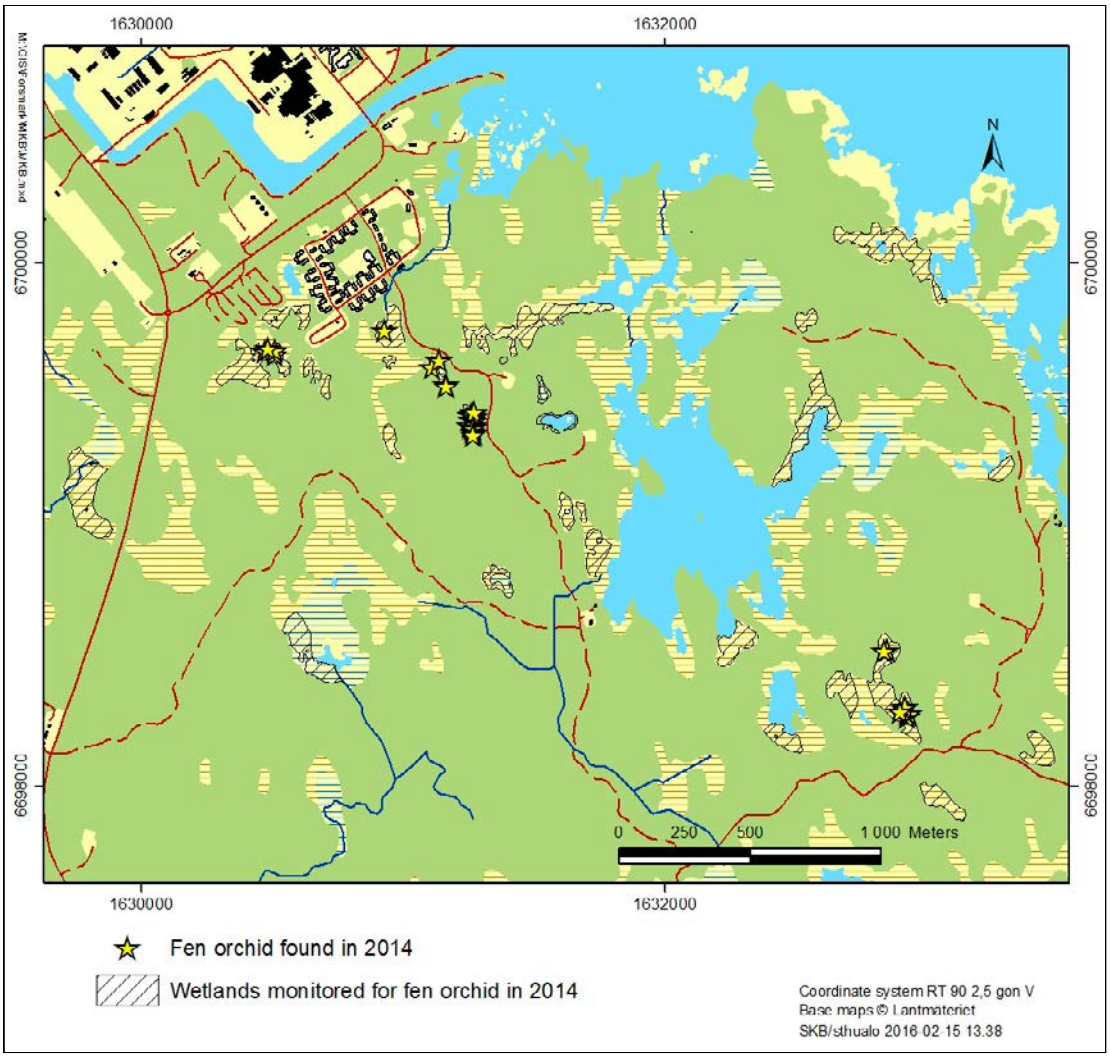

Figure 7-8. *Map showing fens visited in search for the fen orchid (Liparis loeselli). Each star indicates a group of individuals in 2014 (after Collinder 2014).*

The fen orchid seems to be sensitive to the local hydrology, such as changes in the depth to the groundwater table. Another factor of importance is changes in the vegetation community, where successionally induced changes, such as ingrowth of shrubs and trees, will severely affect the potential of established populations to persist (Sundberg 2006). Mainly the first of these factors might explain the large inter-annual variation in population size that has been observed, whereas the second factor might be an important explanation to long-term change. Many of the fen-orchid localities that are followed are found in areas with a long history of haymaking and/or livestock grazing. This suggests that the populations are very dependent on variation in management intensity and that the management is maintained.

In the case of Forsmark, with a long history of human land use such as intensive forestry, it is reasonable to assume also that near-coastal wetlands were used for haymaking, as was done in other areas along the Uppland coast. However, the Forsmark area seems to have had a land-use intensity decrease that began earlier compared to for example the Hållnäs parish north of the Forsmark area (Figure 7-1). With that perspective in mind, a project was initiated 2015 that will investigate the effects of haymaking on the rich fen community in general and on the fen orchid especially.

Pond vegetation and macrofauna

A programme investigating four ponds was set up during 2009 and 2010 with, in total, 12 visits. The aim is to describe this type of habitat that hosts several red-listed species. Four new ponds were constructed in 2012, and these were also studied by, in total, 12 visits in 2012 and 2013 and later on with 3 visits annually. Two additional ponds were constructed in early 2014, and these ponds will be monitored with 12 visits during the forthcoming years in order to establish a baseline. In 2012, two of the four originally investigated ponds were again part of the monitoring programme (3 visits per year), as these four are considered as reference objects for the development of the total of six constructed ponds (Figure 7-9). Most variables included in the programme are related to surface-water chemistry (see Chapter 6), whereas those related to vegetation in this programme are 1) concentration of chlorophyll and pheophytin in the water, which is an indirect measure of the amount of photosynthesising phytoplankton (by its relation to biomass), 2) turbidity, which is a measure of the particulate matter in the water (i.e. plankton and organic matter), 3) photographs of the six constructed ponds (Qvarfordt et al. 2014a). Furthermore, both the two reference ponds and the six constructed ponds are monitored in terms of benthic vegetation and macrofauna (Qvarfordt et al. 2014b).

In order to describe the succession of the artificial ponds in comparison with the reference ponds, monitoring methods aim to underpin a systematic comparison of inter-annual vegetation and macro-fauna communities. Vegetation was monitored by 1) transects, in the same way as in the national environmental monitoring of benthic vegetation in the sea (Naturvårdsverket 2004), to describe the benthic substrates, vegetation distribution and abundance covering larger areas, 2) squares located at the bottom as in the national environmental monitoring of shallow bays (Persson and Johansson 2005), to enable statistical analysis within and among ponds, 3) general vegetation description of the pond, and 4) photographs below the water surface. The starting and endpoints of transects were marked permanently to ensure that they could be located at the same place each year. The squares (0.5 m by 0.5 m) were located along each transect at specified distances, and some variation will inevitably have been introduced due to the semi-permanent square locations.

Macrofauna was monitored in a standardised manner by a so called "sparkprov" where a certain area is disturbed by using the foot and a net with specified measurements is used to trap the macrofauna that becomes suspended in the water. This method is used for national environmental monitoring (Naturvårdsverket 2007). This data have so far been used to evaluate the succession of the constructed ponds in comparison to the succession of the two reference ponds. By using multivariate statistics (multidimensional scaling) on species presence and coverage during 2012 and 2013, it has already been possible to show that the four constructed ponds have become similar to the reference ponds in terms of both benthic vegetation and macrofauna, which suggests fast colonisation and establishment of many taxa.

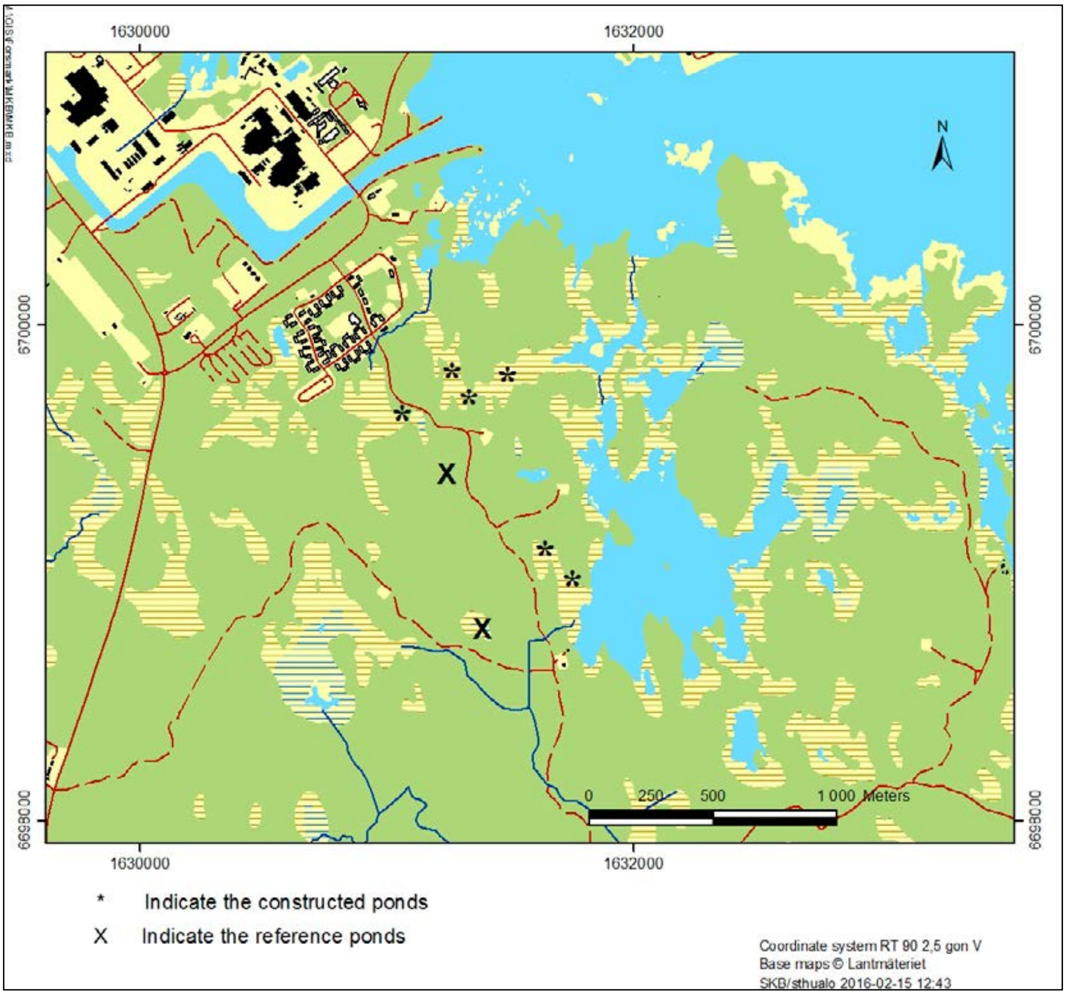

Figure 7-9. The location of the two natural reference ponds and the six constructed ponds in the Forsmark area.

7.2 Other activities initiated during the site investigation programme

During the site investigation programme that started during 2002 a number of activities were initiated in order to describe different aspects of the biosphere. Apart from the general site understanding, these descriptions were also used to underpin conceptual models and feed safety-assessment models with parameter values. In the descriptions below, the criterion for being included is that the activity is repeatable and relevant, i.e. the locality has to be specified, and the measured variables are of interest in the forthcoming monitoring context. Table 7-2 provides an overview of the identified activities.

7.2.1 Wildlife

In 2004, a bat inventory was made in the Forsmark area using ultrasound detectors and trapping in mist nets during the period July 17 – August 9 (de Jong and Gylje 2005). The aim was to describe the occurrence of different bat species, and to identify colony sites and important foraging areas. The ambition was also to make rough estimations of abundance of different species. Suitable sites were visited (Figure 7-10) and line-transects were used in order to estimate abundances (Figure 7-11).

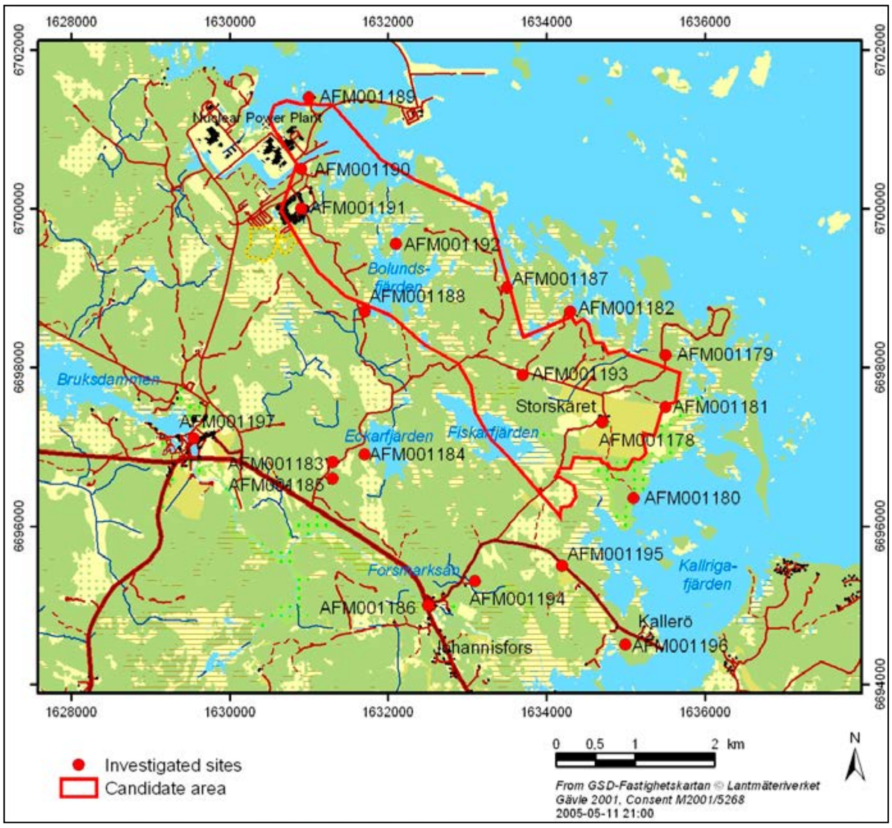

Figure 7-10. *Location of the investigated localities in the bat inventory within the Forsmark area (de Jong and Gylje 2005).*

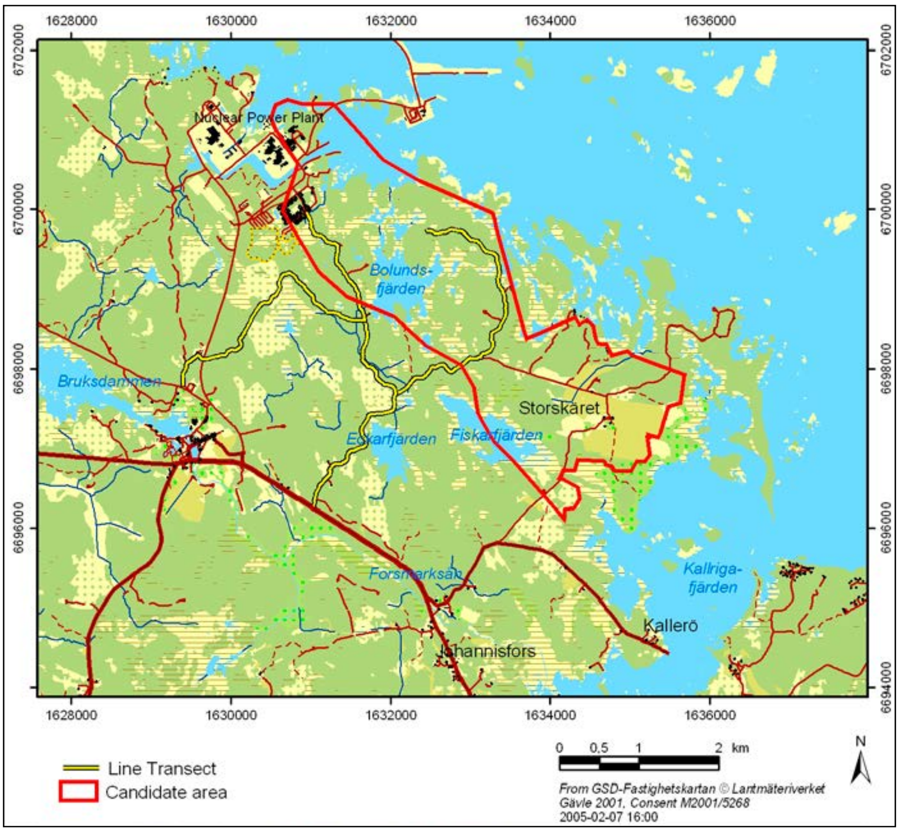

Figure 7-11. *Location of line-transects used to estimate bat abundance in the central area of Forsmark investigation area (de Jong and Gylje 2005).*

The number of bat species (9) and bat abundance in the Forsmark area is high with several interesting and red-listed species. All of the most interesting localities, except one (Storskäret) were located outside the main area of the Forsmark site investigation. The eastern part of the main area is much more varied with pastures, fields and deciduous forest. Other areas within the main area that might be interesting for bats are around the lakes and along the coast. Besides this, the area is not very interesting with regards to the bat fauna. The most common species in the Forsmark area is the northern bat (*Eptesicus nilssonii*), which occurred all over the area and at several sites in very high abundances. Also the pipistrelle bat (*Pipistrellus pygmaeus*) and the Brandt's bat (*Myotis brandtii*) were common and occurred at about 50 % of the investigated sites, and in most cases in high abundances. Activities in the main area that might affect the abundance and distribution of bats in a negative way are drainage, and regrowth of vegetation in old pastures (de Jong and Gylje 2005).

There are potential reference areas for comparison in proximity to the Forsmark investigation area. The bat fauna at Forsmarks bruk and Kallerö are included in the monitoring programme of the County of Uppsala and have been visited several times (de Jong et al. 1997, de Jong and Gertz 2001, Gylje, 2004b). Forsmarks bruk and Johannisfors have also been inventoried in a bat survey of the whole province of Uppland (Ahlén and de Jong 1996).

7.2.2 Large scale vegetation distribution

There are a number of potential remote-sensing data sources that can be used to describe vegetation types and their distribution across the landscape. A number of such data sources have so far been used and related data are now stored in the SKB GIS database (Table 7-7). For example, the spatial distribution of vegetation types was presented by Boresjö Bronge and Wester (2003) in a vegetation map that was produced based on remote sensing (SPOT4 from 1999), a soil map and field checks. The spatial resolution is based on the topographical map (5 m) but the resolution of the SPOT4 is 20 m. The vegetation map was later verified by field visits (Alling et al. 2004). It was concluded that the vegetation map identified wetlands with acceptable accuracy, but it was less accurate in distinguishing fertile tree-dominated land from less fertile coniferous woodland.

This map was later updated with regard to clear-cuts in the area using information from the Swedish Forest Agency (Sw: Skogsstyrelsen) for the period mid-2000 to mid-2006 (Löfgren 2010). The map has been used for a number of different purposes, such as environmental impact assessment (EIA) issues, hydrological modelling (MIKE SHE), long-term safety (SR-Site, SR-PSU, Löfgren 2010) and forestry planning in the area. Tagesson (2006) used Landsat 5 satellite images to derive a normalised difference vegetation index (NDVI) and compare with measured leaf area index at the stand level.

Orthophotos generally have a higher resolution than the vegetation map described above and these can be used for extracting further data describing the vegetation. A number of orthophotos are available for the area around Forsmark. Some are already in SKB's possession (Table 7-7) and some are available from Lantmäteriet (the National Land Survey of Sweden). Another product that could be a potential tool for describing vegetation and its change over time would be airborne Lidar data (see also Chapter 4). Lidar (light detection and ranging) is a remote sensing technique using a laser to sample the landscape surface at high resolution, creating 3D images with different densities. Data are available from two earlier scannings of the area. However, only the later one would be applicable, due to the small area that was covered by the first Lidar scanning.

Table 7-7. Description of data sources for Forsmark in SKB's possession useful for remote sensing.

Type of data	Resolution	Year	Reference
SPOT4	20 by 20 m	1999	Boresjö Bronge and Wester 2003
Landsat 5	30 by 30 m	1989, 2000	Boresjö Bronge and Wester 2003, Tagesson 2006
Orthophoto (1:30 000)	0.5 by 0.5 m	1992	Boresjö Bronge and Wester 2003
Orthophoto	1 m by 1 m	2001	Boresjö Bronge and Wester 2003, SDEADM.LMV_FM_FJA_42
Orthophoto (IR)	0.2 by 0.2 m	2001-06-23	SDEADM.MET_FM_FJA_1407
Orthophoto (IR)	0.8 by 0.8 m	2001	SDEADM.GV_FM_FJA_1859

7.2.3 The Sea

In 1998, a survey of the phytobenthic plants and macrofauna was done in order describe the plant and animal communities in the sea in the SFR area (Figure 7-13) (Kautsky et al. 1999). The depth distribution of biomass was estimated in five transects, and sediment cores were investigated from one of the transects and from one deep location. The position of each transect was estimated with a hand-held GPS (precision 60 m), and each transect was documented with photographs and on a map. The investigation method is in accordance with the national monitoring programme of the vegetation-covered substrates of the Baltic Sea, run by the Swedish Environmental Protection Agency (Naturvårdsverket 2000b) and HELCOM guidelines (Helcom 1996). Three transects were also established by Borgiel in 2003 (2004b) in different habitats representative of the area using the same methodology. The coordinates of the transects were obtained using a hand-held GPS and the transects were documented with photographs and on a map. Benthic fauna and macrophytes were described and biomasses estimated.

Further transects were established 2004 (Borgiel 2005) in the sea bays Asphällsfjärden (16 transects), Tixelfjärden (10 transects) and Kallriga (11 transects) (Figure 7-12). In this investigation, a somewhat simplified approach was used in comparison with that adopted earlier but with the same aim to describe the benthic fauna and vegetation. In 2012, vegetation in transects and benthic fauna were again investigated in three areas around SFR (Qvarfordt et al. 2012b). One of the areas was at the inlet to the sea bay Asphällsfjärden. The aim was to establish a baseline and evaluate nature values before potential disturbances in connection with the extension of the SFR repository. The new transect in Asphällsfjärden was compared with transects made in 2004 in Asphällsfjärden and with potential reference areas in Tixelfjärden and Kallrigafjärden. Due to differences in the methodology, it was difficult to make exact comparisons. It also turned out that Asphällsfjärden had more sandy and stony habitats, whereas Tixelfjärden and Kallrigafjärden had more soft bottoms with clay.

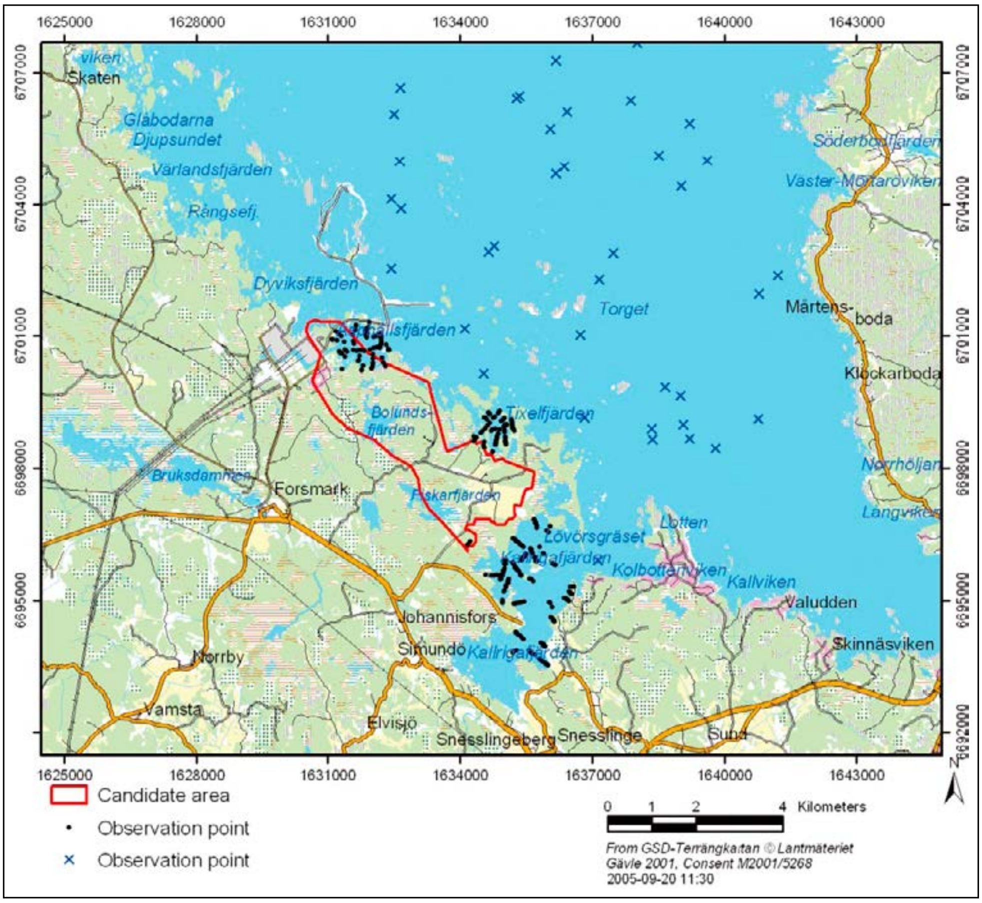

Figure 7-12. *Locations of investigations made in sea localities outside of Forsmark. Dots denote boat and diving transects, crosses denote locations of video recordings. The candidate area, where most site investigations are performed, is shown in red. Figure from Fredriksson (2005).*

Tobiasson (2003) documented the sea bottom outside Forsmark at 48 localities using a video camera. Vegetation coverage and bivalve (*Mollusca*) bottom coverage were analysed in this study. The field work was performed relatively fast and the video was analysed afterwards. This may be regarded as a fast and cost-efficient method, but with a somewhat lower accuracy in terms of identifying species. One important feature is that the video is available afterwards for comparison with future follow-ups.

In order to validate a descriptive marine vegetation model of Forsmark (Fredriksson 2005), Aquilonius et al. (2011) described the benthic vegetation and bottom substrate at 29 randomly selected sites in previously unvisited marine areas. The coordinates of the sites were obtained using a hand-held GPS and the sites were described in accordance with the line-transect method used in the national monitoring programme of benthic vegetation communities on the Swedish east coast (see above).

In nearby areas, at least four earlier surveys of the phytobenthic communities have been performed during the last 50 years (i.e. Waern 1952, Kautsky et al. 1986, Eriksson and Bergström 2005, Eriksson et al. 1998). In the vicinity of the Forsmark area, quantitative data have been collected in the eastern Gräsö–Singö area in the 1940s (Waern 1952), and at a revisit to Waern's stations that was made in 1984 (Kautsky 1989, Kautsky et al. 1986). Hansson (2010) made a study of macrophyte vegetation along 13 transects around Östhammar in 2009, as part of the national monitoring programme coordinated by the Swedish Environmental Protection Agency.

More recently, Hjelm et al. (2012) compared data of species distribution and abundance in bottom vegetation, and young-of-the-year (Y-O-Y) fish communities based on yearly data from 2007–2008 in three shallow sea bays in the western part of Öregrundsgrepen. The bay Stångskärsviken is located north of the nuclear power plant, whereas the bays Hatten and Långörsviken are situated in the nature reserve of Kallriga, south of the power plant. These bays have been monitored since 2002 and these long-term time series are unique. Hansen et al. (2008) evaluated the time series and additional data covering the east coast. It was found that a general problem with comparing the same transects over time is that it is not possible to find the exact location of all transects, which causes the introduction of large uncertainties. Moreover, Hansen et al. (2008) found large variations of inter-annual vegetation coverage depending on the sea-water temperature, whereas it was found that the species assembly is fairly constant between years. Large inter-annual variations, both in terms of vegetation distribution and abundance, were found for enclosed and isolated soft-bottom bays. Hence, such sea bays may need longer time series to generate a suitable baseline.

Heibo and Karås (2005) compiled data of the occurrence and biomass of different fish species in coastal areas at the Swedish east coast. Variation in catch per unit effort and species composition was studied with multi-mesh gill-nets for six localities in the Baltic Sea outside the coast of mid-eastern Sweden. The Forsmark area was compared with the five other areas. In terms of fish catches, there were relatively large differences between coastal areas in general. However, there were small differences between Forsmark and the two areas close to Forsmark. Calculated data for biomass per hectare based on catch per unit effort have considerable uncertainties, but a comparison with literature data for perch and total biomass showed that they are not unrealistic. Thus, they are within the variation that the literature data show for the type of fish community studied.

7.2.4 Lakes

Huononen (2005) and Karlsson and Andersson (2006) made studies of the Lake Fiskarfjärden and Lake Bolundsfjärden, respectively, in order to make a characterisation of the lakes. Huononen (2005) characterised both the benthic vegetation and the macrofauna, whereas Karlsson and Andersson (2006) focused on the benthic vegetation. Sampling locations were randomly distributed within different strata of the lakes. At least the work of Huononen (2005) was in accordance with the methodology suggested by the Swedish Environmental Protection Agency (Naturvårdsverket 2004) making a comparison with similar studies possible.

Blomqvist et al. (2002) sampled water chemistry, plankton, microphytobenthos and sediment bacteria in Lake Eckarfjärden on monthly or shorter intervals during the period January 2000–November 2001. Based on these results, Lake Eckarfjärden was compared with the Swedish lake population using the Swedish National Surface Water Survey 1995 (Wilander et al. 1998). Moreover, Andersson et al. (2003) sampled water chemistry, zooplankton and microbiota monthly or biweekly during the period January 2002–March 2003 in Lake Eckarfjärden. Benthic fauna was also sampled in March 2002 at ten randomly chosen sites with known coordinates. The samples were taken with an Ekman grabber with an area of 2.5 dm^2 and sieved (Ø 0.5 mm). The benthic animals were identified to species, counted, and weighed.

7.2.5 Streams

At present, there is no ongoing ecological monitoring of streams. The hydrochemical monitoring programme includes a number of streams, but this programme does not include chlorophyll or turbidity measurements in those streams. In 2005, a survey was made covering almost seven kilometres of total stream length in the Forsmark area. This survey included variables such as bottom substrate, vegetation, shading, morphometry, periodically flooded areas and description of physical excavations (Carlsson et al. 2005, see Figure 7-13). Generally, the streams in Forsmark are small and approximately 30 % of the surveyed stream length is periodically dry. Approximately 80 % of the stream length that was investigated has been excavated.

In order to establish correlations, the study mentioned above was later complemented by another study that compared vegetation coverage and biomass estimates (Andersson et al. 2011). There are national monitoring programmes describing chemistry, benthic fauna and fish populations in streams. However, the streams included in national monitoring programmes, such as Forsmarksån, which is included in a national chemistry monitoring programme, are much larger than the streams in Forsmark. The closest stream included in the monitoring of benthic fauna is Sävjaån at Ingvasta south of Forsmark.

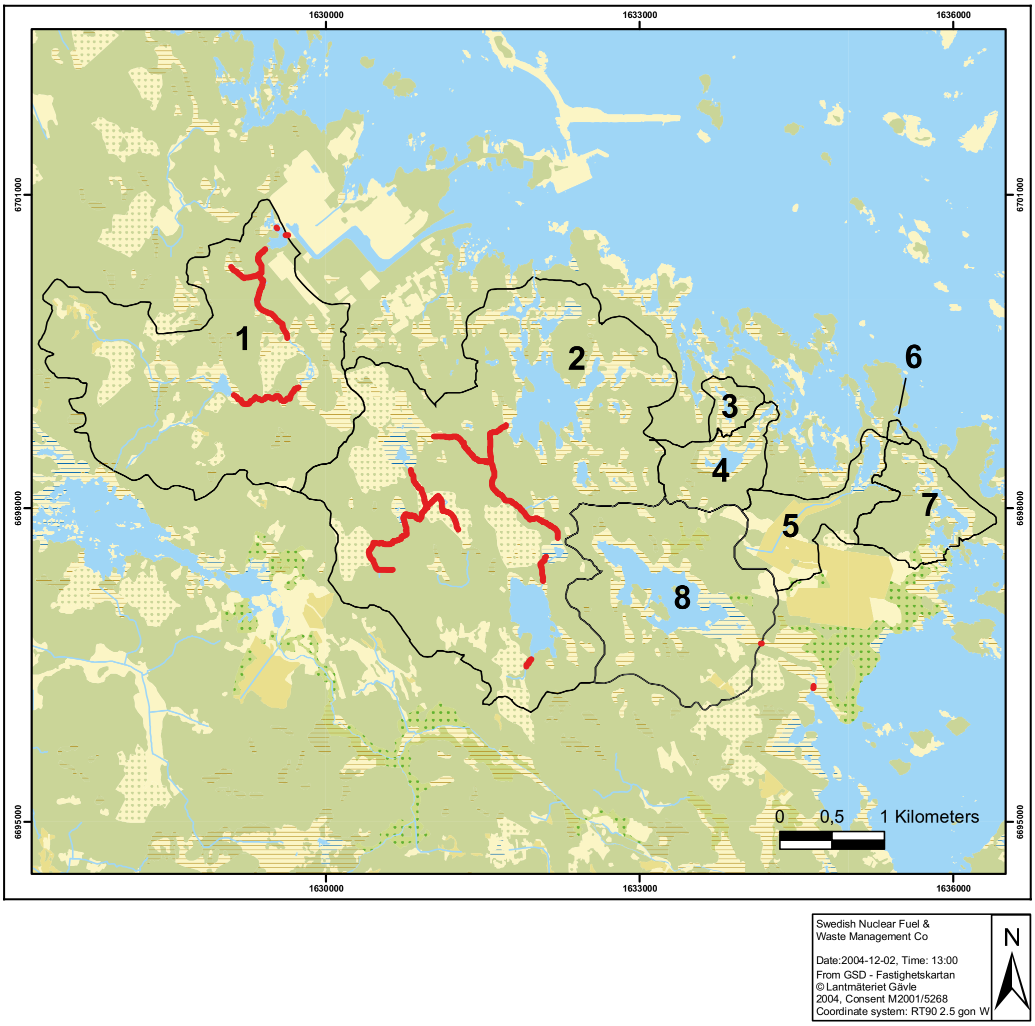

Figure 7-13. Stream sections investigated during a characterisation study in Forsmark (Carlsson et al. 2005).

Loreth (2005) studied the fish migration in a small, narrow and short stream between the sea bay Asphällsfjärden and Lake Norra Bassängen. During a period from March to May in 2004, an attempt was made to catch all migrating fish by using a fyke-net. The catch was registered by species composition, weight classes and amount caught of each of the species. During the six-week period over 18 000 fish were caught and released. This illustrates the importance of small streams for giving access to suitable spawning habitats for coastal fish populations.

In 2013, Olsson et al. made a similar study to describe the fish migration further on up to Lake Bolundsfjärden and Lake Puttan during 14 days in April to May 2013. 2 259 fish were caught (Olsson et al. 2014). The study showed that the majority of the migrating fish were going up to Lake Bolundsfjärden, which is more suitable in terms of stream depth and width compared to the narrow stream up to Lake Puttan. SKVVF (Svealands Kustvattenvårdsförbund) yearly monitor fish migration in nine rivers, of which Forsmarksån and Tämnaren are close to the Forsmark area (SKVVF 2015). However, these streams are much larger than the streams in Forsmark.

7.2.6 Terrestrial vegetation descriptions

In 2001 and 2002, a number of sampling localities were identified in order to provide detailed vegetation data and future monitoring possibilities (Abrahamsson 2003) for terrestrial vegetation types. Three areas were located close to drill sites and a further three were located to cover forest, wetland and coastal areas (Figure 7-14). In these areas, 38 large squares were evenly distributed. Within each large square 24 small permanently marked plots (1 m by 1 m) were located both in a systematic and a random design, where species and their coverage in the bottom, field, shrub and tree layer were estimated (Table 7-8). Moreover, the volume of standing wood was estimated based on basal area and mean height, making it possible to detect effects on the tree net primary production. The spatial distribution of these areas make them suitable for comparing potential effects on the vegetation of a groundwater-table drawdown as they are found both inside and outside the area where the groundwater-table drawdown may occur.

Table 7-8. Distribution of the monitoring among vegetation types, localities, large plots and small plots by Abrahamsson (2003). Each large plot contained a set of small plots (1 m × 1 m) placed in a systematic (n=9) and a random design (n=15).

Vegetation type	Localities	Large plots (30 m by 30 m)	Comment
Wetland	2	4	One locality with three large plots
Coastal wetland	1	1	
Forest	2	28	Forested plots were located within five of the six localities
Agricultural land	1	5	

The Swedish National Forest Inventory has permanent and temporary plots located in the vicinity of Forsmark (SLU 2002). Data include the presence and development stage for 267 different plant species and groups. Percentage coverage is also recorded for 71 species. Data are collected every 5th year, which can be used as reference for comparing trends on a regional or national level. Tagesson (2006) used data from such temporary plots and four other stands located at Forsmark (Figure 7-15) in his study of how stand characteristics, such as tree volume and age, affect the leaf area index.

In 2004, Löfgren (2005) sampled six different vegetation types with the aim of describing distribution of biomass and net primary production. The sampled sites were located at the same places as the investigation made according to The Swedish Forest Soil Inventory (see below). However, the rather few replicates (five) within each plot would cause difficulties when comparing changes between years, if no large changes are expected.

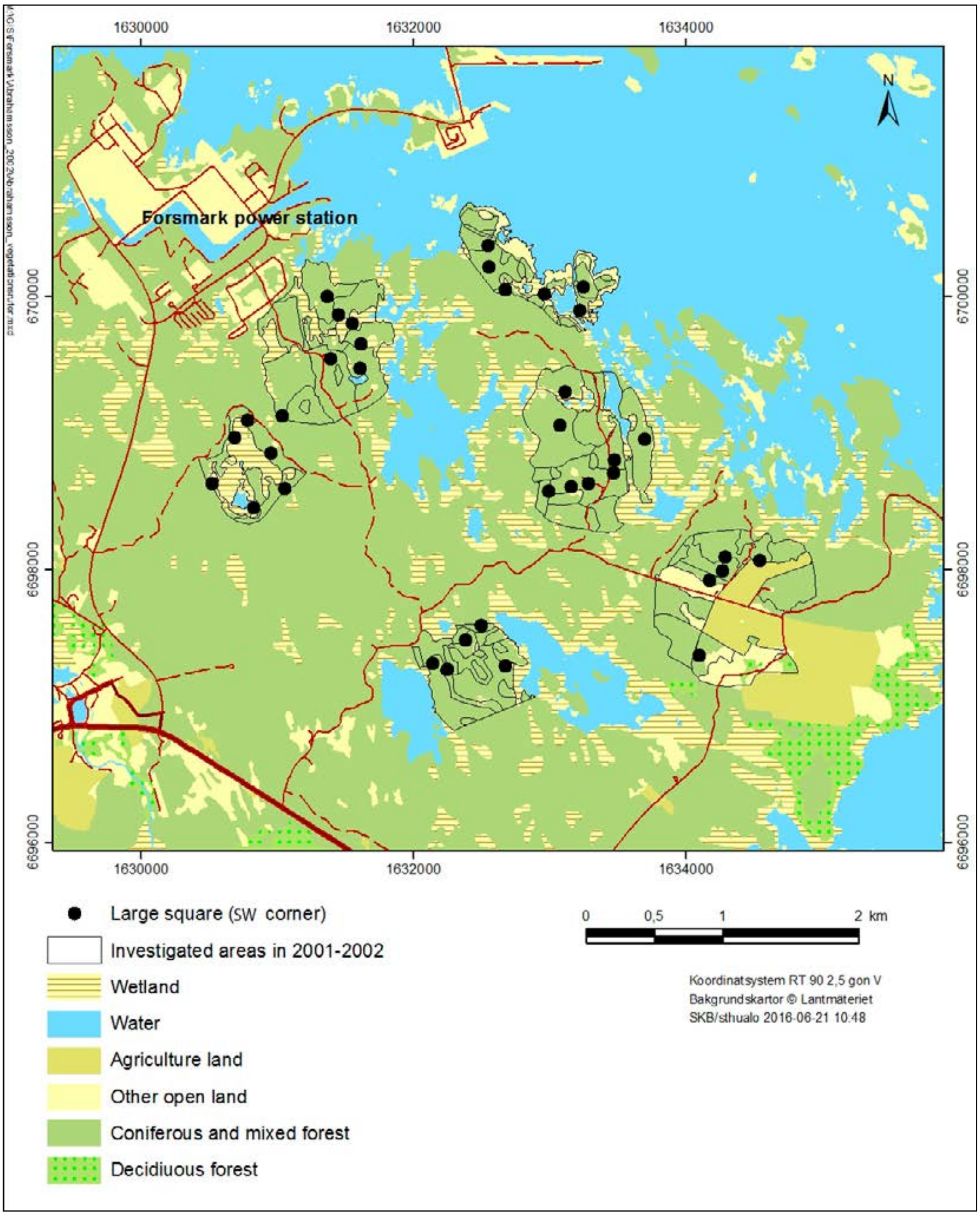

Figure 7-14. *Distribution of investigated areas presented by Abrahamsson (2003). Each square corresponds to a "large square" in Table 7-8.*

In the Forsmark area, the Swedish Forest Soil Inventory identified eight site types that were selected and representative plots were thoroughly investigated (Table 7-9, Lundin et al. 2004). Each of the eight types had two replicates, making up 16 investigated plots. Vegetation types and dominating species within the list of species used in The Swedish Forest Soil Inventory and percentage of coverage were determined. Soil samples from the ground surface down to a maximum depth of 1 m were analysed for a range of variables including pH, nitrogen, carbon, base saturations and heavy metals.

Figure 7-15. The location of the temporary plots from The Swedish National Forest Inventory (NFI) and the additional plots that Tagesson (2006) used in his study of how tree volume and stand age affect the leaf area index.

Table 7-9. The eight soil and site types that were identified and sampled using the methods of The Swedish Forest Soil Inventory (Lundin et al. 2004).

Soil class	Vegetation type
Histosol	Peatland
Gleysol	Swamp forest
Cambisol	Deciduous forest
Regosol/Gleysol	Arable land
Regosol/Gleysol	Coniferous forest
Arenosol/Gleysol	Shoreline
Regosol	Esker
Leptosol	Thin soil and bedrock

7.2.7 Description, characterisation and identification of nature values

Hamrén and Collinder (2010) described the nature values of conservational interest in the area around Forsmark, both in general terms and in more specific terms. Habitats of special interest, such as wetlands and forest areas, were identified, and also species found in such habitats, e.g. wetlands species, dragonflies and molluscs. For example, species lists of land molluscs and dragonflies were put together for 13 different wetlands, and benthic fauna and vegetation were described for four ponds. These inventories and others (fish and fungi) were aiming at making descriptions of the species present and to enable use of the species list as an input to evaluate the conservational value of the habitats. Therefore, it is difficult to use these as a direct input for detecting changes if not large changes would be expected.

Göthberg and Wahlman (2006) made a characterisation of 19 wetlands in the Forsmark along the gradient extremely rich fen – fen – bog using a set of species indicating different abiotic conditions. In total five extremely rich fens, eleven rich fens, one fen and two mixed wetlands were identified among the 19 wetlands. An inventory designed for classification and characterisation of nature values in rich fens was applied on 12 wetlands (Sundberg 2007) whereas further 53 wetlands was described in regard to the presence of certain indicator species (Hamrén and Collinder 2010).

The Swedish national wetland inventory (VMI) has surveyed in total 35 000 objects (Gunnarsson and Löfroth 2009). This inventory has been focused on the characterisation, delineation and identification of nature values in wetlands – not on environmental monitoring per se. VMI has used a size limit to the visited wetlands, where objects with a high nature value above 10 ha have been visited. The vegetation type classification within wetlands is made according to a Nordic classification scheme (Påhlsson 1994), which would be a valuable tool in combination with monitoring using remote sensing.

A number of different taxa have been included, e.g. vascular plants and bryophytes, and assigned to the different vegetation types, but it has not been a systematic approach that would be useful in a comparison on a shorter time scale where more exact distribution and abundances of species would be necessary information. Overall, this makes VMI biased towards larger wetlands with high nature values. Nevertheless, approximately 18 large wetland-lake complexes have been described within VMI in the Forsmark area. In Hamrén et al. (2010) and Allmér and Collinder (2014), more specific analyses were made of how activities during construction works at the site would affect areas and species of conservational interest.

8 Recommendations

This chapter describes the recommendations resulting from the discipline-specific analyses in the preceding chapters (i.e. Chapters 4–7), and summarises the inputs from each discipline to the updated programme presented in Chapter 9. The recommendations are presented in sub-sections in the same order as Chapters 4–7, i.e. geology is reported in Section 8.1, meteorology and hydrology in Section 8.2, hydrochemistry in Section 8.3 and ecology and nature values in Section 8.4.

8.1 Geology

As mentioned in Chapter 1, technical installations for geoscientific and ecological monitoring at Forsmark started in 2002, and the monitoring programme was successively expanded during the years that followed. Nevertheless, some monitoring systems, among others for seismic as well as aseismic monitoring, are today awaiting set-up and/or continuation. For the nano-seismic network, design and construction must be completed. For the GNSS monitoring the stations need maintenance and upgrading. This is explained in detail in sections 8.1.3 – 8.1.5. Although the available time for *baseline* monitoring is still several years, it is important that initiation of the remaining monitoring systems can be accomplished in a near future.

As regards monitoring of the extremely small local seismic as well as aseismic motions that are supposed to prevail in the area, a complicating factor is that advanced, non-conventional methodology is indispensable in order to achieve the demanded accuracy. However, to assess which of the methods available today are the most appropriate from technical, geoscientific and economic aspects is not trivial, but selection of methods must be done. In Section 8.1.2 the continued efforts to establish a local, high-resolution seismic network are presented, and in Section 8.1.3 and Section 8.1.4 two methods for measuring aseismic motion are suggested, whereas in Section 8.1.5 an alternative method is commented on. A final selection of methodology ought to be made as soon as possible.

The deformation zone pattern, as illustrated in for example Figure 4-10, is one of the most important governing factors when planning design and determining likely field performance of rock deformation measurements using current and future measurement systems at Forsmark.

8.1.1 SNSN monitoring

The agreement between SKB and Uppsala University regarding seismic monitoring within SNSN (the Swedish National Seismic Network) was re-negotiated early in 2012. The current agreement, which is valid from 2012 to 2021, states that the seismic monitoring should continue according to basically the same principles as during the period 2002–2012. According to the agreement, Uppsala University shall:

- Maintain management and upkeep of the seismic network.
- Carry out routine analyses of seismic data.
- Discriminate (as far as possible) non-seismic events, like blasting, from real earthquakes.
- Take adequate measures in case of strokes of lightning.
- Maintain preparedness in case of earthquakes.

The university shall also analyse seismic data from the network and perform quality checks on delivered data according to a quality plan agreed by SKB and Uppsala University. For earthquakes registered by three or more stations, the following parameters shall be assessed by the university:

- Focus (hypocentre) time, localisation and depth.
- Orientation of possible fault planes and directions of motion.
- Local magnitude and seismic moment.
- Fault radius, maximum motion and static stress release.
- Confidence coefficients for the parameters above.

Uppsala University shall quarterly deliver data to SKB regarding the parameters mentioned above. Based on this agreement an extensive, high-quality seismic dataset will be created, covering first a *baseline* period of substantial length and later also at least part of the *post-baseline* period.

8.1.2 Establishing a local, high-resolution seismic network

Part of the preparatory work necessary in order to achieve a good functionality of the planned local, high-resolution seismic network was described in Section 4.2.1, among other activities including two studies of seismic and electromagnetic background noise at the Forsmark site (Lund et al. 2012, 2017).

From these studies, it is obvious that the seismic noise in the Forsmark area is considerably higher than would be optimal for seismic monitoring. One of the main results of the study performed in 2013 (reported in Lund et al. 2017) is the realisation that with geophones with too low a sensitivity (corresponding to normal single geophone sensitivity) it is impossible to record true ground motion in the frequency band of interest for the repository seismic network. It was found that geophones with nominal sensitivity of at least 400 V/m/s, given the noise characteristics of the IMS digitiser, should be used to be able to record true ground motion over the entire repository area. An additional, external high-quality pre-amplifier would also increase the sensitivity. Borehole geophones should be used, and once these are effectively connected to the bedrock, e.g. by cementing, the response will most likely improve in certain frequency bands over what was observed in the 2013 study.

There is significant seismic noise from the nuclear power plants in the repository region, both wide-band noise below 100 Hz and narrow-band high-noise levels at higher frequencies. This will be a challenge for the repository seismic network. The seismologists at Uppsala University suggest that the network initially is instrumented with a limited number of high-sensitivity geophones, ideally placed in boreholes at 30–200 m depth, below the gently dipping fracture zone that covers much of the repository area. The borehole stations should be augmented by a few surface stations, especially in the vicinity of the construction of the tunnel. As excavations progress and seismic events from the construction are being analysed, the network should be gradually expanded based on the need to improve the analysis and to cover certain volumes more accurately. If smaller seismically active volumes are identified at depth, then there may be a need for a dense installation of geophones or accelerometers in that volume. The repository network should also be linked to SNSN in order to improve the analysis of larger events.

As a next step toward the realisation of the network, it is proposed that a detailed network design phase where the seismic noise studies (Lund et al. 2012, 2017) are combined with information on available boreholes, suitable sites for surface installations and the repository layout. In addition, a thorough inventory of commercially available hardware, software and support should be performed to aid the design decisions. Issues such as time synchronisation, downhole digitisers and data communication should be analysed. Experience from running local, high resolution networks should be gathered from e.g. the Finnish repository network at Olkiluoto and the LKAB mines in Kiruna and Malmberget.

8.1.3 GNSS monitoring

Based on the results and experience from the GPS field campaigns and the subsequent analyses described in Section 4.2.1, it is recommended that the GNSS monitoring (Global Navigation Satellite System), which was interrupted in 2009, is resumed. Furthermore, the equipment and measurement procedures should be adjusted to be optimal also for registration of non-linear motions with an accuracy of better than one mm/year. The aim is primarily to identify the amplitude and periodicity of all Fourier components with a periodicity shorter than twice the length of the measurement campaign. The periodicities based on the measurements 2005–2009 may possibly be seasonal and of meteorological-hydrological origin, but other physical processes like solid earth tides governed by, for example, the Sun, the Moon and the planets Venus and Jupiter cannot be ruled out. Long-term motions are treated as linear components which are expected to be resolved as the measurements continue.

The purpose of resumed GNSS monitoring with subsequent analysis consisting of system identification and spectral analysis is to, with a high degree of accuracy, establish the magnitude of the long-term motions. In addition, these motions should be further characterised, thereby procuring a foundation that in a longer perspective may promote identification of the underlying processes, with the ultimate goal of making predictions of future rock behaviour possible. Re-commenced GNSS measurements should avoid aliasing effects (see Section 4.2.1). Therefore continuous instead of intermittent measurements are suggested. The monitoring should be automated to normally provide continuous data, and the data sampling stations controlled via the Internet. To secure availability of sampled data, the system should be supported by a back-up system, for example the possibility of manual data dumping at each sampling station in case of breakdown of the primary system. It should also be emphasised that longer data sets increase the data confidence regarding rock deformation.

Furthermore, experience from analyses of very small deformations stress the importance of avoiding sources of error related to the satellite constellation. Besides the GPS it is now possible to employ the completely independent GLONASS constellation (see Section 4.2.1), which has a different geometrical distribution in the firmament than GPS, and also an independent clock error. However, the Galileo, Beidou and IRNSS constellations are not yet operational, but may later be available. It is therefore proposed that GNSS monitoring initially is performed by using the two currently available independent navigation-satellite systems, GPS and GLONASS, on the L1 and L2 bands. It is also recommended that L1 and L2 data are analysed separately in order to possibly reveal any atmospheric systematic error source. Finally, it is recommended that GNSS systems under development are kept under review by SKB, with the purpose of being in a state of readiness to later integrate new satellites into SKB´s GNSS monitoring system.

Regarding instrumentation, it is suggested that the existing GPS stations at Forsmark are replaced by GPS L1/L2 plus GLONASS L1/L2 stations with integrated mobile connections to the Internet. The stations should be equipped with batteries (24 hours of battery-powered operation) connected to a solar panel and an internal Windows PC. When changing antenna, the phase centre is dislodged, and therefore instrumentation adjustments need to be undertaken to address this issue.

However, the original GPS stations ought to be inspected and, if needed, repaired and upgraded, and hence made fit for continued measurements so that at least one measurement campaign can be used to connect the geometry of the new set of stations to the old set. It is also suggested that the old GPS stations are kept long-term operable to enable future independent quality checks. If one or several of the new stations indicate diverging or in any other respect suspect values, some of the old stations may be used. The new stations are proposed to be located close to the old ones, however with consideration to best possible visibility and other practical circumstances at the respective locations. Those of the old stations in good shape are suggested to be used in one or a couple of measurement campaigns per year for integrity control of the entire system.

A sampling frequency of 1 Hz is suggested, which leads to a quantity of data of 250 Mb/24 h that can be transferred during less than 5 minutes at typical transfer rates of 1 Mb/s. Post-processing of data from the entire measurement period will be performed with the purpose of identifying motions with a periodicity of down to one day.

8.1.4 DInSAR measurements

It is recommended that DInSAR analyses of the Forsmark area are taken up again as a complement to GNSS measurements. It is of vital importance that monitoring with these two methods covers a period before and after the start of underground constructions at Forsmark. A combination of the two between themselves independent technologies GNSS and DInSAR vouches for determination of the 3D deformation characteristics of the Forsmark site of highest possible quality with regard to today´s existing technology.

For future monitoring applications, which preferably again should employ the PSInSAR methodology, it would be useful to install a number of artificial reflectors of the types illustrated in Figure 8-1 in well-chosen locations. By installing these reflectors on bedrock, it can be assured that any motions measured are not due to compaction or other local phenomena. It would be advantageous if the reflectors could be located close to the GNSS stations, on the same outcrop, presupposing that the reflectors do not deteriorate the visibility of the GPS stations and vice versa.

Figure 8-1. Artificial PS corner reflector installed near Tafjord, in Norway. The reflector is constructed of 10 mm thick aluminium. Figure from Dehls (2006, Figure 4-1).

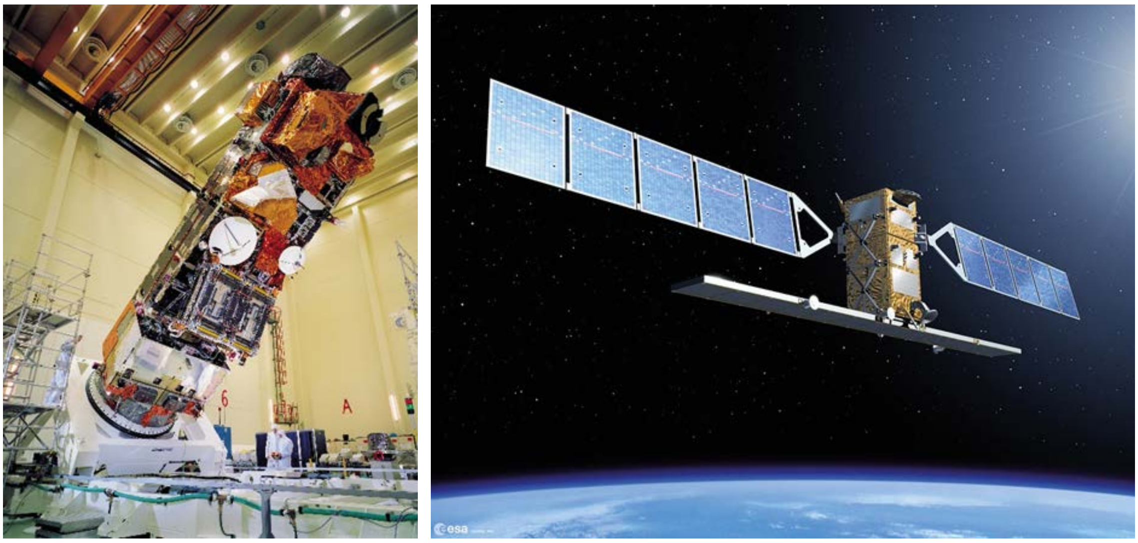

Figure 8-2. The ENVISAT satellite. Left: Interior. Right: In operation. Figures from Wikipedia.

With the failure of gyroscope 1 onboard ERS-2 on January 7th, 2001, very few images have been of sufficient quality to use for interferometry since then. However, the ESA satellite ENVISAT (*ENVironmental SATellite)*, launched in March, 2002 (see Figure 8-2), is in the same orbit as ERS-2 and is able to obtain very similar images using its ASAR (*Advanced Synthetic Aperture Radar*) instrument. It is possible to combine ERS and ASAR images to do PS analysis (Colesanti et al. 2003). Another possible source of radar images is the Canadian Radarsat 1 and Radarsat 2 satellites. Unfortunately, all of these satellites only acquire images upon request. It would be advantageous if SKB arranged for the acquisition of both ENVISAT and Radarsat images over possible monitoring sites on a regular basis.

8.1.5 Lidar

A third method for measurements of aseismic ground motion that may be worth considering for the monitoring programme is so called Lidar (a merger of "light" and "radar") measurements. Lidar is a remote sensing technology similar to radar that measures distance by illuminating a target with laser radiation and analysing the reflected light, i.e. Lidar (like radar) represents a two-way measurement application. The most important difference compared with radar is that the carrier wave is shifted towards higher frequencies and that the ray is collimated. Lidar uses ultraviolet, visible and near infrared light frequencies (c. 10^{16} to 10^{14} Hz) to image objects. High frequencies and collimated radiation are advantageous factors regarding accuracy.

However, Lidar has so far primarily been used for ground-based applications. Measurements along the ground surface, irrespective of method, are associated with several methodological problems, for example difficulties to keep the line of sight free and atmospheric disturbances, which in many cases are especially large close to the ground. Hence, ground-based Lidar does not appear as an optimal option for replacing GNSS or DInSAR measurements in the SKB monitoring programme. The use of Lidar measurement as double-check of one or two baselines, where free line of sight is possible, may be considered, presupposing that the main methods for deformation measurements are GNSS and DInSAR.

Another possibility is airborne Lidar, in other words laser measurements made from an aircraft. However, with a moving aircraft as the measurement platform, the system is dependent on GPS for determination of its position, and the error sources are therefore the sum of those for GPS and those of the Lidar system itself. Therefore, this system is not favoured, at least not if a very high accuracy is required.

Finally, Lidar measurements could be made from satellites (so called laser ranging), which in theory would be a favourable solution for ground deformation applications, however, not completely without error sources. Even a laser beam is somewhat degraded over large distances, which deteriorates its accuracy. However, it is recommended that SKB follows future technological Lidar developments. An investigation ought to be made, aiming at answering a number of questions. For example, are satellites available for commercial laser ranging? In other words, the question is whether satellite-borne Lidar data will be available for SKB and, if so, from how many satellites. What would be the costs for data ranging, compared with GNSS and radar monitoring, and what level of data accuracy may be expected?

8.1.6 Monitoring of earth electrical currents

As described in Section 4.3, monitoring of earth electrical currents is difficult and the results and usefulness of monitoring data are often questionable. However, some measurements are useful and therefore continuous measurements of the electrical field in the ground outside drill site 1 will be made starting in 2015. Measurements in KFM04A with the zinc electrode will continue, and the monitoring staff will follow-up the actions taken against corrosion. Also, signals from the active cathodic protection will be connected into HMS for continuous monitoring. The measurements are carried out in close collaboration with experts on corrosion and cathodic protection.

8.1.7 Monitoring of the global magnetic field

Surveying of borehole deviation with magnetic methods relies on knowledge of the local declination of Earth's magnetic field. Measurements during magnetic storms should therefore be avoided since they may cause declination variations (Figure 4-32 and Figure 4-33). If measurements accidentally were made during unstable magnetic conditions, they should be flagged as bad and not be used in further analyses. Information about magnetic activity is easily available, e.g. from the magnetic observatory at Fiby.

Taking the above into account it may seem that it is not necessary to monitor the magnetic field locally at Forsmark. However, since declination variations are different at different locations (cf. Figures 4-32 and Figure 4-33), at some point the question will arise as to whether a borehole survey must be rejected due to temporal declination variations when the variations are close to a set acceptance threshold value. It would then be beneficial to have declination measurements available from a local instrument at Forsmark, and it is therefore recommended that a local monitoring site is set up. Magnetic monitoring with an acceptable accuracy for this application can be set up at a reasonable cost.

Magnetic monitoring does not have to be carried out continuously. Measurements during borehole surveying or other magnetic measurements will suffice. Another motive for setting up a monitoring site is that it at the same time can serve as a calibration and check site for downhole magnetic surveying tools.

It is important that magnetic borehole surveying tools are regularly checked. A test rig where the probe can be rotated is a helpful tool. It is also important to check that the correct magnitude of the magnetic field is measured by the three orthogonal sensors and that they are not significantly disturbed by e.g. batteries, electric wiring or logging cable sheath. Measurements with the logging tool at a test rig should preferably be checked against an independent calibrated magnetometer, e.g. a magnetometer that is also used for monitoring. Tool checks for magnetic instruments are described in Sindle et al. (2006).

8.2 Meteorology and hydrology

This section presents the recommendations for continued meteorological and hydrological monitoring at Forsmark. The presentation consists of a set of general recommendations that concern common issues such as data handling, followed by subsections dealing with recommendations focusing on the specific monitoring categories described in the subsections of Chapter 5. The recommendations are primarily derived from the evaluations in Chapter 5, with some additional general considerations not described there.

8.2.1 General recommendations

The following general recommendations are given regarding the meteorological and hydrological monitoring.

- Continued monitoring and associated data evaluations will be directed towards two main user groups: site-descriptive modelling/safety assessment, and environmental impact assessment/repository design and construction. In principle, the first group handles the undisturbed (natural) system and its short- and long-term developments, whereas the second group handles disturbances and measures to reduce or eliminate them during construction and operational activities. Moreover, the magnitude and spatial/temporal distribution of disturbances also provide important information for the site understanding. There is hence a need to develop methodologies and tools to detect and quantify short- and long-term changes, and to discriminate between natural and man-made changes. Such detection and discrimination requires interdisciplinary monitoring data evaluations (hydrology-hydrogeology, chemistry and ecology), and continuous access to reference data. These needs strongly support a continuation of the methodology development that has been initiated at SKB.
- The latest exhaustive evaluation of meteorological and hydrological monitoring data from Forsmark was performed in conjunction with SDM-Site using time series recorded up to March 2007, whereas a slightly less extensive evaluation was performed as a part of SR-PSU based on data covering the period until the end of 2010. This means that a significant amount of data has accumulated since the latest data evaluation, but also that the monitoring network has undergone changes; some monitoring installations are no longer in operation, but there are also a relatively large number of new ones. It is recommended that a data evaluation, similar to the one in SDM-Site, is performed. Until this has been done, it is difficult to make a comprehensive assessment of the presently available monitoring network. All recommendations below concerning additions to and reductions of the network should be regarded as preliminary, and a more fully elaborated proposal should be produced when the recommended data evaluation is finalised.

- There is a need for significantly faster data flows from measurements via databases to users. In particular, this will be critical once underground construction works have started and monitoring should give feedback regarding consequences of ongoing activities. However, an improved data handling system must be developed and put into operation much earlier than that, i.e. well in advance of any preparatory activities that could affect surface and/or subsurface systems. One possible direction of this development is to complement the present system with an "on-line monitoring/early warning system" where monitoring data can be observed and checked for outliers, problems, errors, and also against threshold values, continuously and more or less immediately after they are recorded.
- Previously produced datasets with basic site data should be merged and continuously updated as new data are collected. The main motivation for this is that SKB must provide consistent information about the site in all the different contexts such information is required. Therefore, such information must be readily available. Which parameters to include could be determined at a later time, but the mean annual air temperature and basic water balance parameters such as the mean annual precipitation, evapotranspiration and runoff should be included in the dataset.
- The annual reporting of monitoring data should be developed to contain also a basic data evaluation (evaluation of the actual data collected during the year and what can be said about site conditions and their change). One motivation for this evaluation is that SKB always should have access to up-to-date information about the site (e.g. in the above-mentioned dataset). It is also important to frequently make a general check of information provided by the time series monitoring, e.g. to identify and rectify problems with monitoring installations.
- Wetland environments are central to many aspects of site understanding, short- and long-term site development, and consequences of repository construction and operation. It is therefore recommended that a separate study is carried out to identify and describe additional monitoring needs related to wetlands. Possible complementary monitoring includes measurements of water saturation dynamics in soil near wetlands, distributed temperature measurements in order to understand when and where freezing takes place (and possibly also to detect groundwater discharge), and measurement campaigns in existing "multilevel sampling nests" in three Forsmark wetlands.
- Modelling results have shown that potential future discharge areas for groundwater from the planned spent fuel repository volume are often located along future streams. It should be assessed whether the streams within the present land area are relevant and representative as analogues for streams in future land areas and, if so, how monitoring of groundwater conditions in the vicinity of streams could be arranged.
- Criteria for when data are to be removed from the time series used in site descriptive and numerical modelling (i.e. when data are considered "erroneous") should be developed and documented. It is also recommended to change the HMS routines so that complete raw-data sets, including all data removed as part of quality control (i.e. "erroneous" data), are kept in HMS to enable further analyses at later stages.
- It is recommended that methods are developed and documented on how missing data for important parameters shall be estimated as a basis for the baseline, water-balance calculations, model calibrations, and to provide continuous boundary conditions (i.e. how to fill in gaps in time series).
- Systematic analyses of differences in water levels and calculated discharges using temperature-compensated and uncompensated water levels are needed. Wherever possible, it is recommended to change Mitec data loggers to temperature-insensitive loggers.
- Previous, not yet reported, and forthcoming monitoring data and installations should be reported in one of SKB's public report series.
- Manual measurements in surface-water level gauges and groundwater-monitoring wells should be stored in Sicada, for gauges and wells in which only manual measurements are done. At present, manual measurements are only stored in the "Lodis" database.

- The SKB method descriptions for hydrological measurements and groundwater monitoring should be supplemented by estimates of measurement uncertainties, and issues of relevance for continued, long-term monitoring, such as quality control, function controls, maintenance and control measurements. For instance, it should be made clear what to do when different types of equipment fail, that is whether the "default" should be to replace it or not, or if a study evaluating the need for replacement should be initiated.
- Finally, it should be noted that even though relevant method descriptions obviously are needed they cannot cover every possible issue and situation. It is therefore important to have people available with knowledge of the natural processes under monitoring and of the use of the data in modelling and impact assessments involved in decision making related to monitoring. Preferably, this could be done by having designated persons responsible for each modelling discipline to provide a link between monitoring and modelling.

8.2.2 Meteorology

Recommendations

The following recommendations are provided regarding the meteorological monitoring.

- Procedures for checking data deliveries should be developed to give assurance that datasets from surrounding SMHI stations that are stored in Sicada are complete and well documented, and that annually delivered datasets are relevant, e.g. as redundancy in case of instrument failure.
- SKB is recommended to compile and evaluate all AMS (automatic meteorological station) data, from the local stations and the surrounding SMHI stations, to assess differences and correlations between locations, sensors, and potential errors and differences. The evaluation should include methods for quality control, methods to fill in missing data and needs for redundancies.
- Some of the most important meteorological parameters are obtained from procedures involving model calculations or corrections. SKB is recommended to evaluate these data post-processing procedures, such as precipitation corrections and calculations of potential evapotranspiration.
- Accumulated precipitation is recorded, which offers a possibility to fill data gaps. Therefore, the recommendation is that the time series of accumulated precipitation are reported to Sicada, and guidelines for how they should be used in filling data gaps should be developed.
- It is essential that the immediate surroundings of the AMS are not allowed to change such that measurement conditions are affected. Therefore, a plan for regular removal of trees, bushes and similar maintenance of the AMS surroundings should be devised.
- SKB should secure the access to technical and other types of support for long-term AMS monitoring.
- Concerning the monitoring of "winter parameters", it is recommended that the procedure and criteria applied when recording times for ice freezing and break-up in Lake Eckarfjärden and at the sea are documented.

Main inputs to the update of the monitoring programme

The meteorological monitoring programme is summarised as follows.

- The general recommendation concerning the AMS monitoring is that it continues according to present plans. This means that one local AMS (i.e. one measurement location) is judged sufficient to fulfil the data needs, and the move of the AMS to the new location at drill site 1 was finalised once sufficiently long overlapping time series were available. In order to assess potential instrument errors and for redundancy purposes, parallel measurements are currently in operation using "new" and "old" equipment at the new AMS location (Labbomasten).
- As a basis for recommendations regarding long-term ground-frost measurements, which were discontinued due to various technical problems, it is recommended to evaluate the potential usefulness of and appropriate methods for such measurements. It is also recommended to evaluate the design of the current snow-depth and ice-cover monitoring programmes (Section 5.3.1).

8.2.3 Hydrology – streams

Recommendations

The following recommendations are given regarding the hydrological monitoring of streams.

- Refurbishments and buildings are required to make stream-gauging stations suitable for long-term monitoring, and the effects of the PFM005764 and PFM002669 refurbishments should be evaluated. As part of the design of future refurbishments, the current two flumes at the PFM002667 station should be replaced with a single flume, with higher accuracy in a narrower discharge range.
- It is essential that datasets delivered from the SMHI station Vattholma are complete and well documented, and that annually delivered datasets are relevant, e.g. as reference for the stream-gauging stations at Forsmark.
- It is recommended to test and evaluate at least one alternative method for regular, independent discharge measurements in order to check the function of the stations.
- Further knowledge should be gained regarding the influences of, for instance, flume and observation-well movements and altered inflow conditions on calculated stream discharges.
- The Sicada database contains estimated stream-discharge data up to the end of 2010. It is recommended that estimated discharge data are labelled as estimated in Sicada.
- In order to attain higher accuracy in the stream-discharge monitoring, it is recommended to consider methods other than pressure sensors, such as ultrasound devices, to measure water levels in flumes.
- The SKB method description neither provides specific information on discharge measurements using flumes, nor does it include EC and temperature measurements. The relevance of the method description can therefore be questioned, and an update is recommended.

Main inputs to the update of the monitoring programme

The programme for hydrological monitoring of streams is summarised as follows.

- The general recommendation concerning the stream-gauging stations is that the monitoring continues at all four stations, with the most downstream station (PFM005764, near Lake Bolundsfjärden) being the main and prioritised one (see Section 5.4.1). Of the other three stations, the two upstream stations at Lake Eckarfjärden (PFM002668) and Lake Gunnarsboträsket (PFM002669) have worked well and are considered valuable reference stations. They should remain in the programme and be refurbished, if necessary. Conversely, the fourth station (PFM002667) shows measurement problems in certain flow situations, and the long-term need for and use of this station should be assessed as soon as major maintenance needs arise.
- It should be evaluated whether EC and temperature are to be part of the long-term monitoring. If judged motivated to continue the monitoring, there is a need for methods that produce reliable EC and temperature data. The refurbished PFM005764 station could be used in such a study of measurement methods.
- The usefulness of the SMHI station Vattholma to provide reference discharge data should be evaluated, and it should also be investigated whether data from Forsmarksån could be obtained.
- In conjunction with the assessment of the potential need for monitoring hydrological interactions between streams and groundwater, it should be considered whether monitoring of stream water levels should be performed (other than that at the discharge stations), and how it could be performed. It should also be considered to use indirect methods to monitor such interactions, such as DTS (distributed temperature sensing).

8.2.4 Hydrology – lakes, ponds and the sea

Recommendations

These are the recommendations concerning the hydrological monitoring of lakes, ponds and the sea.

- There is a need for developing more sustainable technical solutions for long-term water level measurements in lakes and ponds, since the present installations tend to move vertically due to the effects of ice and/or unstable foundations. It is therefore recommended to improve gauge and monitoring well installations below surface water by (preferably) developing the monitoring installations, and/or to develop simpler methods for regular displacement checks of the equipment.
- The SMHI sea-level gauge is important for quality control and as a redundancy for SKB's sea-level gauge. If the SMHI gauge is decommissioned during the course of the long-term monitoring programme, SKB is recommended to install a second sea-level gauge for the given purposes.
- Water temperature is important for many of the processes and species associated with nature values of ponds and wetlands. Methods for long-term monitoring of water temperature in ponds need to be improved. One alternative that should be considered is to use indirect methods such as DTS (distributed temperature sensing), which could provide data for assessment of freezing/thawing processes and groundwater recharge and discharge in wetlands.

Main inputs to update of monitoring programme

The programme for hydrological monitoring of lakes, ponds and the sea is summarised as follows.

- The general recommendation regarding this part of the programme is that the present monitoring continues (see Sections 5.5.1 and 5.5.5). As an extension of the present programme, it is recommended to install a surface-water level gauge (or some other surface-water level monitoring equipment) in Lake Puttan. As described above, the primary development needs are related to the measurement installations themselves.
- During the last few years, several monitoring locations in ponds, both natural and new man-made ones, have been added to the programme. These installations have been made primarily for the purposes of the environmental impact assessment, as a part of the measures undertaken to monitor, and in some cases compensate for, hypothetical future effects of the spent fuel repository on nature values. Data from these relatively recent installations should be part of the general data evaluation recommended above, such that their contribution to the bigger picture of site understanding can be assessed and described.
- Cooling water for the nuclear power plant is taken from Asphällsfjärden, via a channel that runs along the area planned for the surface facility of the spent fuel repository. As a basis for developing the understanding of the hydrological conditions in Asphällsfjärden and adjacent land areas, SKB should secure access to time series data on the flow of cooling water taken into the power plant.

8.2.5 Near-surface hydrogeology

Recommendations

The following recommendations are provided regarding the monitoring of near-surface hydrogeology.

- It is recommended to investigate the current status of some of the present groundwater-monitoring wells to evaluate the maintenance needs. A programme for regular checks of the groundwater monitoring wells should be devised. This programme should include repeated slug tests (or some other type of hydraulic testing) to evaluate the functioning of each well.
- Similarly to the surface water monitoring, there is a need for developing sustainable technical solutions for groundwater monitoring in lake and wetland environments. Specifically, it is recommended to evaluate different methods for monitoring of near-surface groundwater (level and/or discharge) in the upper part of the soil profile in fen areas, in which wells are prone to be affected by vertical displacement.

- Additional monitoring for following groundwater/surface water dynamics in connection with wetlands, primarily in the form of water saturation measurements, should be considered. One alternative that should be studied is to use indirect methods such as DTS (distributed temperature sensing), which also could provide data for assessment of freezing/thawing processes and groundwater recharge and discharge in wetlands.
- SKB should perform slug tests in those recently installed groundwater-monitoring wells where hydraulic testing has not yet been performed.
- Given the specific demands and problems associated with monitoring of near-surface groundwater, it is recommended that SKB produces a separate method description for monitoring of groundwater levels in the regolith.

Main inputs to update of monitoring programme

The programme for monitoring of near-surface hydrogeology is summarised as follows.

- The monitoring of near-surface hydrogeology consists of groundwater-level measurements in a relatively large number of monitoring wells (see Sections 5.6.1 and 5.6.5). However, the monitoring network has undergone changes in recent years, in the form of additions of new monitoring wells and termination of monitoring at some locations. As indicated above, it is recommended that an evaluation of the presently available dataset is performed before the implications of recent changes and potential needs for other modifications are assessed. Hence, detailed recommendations regarding additional monitoring locations are not given at this point.
- However, in addition to the possible needs for supplementary installations for monitoring in wetlands and along streams, the preliminary assessment has identified that additional groundwater level monitoring in regolith could be needed in some areas where bedrock deformation zones are expected to connect to the regolith. Furthermore, it should be evaluated whether different types of vegetation, higher-elevation areas, and the most important bedrock borehole locations are adequately represented in the programme for near-surface hydrogeology.
- Before monitoring is terminated at locations considered remote or otherwise of limited interest with respect to consequences of repository construction and operation, the need for reference areas within Forsmark should be considered. In other words, some of the existing observation wells might be useful because they are remote and supposedly unaffected by existing and planned repositories. This could relate to existing monitoring wells that are used in the present monitoring programme, and those that are not.
- The status of private wells in Forsmark should be investigated, and it should also be considered whether to include them in the hydrogeological monitoring programme (at present, three private wells are included in the hydrochemical monitoring programme).

8.2.6 Bedrock hydrogeology

The monitoring sections in the existing boreholes in the Forsmark-Lens area are adapted to the current understanding of the structural geology. At present, there is no need to alter the existing monitoring sections. However, there exists a need to review the installations close to planned locations of access tunnel and shafts and decide how to adapt them to cope with the projected drawdown due to the excavations.

The recommendations regarding the monitoring of bedrock hydrogeology are as follows.

- New technical components are installed to deal with corrosion of monitoring equipment in the Forsmark-Lens area due to the Fenno-Skan. The functionality of the new installations should be followed closely.
- It is recommended to evaluate if measurements of the groundwater temperature could be of value for interpreting monitored hydrological and hydrogeochemical disturbances during construction and operation, and, if so, how such measurements should be performed.
- The decision not to measure the density of the groundwater in the bedrock in the Forsmark-SFR area should be scrutinised as the planned expansion, SFR 3, will be constructed at a greater depth.

- It might be found impractical, or at least confusing, to work with two hydraulic head definitions in parallel while interpreting and modelling groundwater levels in Forsmark. It is therefore recommended to store underlying data such that any head can be calculated later on if decisions are made to change the use of a certain head. To use a common head definition in the two areas of interest, both for boreholes drilled from the surface and those drilled from the subsurface (e.g. SFR tunnel boreholes), will facilitate future site descriptions and modelling.
- Boreholes from the ground surface are not allowed to intersect the repository layout. Hence, it needs to be checked continuously throughout the design process that planned underground constructions do not cross the existing boreholes. Similarly, the design of surface facilities must take existing monitoring installations into account, such that those of major importance (primarily the deep core-drilled boreholes) are accessible during and after construction works.
- Additional hydraulic tests are planned in the Forsmark-SFR area. It is recommended to drill at least two new boreholes from platforms in Asphällsfjärden, one on each side of the Singö deformation zone, and monitor potential responses across this zone.
- It will be necessary to extend the monitoring programme in the Forsmark-SFR area once the permit to expand the existing SFR facility is received.
- It is possible that the construction works for the expansion of the existing SFR facility in the Forsmark-SFR area and the deep repository for spent nuclear fuel in the Forsmark-Lens area will be run in parallel. It is recommended to start evaluating whether there should be one monitoring programme for both areas or two separate programmes.
- During 2011–2012, eleven additional core-drilled boreholes (KFM13–23) and three percussion-drilled boreholes (HFM39–41) were drilled as part of the preparatory investigations for the construction of ramp and shafts. The testing of these boreholes should be documented properly.

8.3 Hydrochemistry

The present hydrochemical monitoring programme has been reviewed both considering the included sampling locations and determined parameters/constituents. Furthermore, requests for analyses or measurements that are not appropriate in the regular analytical protocol for long-term monitoring have been suggested for inclusion in specific supplementary sampling campaigns. The main reason for this is that only a limited dataset is needed in these specific cases, but complexity and costs are other aspects that must be considered. This section summarises the recommendations for continued hydrochemical monitoring in Forsmark.

8.3.1 General recommendations

Long time series are frequently required and it is considered important to continue the hydrochemical monitoring for as long as possible at all sampling locations that already today have long series of data. The number of objects included in the present monitoring programme is already cut down to a minimum and removal of objects with reasonably long time-series is therefore not recommended.

The selection of parameters to be determined in the monitoring programme or any other investigation programme should primarily be based on requirements from different end-users of data for different purposes (e.g. safety assessment and construction/design). However, there are also other aspects related to how to obtain as much useful information as possible at reasonable costs and furthermore, to create a simple and intuitive analytical protocol that facilitates the sample handling and the sending of the samples to different laboratories. The use of a few well-defined analysis packages will both ensure that the selected analyses are appropriate for several purposes, and facilitate administration and sampling. An important principle is that basic analyses (general water composition) should always be included when expensive and advanced analyses are performed, in order to have full control of the sample quality and to make the dataset useful in many contexts. Furthermore, it is important that sampling routines and the extent of analyses are well established and not changed too often without very good reasons.

To keep track on sample treatment, SKB has used five different standardised classes (SKB chemistry classes 1 to 5) to indicate sampling procedures and state the analyses to be performed in analytical programmes/activity plans. The purpose of this classification and grouping has been to restrict the number of possible combinations of constituents and parameters to be determined and to secure equivalent and adequate sampling methods and sample handling procedures within each class.

In the planning for the detailed investigations during the construction of the repository for spent fuel, a need to modify these classes was identified and proposed. New chemistry classes are suggested for all water types (see list below). The number of classes has been reduced from five to four, and the definitions of each class have been slightly changed. The analyses included in each proposed SKB chemistry class and supplement group are listed in Karlsson (2017).

- **SKB chemistry class I** is intended for simple checks of salinity changes or pH impacts for example for monitoring of impacts from sea water intrusion, or in order to check the stability of the water composition during pumping and exchange of water.
- **SKB chemistry class II** is designed for simple and fast sampling for major constituents and the most important isotopes. It may be adequate to collect samples for less extensive analyses when there is lack of time, or if no trained personnel are available for collection of samples that need filtering or conservation and are susceptible to contamination. The analytical protocol will still cover most requirements. It should be possible for anybody that is available to perform the sampling, for example drilling personnel.
- **SKB chemistry class III** includes the major constituents and also components with lower concentrations, such as redox-sensitive parameters and nutrients. The sampling procedure includes filtering in the field and generally on-line (filter connected to the water outlet from a pump), the use of acidified bottles, preservation of samples and above all, the personnel performing the sampling should be trained and possess knowledge about sampling methods and contamination risks. For instance, SKB chemistry class III may be suitable in order to identify/follow possible impacts from blasting and excavation on the concentration of nitrogen compounds. This class is also the most frequently applied to surface waters and near-surface groundwater, in combination with specific supplements for surface waters and shallow groundwater, respectively.
- **SKB chemistry class IV** is intended for complete characterisation, for example of the final sample in a sample series or less frequent sampling of surface water and shallow groundwater. A large number of isotopes are included, as well as the entire package of trace metals. Special isotopes that are very expensive or difficult to sample are included as options.

8.3.2 Surface waters (lake, stream, sea and precipitation)

Recommendations for monitoring of surface waters

The monitoring of surface waters in the present monitoring programme is restricted to the target area for the respective repositories (including also the planned SFR extension). It is recommended to include some of the previously sampled objects at the site or new objects, situated at a distance from the target areas within or outside the Forsmark site, in order to obtain local reference data. The selection of local reference objects should be further investigated in order to meet the future needs during the construction and operation phases, and more specifically, the requirements of the assessment of environmental impacts.

To meet the requirements of the assessment of environmental impacts, it is recommended to add sampling locations in the Baltic Sea. The single sampling location in the present monitoring programme is situated in Asphällsfjärden (PFM0062), and it is significantly influenced by the cooling-water intake to the nuclear power plant (Figure 8-3). The normal cooling water flow is around 100 m^3/s, which corresponds to 1/3 of the average discharge in the large river Dalälven. Thus, PFM0062 gives an integrated measure of the conditions in Öregrundsgrepen rather than reflecting the conditions close to the coast. The sampling location at the cooling-water outlet in Lake Biotestsjön (PFM102269), which presently is used only for checks of tritium releases, will probably be the first point of the present programme that may be affected by emissions due to the construction and operations work. It is therefore recommended that this location is upgraded to include an analytical protocol identical to the one employed for the other sea water locations. It should, however, be further evaluated if the measurements at the cooling-water outlet could be influenced in other respects than tritium by the power plants or the buffering effect of Lake Biotestsjön (cf. Figure 6-6).

Undisturbed sea-water reference data will probably be of great importance for the assessment of environmental impacts, specifically to evaluate possible emissions of suspended matter and nitrogen compounds. It is therefore recommended to resume the sampling at two previously sampled sea locations (PFM000065 or PFM000084, and PFM000083), and it should be investigated if sampling from land is sufficient (e.g. PFM000084 instead of PFM000065). It is probably also necessary to add a new reference location where the probability of disturbance from the construction work is very low. A possible sampling location could be the outer coast of Ängsskär north of the Forsmark area, but the final location must be further investigated.

Monthly measurements are required to correctly reflect the seasonal variation of nutrients. However, to reduce costs and work load, monthly sampling is suggested only at the cooling-water outlet (PFM102269), whereas other sea-water sampling locations may be sampled four times per year.

Surface-water sampling is conducted monthly in six ponds that have been constructed to compensate for the loss of reproduction localities for the endangered pool frog when the construction of the repository facilities above ground starts. For comparison as reference locations, two existing natural ponds are also sampled. The monitoring of these eight ponds has until now been performed solely for environmental-protection purposes, but they represent a water type characterised by larger contents of organic carbon and higher absorbance compared to the larger lakes of the current programme. Further understanding of this water type is important for the safety assessments, in which ponds and wetlands in general are important types of biosphere objects representing potential recipients of releases from the repositories. It is therefore suggested that they (or at least the natural reference ponds PFM007442 and PFM007443) should follow the same analytical protocol as the streams in the monitoring programme (Figure 8-4).

Figure 8-3. *Photo montage including planned future surface facilities related to the spent fuel repository and the present single sea-water sampling location in Asphällsfjärden (PFM000062) as well as a suggested sampling location at the cooling-water outlet in Lake Biotestsjön (PFM102269). The first location is significantly influenced from the cooling-water intake to the nuclear power plant. The sampling location at the cooling-water outlet in Lake Biotestsjön (PFM102269) is presently used only for checks of tritium emissions and it is recommended to introduce the same analytical protocol as for the other sea-water locations at that location. Along the coast, there is a predominating north-south coastal stream, and the dashed line marks the likely circulation of the cooling water from the nuclear power plant.*

***Figure 8-4.** Sampling of the natural pond Lake Kungsträsket.*

There is probably also a need for additional undisturbed reference data for lake water and stream water. The current monitoring of surface water in lakes and streams includes three lake systems: Lake Bolundsfjärden, Lake Eckarfjärden and Lake Labboträsket. Lake Bolundsfjärden could be indirectly affected by the lowering of the groundwater table. Lake Eckarfjärden, which is located at a higher altitude than Lake Bolundsfjärden, may serve as an undisturbed reference. However, it could be questioned if the smaller Lake Labboträsket is suitable as an undisturbed reference. The simulation of the construction/operation conditions illustrated in Figure 3-3 indicates that this lake is located within an area that may be affected by groundwater drawdown (see also Mårtensson and Gustafsson 2010).

Lake Fiskarfjärden might also serve as an undisturbed reference to Lake Bolundsfjärden due to limited impacts in the form of groundwater drawdown, and due to similarities to Lake Bolundsfjärden (similar location in the landscape, but more nutrient rich). If there are incentives for an additional reference, resumed sampling in Lake Fiskarfjärden is a possibility. Furthermore, with the addition of Lake Fiskarfjärden, the monitoring would also cover more nutrient-rich conditions compared with the more northern lakes. Further studies of potential modifications of the monitoring programme are suggested.

Precipitation was sampled 2002–2010, with an interruption during 2009 and at a reference location in Småland 2011–2012. It may be justified to resume this activity since the data are important for the understanding of the composition of the meteoric input to the recharging groundwater. In particular, it is recommended that the environmental isotopes (δ^2H, $\delta^{18}O$, ^3H), but also pH, and major constituents are included. Due to the low concentrations, the selection of analytical methods is crucial.

Some recommendations concerning potentially new parameters to be included in the analytical protocol and needs for modifications and improvements are the following.

- A few additional trace metals are recommended to be included in the analytical protocol (Se, Nb, Pd, Ag and Sn). These elements are proposed since they may serve as natural analogues for some radionuclides that are studied in the safety assessment. However, it is necessary to check if the concentrations in surface waters are sufficiently high to give values above reporting limits.
- Many analyses of Br, Li, F and I fall below reporting limits. Br and F are determined by ion chromatography. Iodide and bromide are determined by ICP AES (Inductively Coupled Plasma Atomic Emission Spectroscopy). Li is generally also determined by ICP AES, but detection could probably be improved by using some ICP MS (Mass Spectroscopy) technique. A supplementary potentiometric method is regularly used for F, but its reporting limit is similar to ion chromatography. The Li analyses are most often above the reporting limit for groundwater, and exclusion of Li in the ICP AES analysis package for some of the surface waters will just add one more variant but not reduce costs. It should be investigated if the analyses done by ion chromatography could be improved. To exclude any constituents is not worthwhile since Cl, SO_4, Br and F are obtained in the same run of the sample.

- The relatively large variation in the concentrations of TOC/DOC and the fact that DOC concentrations are quite often higher than the corresponding TOC values motivates further studies in order to improve the analytical quality. It may be that sterile bottles and sterile sampling equipment should be used. A shift may be observed around 2006 when the mean level and total variation changed. It should be investigated if this was due to a methodological or climate factor.
- Almost all analyses of Cs and Th fall below reporting limits. It should be investigated if the reporting limit could be lowered.
- A significant fraction of the determinations of suspended solids are below the reporting limit. Nowadays, laboratories report also values below the reporting limit (outside the accreditation), and the larger analytical uncertainty is probably acceptable for this type of data.

It is recommended that the hydrogeological and the hydrochemical monitoring are included in the same annual data reports, so that possible correlations between, for example, stream discharge and hydrochemistry are more readily observed. The primary data evaluations and also the integration between the hydrological and hydrochemical disciplines will be facilitated by presentation of hydrochemical and hydrological data in the same reports.

Inputs to monitoring programme for surface water

The check for suitable local surface-water reference objects within the site has resulted in the suggested addition of one previously sampled lake location in Lake Fiskarfjärden (PFM000127 and/or the outlet PFM000072), resumed sampling at two sea locations (PFM000065 or PFM000084, and PFM000083) and addition of one new undisturbed reference location north of the Forsmark area. Furthermore, the sampling location at the cooling-water outlet (PFM102269) will probably represent the most strongly affected sea location during the construction and operation of the repositories. This location should therefore be included in the full hydrochemical monitoring programme, with a sampling frequency of 11 times per year (July is omitted due to summer vacations).

At least two of the eight ponds (PFM007442, PFM007443) that have been sampled in connection to the creation of new reproduction localities for the endangered pool frog are proposed to be included with the same analytical protocol as the larger lakes, since they represent a water type that is not covered in the present programme. The proposed monitoring programme for surface waters and precipitation is listed in Table 8-1. Sampling frequency and SKB chemical analysis class are assigned per object (cf. Section 8.3.1 and Karlsson (2017) for explanation of the analysis classes).

The following supplementary sampling campaigns are suggested to be conducted besides the regular monitoring programme on a total of four occasions during 2016 (different seasons). The design of these special sampling campaigns will be optimised after the first sampling occasion.

- Carbon-14 (as percent modern carbon or pmC) is an important tool for the evaluation of groundwater residence times, and it is therefore useful to have some knowledge also about the ^{14}C signatures in the surface waters in order to understand groundwater formation. There is a significant amount of data for inorganic carbon from the early years of sampling, but there are no data on the organic carbon phase. It has proved quite successful using evaporation instead of ion exchange to get a more concentrated sample for organic carbon-14 determination. It is therefore recommended to include ^{14}C (pmC) and $\delta^{13}C$ determinations in both TOC and TIC (or DOC and DIC) for a few of the monitored sampling locations for surface water to verify earlier data, increase knowledge and obtain a larger number of comparable data pairs.
- Also the isotope ^{36}Cl is very useful for interpretations of groundwater residence times (i.e. the ration to stable Cl). However, due to few existing data, it has until now been difficult to fully understand the obtained information. The determinations may need large sample volumes due to the generally low chloride concentrations in most surface waters, but a few samples from different types of sample locations would be helpful in order to interpret measurements in groundwater. The costs are reasonable and there are suitable laboratories available in Europe that report the analytical results within an acceptable time period.

A separate campaign including ^{36}Cl and ^{14}C in TIC and TOC determinations has been initiated as a consequence of the two previous points.

Table 8-1. Proposed monitoring programme for lake water, stream water, sea water, and precipitation. Sampling locations, sampling frequencies and SKB chemistry class with supplements. SKB chemistry classes and supplement groups are described in Karlsson (2017).

Sampling locations	Name/comment	SKB chemistry class including supplementary constituents for surface waters
Lakes: sampling frequence 4 times per year (each season)		
PFM000074	Lake Labboträsket	IIIcij
PFM000097	Lake Norra bassängen (EC)	IIIcij
PFM000107	Lake Bolundsfjärden	IIIcij
PFM000117*	Lake Eckarfjärden	IIIcij
PFM000127*	Lake Fiskarfjärden	IIIcij
Shallow sea bays and sea location: sampling frequency 4 times per year (each season)		
PFM000062	SV Forslingens grund	IIIcij
PFM102269	Cooling water outlet, Lake Biotestsjön	IIIcij (monthly)
PFM000083	Suitable location	IIIcij
PFM000065/84	Long time series available	IIIcij
PFM0000NN*	New undisturbed reference	IIIcij
Streams: sampling frequence one per month (extended sampling 4 times per year, each season)		
PFM000066	Öster Gunnarsboträsket	IIIcde and IIIcdeij
PFM000068	Kungsträsket	IIIcde and IIIcdeij
PFM000069	Bolundsskogen	IIIcde and IIIcdeij
PFM000070*	Norr Eckarfjärden	IIIcde and IIIcdeij
PFM000072*	Outlet of Fiskarfjärden	IIIcde and IIIcdeij
Ponds: sampling frequence 4 times per year (each season)		
PFM007445	AFM001419 (constructedl)	IIIij
PFM007446	AFM001420 (constructed)	IIIij
PFM007447	AFM001421 (constructed)	IIIij
PFM007448	AFM001422 (constructed)	IIIij
PFM007442	AFM001426 (natural)	IIIcdeij
PFM007443	AFM001427 (natural)	IIIcdeij
PFM007415	Constructed	IIIij
PFM007416	Constructed	IIIij
Precipitation: weekly collection, monthly pooling		
PFM002564		Special analysis protocol with ^{3}H, $\delta^{2}H$ and $\delta^{18}O$

* Suitable local reference locations that most likely will be unaffected by the construction and operation of the repositories.

8.3.3 Near-surface groundwater

Recommendations for monitoring of near-surface groundwater

The monitoring of shallow groundwater is, in the present monitoring programme, restricted to the target areas for the repositories (including the planned SFR extension). It is recommended to include some of the previously sampled monitoring wells at the site, situated as far as possible from the target areas in order to obtain local undisturbed reference data. The selection of local reference objects should be further investigated in order to meet future needs during the construction/operational phases, and more specifically, the requirements for the assessment of environmental impacts. A review of all groundwater-monitoring wells should support the selection.

It is proposed that all still functioning monitoring wells that are not included in the yearly monitoring programme should be sampled on a less frequent basis, for example each fifth year. These monitoring wells have not been sampled in many years up to now and it may be appropriate to revisit them at intervals to assure that they can still be used and to take measures in order to maintain them in good condition. Furthermore, this may prove wise since sampling locations may be lost temporarily or permanently for various reasons (e.g. clogging or groundwater drawdown) prior to and during the construction and operation of the repository, and the wells that are not of special interest for the moment may become important later on.

The monitoring wells that are part of the present monitoring programme are mainly located in groundwater discharge areas. It may be of importance for the full understanding of the site and repositories that some monitoring wells representing recharging groundwater in oxidising environments are included in the programme (e.g. SFM0005, -0006, and/or -0057). General knowledge of this groundwater type could be valuable for understanding the groundwater recharging to the bedrock, for example during the construction and operational phases. The additional specific objects could be decided after the proposed review of all monitoring wells. Depending on the localisation of the wells, the information obtained could also be important for understanding local phenomena related to the ponds and wetlands that could be affected during construction and operation of the repository.

There is also a need to initiate recurrent sampling in a larger number of private wells to establish a baseline for drinking-water quality and water yield before the construction of repositories starts. Uranium analyses should be included due to the known uranium anomalies in the area with concentrations usually exceeding the drinking water quality criterion of 15 µg/L. The recurring sampling of private wells is motivated by the necessity to confirm or discount impacts from SKB activities on drinking-water quality.

A number of recommendations of varying importance have been identified as follows.

- The gradually altered chemistry in SFM0051 (with BAT filter tip) should be further considered. If the changing conditions reflect some unwanted anthropogenic influence, this monitoring well might be inappropriate to use in the monitoring programme.
- The sampling procedure that has been used up to present time has implied purging 3–5 pipe/casing volumes of groundwater at a flow rate of maximum 1 L/min. It is recommended to reduce the flow rate during purging and sampling to a maximum of 500 mL/min, see Section 6.3.4.
- Many analyses of Br and I fall below the reporting limits. Br is determined by ion chromatography and by ICP AES and the reporting limits are similar. Iodide is also determined by ICP AES and I-129 is an important radionuclide in assessments of long-term safety. It should be investigated if these analyses could be improved (cf. Section 8.3.2).
- The varying concentrations of TOC/DOC and the often higher DOC than the corresponding TOC value is problematic for near-surface groundwater which requires further studies and development of new sampling procedures or methods.
- Almost all measurements of Cs and Th fall below reporting limits. It should be investigated if the reporting limits can be lowered.
- Nitrite and nitrate show many values below reporting limits, and it should be investigated if these limits could be lowered. These parameters might be important for redox modelling and studies of the effects of microbes in the groundwater (Hallbeck 2008).

It is recommended that the hydrological, hydrogeological and hydrochemical monitoring should be included in the same yearly data reports so that possible correlations between for example groundwater level and hydrochemistry are more readily observed. The primary data evaluations, and also the integration between the hydrological, hydrogeological and hydrochemical disciplines, will be facilitated by presentation of hydrogeological, hydrochemical and hydrological data in the same reports.

Inputs to monitoring programme for near-surface groundwater

It is proposed that the monitoring programme for near-surface groundwater remains unchanged (Table 8-2), until the results from an extensive review of all the existing monitoring wells (Table 8-3) at the site has been made. The final selection will probably result in the addition of monitoring wells to the regular monitoring programme, and will also provide the basis for the selection of monitoring wells for an extensive campaign every fifth year. Sampling frequency and SKB chemical analysis class are assigned per object (cf. Section 8.3.1 and Karlsson (2017) for explanation of the analysis classes).

Table 8-2. Proposed monitoring programme for near-surface groundwater in monitoring wells and private wells. New sampling locations will be added after the review of all available monitoring wells. Sampling locations, sampling frequencies and SKB chemistry class with supplements; SKB chemistry classes and supplement groups are described in Karlsson (2017).

ID code	Comments on sampled object Sampling 4 times per year (each season)	SKB chemistry class
SFM0001	Stand pipe connected at drill site 1	IIIkl, IVkl, IIIkl, IVkl
SFM0023	Steel pipe in sediment below lake water	IIkl, IIckl, IIkl, IIckl
SFM0032	Double-pipe for chemistry	IIIkl, IVkl, IIIkl, IVkl
SFM0037	Double-pipe for chemistry	IIIkl, IVkl, IIIkl, IVkl
SFM0049	Double-pipe for chemistry	IIIkl, IVkl, IIIkl, IVkl
SFM0051	BAT-system at drill site 1 (omit?)	Special ^{3}H, δ^2H and δ^{18}O
PFM000001	Private well (revise)	Drinking water quality
PFM000009	Private well (revise)	Drinking water quality
PFM006382	Private well (revise)	Drinking water quality

Table 8-3. List of monitoring wells subjected to further review and possible selection for the extensive monitoring programme performed each fifth year. Reference-location candidates will be selected from this list after the initial review. The filter position denotes the upper and lower limit of the filter part (Secup and Seclow in Sicada) as length from the top of casing (ToC). Sampling is suggested according the SKB chemistry class IIIkl (SKB chemistry classes and supplement groups are described in Karlsson (2017).

ID code	No. of samples	Period	Filter position (m)	Object type
SFM0002	12	2002–2005	4.21–5.21	Monitoring well at Drill site 1
SFM0003	12	2002–2005	8.98–10.98	Monitoring well at Drill site 1
SFM0005				
SFM0006				
SFM0007	1	2003	5.11–6.11	Monitoring well at Drill site
SFM0008	9	2003–2005	5.14–6.14	Monitoring well at Drill site
SFM0009	9	2003–2005	2.00–3.00	Monitoring well at Drill site
SFM0010	1	2003	1.00–2.00	Not drill site, sampled once
SFM0011	1	2003	3.50–4.50	Not drill site, sampled once
SFM0012	10	2003–2005	5.35–6.35	Below open water
SFM0013	1	2003	4.48–5.48	Not drill site, sampled once
SFM0014	1	2003	2.00–3.00	Not drill site, sampled once
SFM0015	10	2003–2005	6.34–7.34	Eckarfjärden below open water, replaced by SFM000126, see below
SFM0016	1	2003	7.50–8.50	Not drill site, sampled once
SFM0017	1	2003	4.00–5.00	Not drill site, sampled once
SFM0018	1	2003	4.50–5.50	Not drill site, sampled once
SFM0019	1	2003	4.50–5.50	Not drill site, sampled once
SFM0020	1	2003	3.00–4.00	Not drill site, sampled once
SFM0021	1	2003	2.00–3.00	Not drill site, sampled once
SFM0022	4	2004–2005	5.30–5.80	Stand pipe in sediment below open water
SFM0024	3	2003	2.71–3.21	Stand pipe in sediment below open water, lifted by ice 2003/2004
SFM0025	9	2003–2005	6.06–7.06	Stand pipe in sediment below open water
SFM0026	1	2003	16.00–17.00	One of two double pipes, sampled once
SFM0027				
SFM0030	1	2003	4.00–5.00	One of two double pipes, sampled once
SFM0034	1	2003	2.00–3.00	One of two double pipes, sampled once
SFM0035	2	2003–2004	2.00–3.00	Not drill site
SFM0053	8	2003–2005	6.01–6.17	BAT-filter tip, Lillfjärden
SFM0056				BAT-filter tip
SFM0057				

ID code	No. of samples	Period	Filter position (m)	Object type
SFM0062	3	2004	3.25–3.65	Below open water
SFM0063	2	2004	3.22–3.72	Below open water
SFM0065	1	2004	4.45–4.85	Below open water
SFM0074	11	2004	2.00–4.70	Filter well not at drill site
SFM0077	2	2006–2007	6.00–7.00	HDPE pipe in till
SFM0078	2	2006–2007	3.50–4.00	HDPE pipe in till
SFM0079	2	2006–2007	4.70–5.70	HDPE pipe in till
SFM0080	2	2006–2007	8.65–9.62	
SFM0081	6	2007–2008	4.85–5.25	GBIZ, steel pipe in till below open water, Bolundsfjärden
SFM0083	6	2006–2008	2.54–2.70	GBIZ, BAT-filter tip in gyttja below open water
SFM0084	9	2006–2008	3.70–4.10	GBIZ, steel pipe in till below fen
SFM0087	9	2006–2008	2.00–2.30	GBIZ, HDPE pipe in sand below fen
SFM0090	3	2006	3.07–5.52	GBIZ, till-rock pumping well close to fen
SFM0091	9	2006–2008	1.90–2.30	GBIZ, steel pipe in till below fen
SFM0094	3	2006	2.24–4.74	GBIZ, till-rock pumping well close to fen
SFM0095	8	2006–2008	5.00–6.00	GBIZ, HDPE pipe in till below bog
SFM0102	6	2006–2008	2.09–2.25	GBIZ, BAT-filter tip in peat below bog
SFM0103	3	2006	4.90–7.40	HDPE in till
SFM000114	2	2013	2.45–2.95	Pipe in wetland object no.16
SFM000121	0		6.00–6.50	
SFM000122	0		7.00–7.50	
SFM000123	0		3.00–3.50	
SFM000124	0		3.00–3.50	
SFM000125	0		4.00–4.50	
SFM000126				
SFM000127				
SFM000132	3	2013	2.10–3.00	Pipe in till near wetland
SFM000133	2	2013	2.10–3.00	Pipe in till near wetland
SFM000134	0		1.10–2.00	Pipe in till near wetland
SFM000135	0		1.10–2.00	Pipe in till near wetland
SFM000136	0		0.99–1.59	
SFM000137	0		1.01–1.61	
SFM000138	0		1.00–2.00	Screen, Slits 0.3 mm
SFM000139	0		2.00–3.00	Screen, Slits 0.3 mm
SFM000140	0		1.00–2.00	Screen, Slits 0.3 mm
SFM000141	0		1.00–2.00	Screen, Slits 0.3 mm
SFM000142	0		0.00–1.00	Screen, Slits 0.3 mm
SFR0001	0		6.70–7.40	On the pier
SFR0002	0		6.50–7.20	On the pier
SFR0003	0		7.60–8.30	On the pier

The following supplementary sampling campaigns are suggested to be conducted on four occasions (four different seasons) besides the regular monitoring programme. The design of these special sampling campaigns will be optimised after the first sampling occasion.

- It is especially useful to have knowledge about the ^{14}C signatures in the shallow groundwater system since it constitutes the present input to the bedrock groundwater. There are data for inorganic carbon from the early years of the site investigation but no data for the organic carbon phase. Therefore, the evaporation method mentioned in Section 8.3.2 is recommended also for this type of sample. It is recommended to include ^{14}C (pmC) and $\delta^{13}C$ determinations in both TOC and TIC for the monitoring wells on a few monitoring occasions to verify earlier data, increase knowledge and obtain a larger number of comparable data pairs.
- The isotope ^{36}Cl is very useful for interpretations of residence times and determinations ($^{36}Cl/Cl^-$ ratios) should be performed on a few occasions and from monitoring wells of different character in order to get a fuller picture, since few data exists today.

- It should be investigated if analyses of CFC and SF_6 could complement age dating with ^3H. The ^3H activities in the atmosphere have diminished, and local emissions of ^3H from the nuclear power plant have to be taken into account in the interpretation of the measurements.

8.3.4 Bedrock groundwater

Recommendations for monitoring of bedrock groundwater

It is proposed to keep all surface boreholes, both percussion and core drilled, and all borehole sections that are included in the present monitoring programme. Furthermore, it is likely that more hydrochemical data will be required from the Singö deformation zone (ZFMWNW0001, see Figure 8-5). Therefore, the two borehole sections of borehole KFR01, which is drilled from the subsurface in SFR, are added to an updated monitoring programme. Furthermore, it should be investigated if the existing percussion-drilled boreholes crossing the Singö zone could provide more relevant chemistry data if borehole sections representing specific flow anomalies are isolated.

The weaknesses associated with the methodology for sampling in the installed fixed borehole sections in ground-based boreholes, in the case of more specific and delicate hydrochemical studies, needs to be considered, see Section 6.4.4. Especially the concentrations of trace elements or redox-sensitive elements often show a large spread, correlated with the purged water volume prior to sampling. Sampling equipment has been developed in an attempt to improve the sample quality by avoiding possible contamination from the water in the stand pipe. This tool has not been tested yet and it is possible that it will solve some of the problems associated with this type of fixed borehole equipment. The fixed borehole installations in surface boreholes are especially unsuitable for redox measurements as well as gas and microbe studies due to the design with standpipes containing stagnant water in contact with the surface. It is recommended to conduct such studies in special campaigns (CCC, cf. Tullborg et al. 2010a) with the mobile chemistry equipment that has been developed especially for this type of study, in conjunction with lifting of the monitoring equipment for maintenance or replacement.

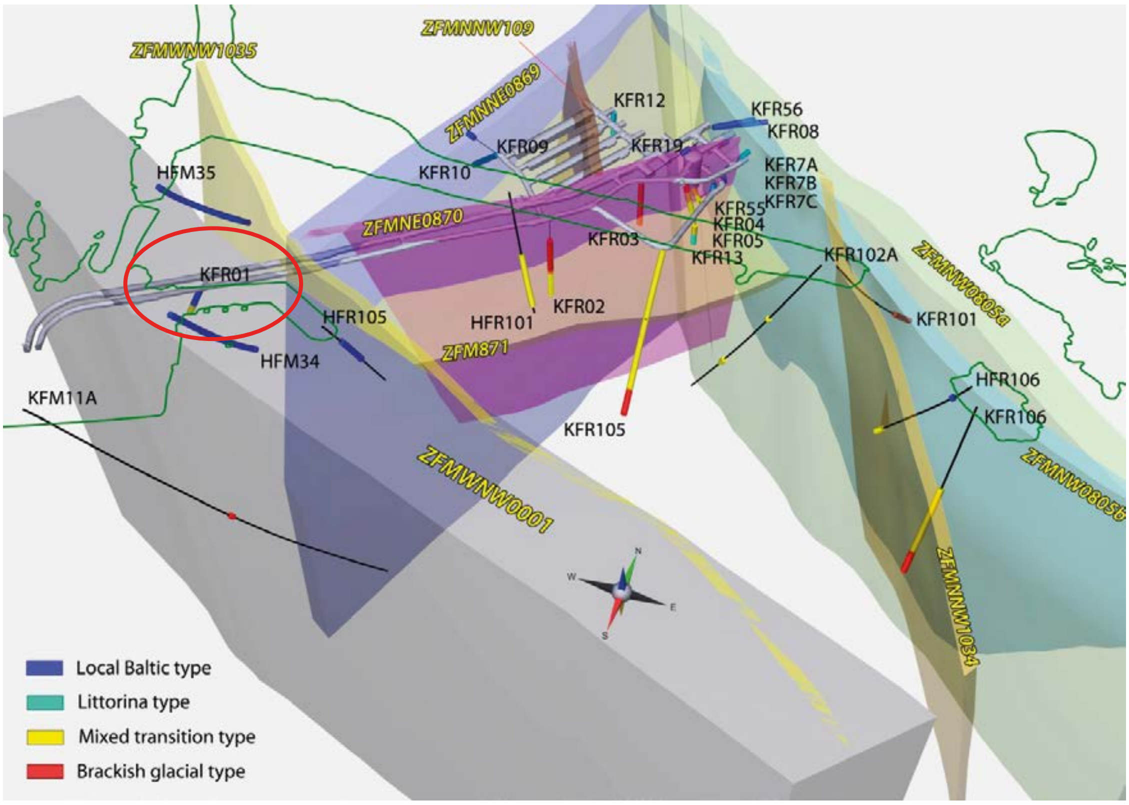

Figure 8-5. *View of SFR from southeast, showing the groundwater-type distribution in relation to major deformation zones within the regional model volume (Nilsson et al. 2011). The green outline at the surface demarcates the coastline with the pier and small islets. The Singö deformation zone (ZFMWNW0001) is coloured grey and the subsurface borehole KFR01 is encircled in red.*

The recommended sampling frequency is once a year, also for the boreholes drilled as part of the SFR extension project, and three samples in a series should be collected at each sampling occasion. From the evaluation of HS- and DOC, it is concluded that the new strategy for estimating the water volume to be purged prior to sampling that was introduced in 2010 has resulted in more stable concentration trends (cf. Section 6.4.4). Therefore, purging of borehole sections prior to sampling should be based on plug flow volume calculations also at future sampling occasions.

Furthermore, it is recommended to continue collecting sample series of three samples, during continuous pumping, according to the SKB chemistry classes III, III and IIIc or III, III and IVc, respectively, depending on sampling object (Karlsson 2017). It is the intention that the series from the four borehole sections in KFM11A and KFM01 as well as the boreholes included (KFM02A:3, KFM03A:4, KFR106:2 and KFR106:1) in a study of high uranium concentrations (Krall et al. 2015, Tullborg et al. 2013) should be collected according to class III, III and IVc to supply information for specific tasks, see Table 8-4. Some of the isotopes are necessary for the interpretation of residence times and this knowledge will be especially important for groundwaters representing the Singö zone. Furthermore, the uranium study obviously requires data on uranium concentrations and uranium isotopes.

Some recommendations of varying importance are the following.

- Appropriate preparations and maintenance of boreholes and borehole installations are very important in order to ensure that expectations continue to be met and to avoid malfunctioning borehole equipment, corrosion, clogging or problems due to drawdown prior to and during the construction and operation of the spent fuel repository.
- The organic constituents have become more and more important due to the sulphide issue (Tullborg et al. 2010a) and it may be necessary to add more analyses of organics (e.g. acetate) or speciation of the organic matter. The relatively large variation in the concentrations of TOC/DOC and the fact that DOC concentrations are quite often higher than the corresponding TOC values also motivates further studies in order to improve the analytical quality. It is recommended that sterile bottles and sterile sampling equipment should be used.
- It is recommended to include ^{14}C (pmC) and $\delta^{13}C$ determinations in both TOC and TIC (or DOC and DIC) for a number of monitored borehole sections in order to verify earlier data, increase knowledge and obtain a larger number of comparable data pairs. Evaporation instead of ion exchange to concentrate samples for ^{14}C (pmC) determinations has proved quite successful (less demand for delicate laboratory work and less possibilities to contaminate the samples) which provides new possibilities to obtain reliable data. Furthermore, the groundwater residence time will be an issue for groundwaters sampled from the Singö zone due to hydrogeological uncertainties and ^{14}C in inorganic as well as organic carbon species will be of special importance.
- There have been only a few determinations of the ^{36}Cl isotope. ^{36}Cl is applicable for interpretations of long water residence times, for which ^{14}C is not informative, and it may be that this parameter should belong among the regularly determined isotopes and not among the options. The costs for its determination are reasonable, and there are suitable laboratories in Europe that report the analytical results within an acceptable time period. However, due to the few existing data, it has until now been difficult to fully understand the available information.
- It may be helpful to investigate if the quality of the analyses of different nitrogen compounds (NO2, NO3, NH4 and total N) can be improved, but generally the concentrations are very low. One task during the detailed investigations will probably be to identify possible impacts from blasting by studying nitrogen compounds. Today, the concentrations of nitrogen compounds show larger variance than most other components. It is suspected that contamination and/or analytical errors are the major causes. It is doubtful if the reporting limits can be lowered and this is probably not an issue since very low concentrations are irrelevant for the evaluation of blasting impacts. They will most certainly show as pulses with relatively large increases of the concentrations.

Table 8-4. Proposed monitoring programme for groundwater in percussion-drilled and core-drilled boreholes. For descriptions of SKB chemistry classes and supplements (small letters), see Karlsson (2017).

Borehole: Section no.	Section (m.b.l.)*	Elevation (m.a.s.l.)	Geological structure (deformation zone)	SKB chem. class with supplements for each one of 3 samples in a series
KFM01A:5	109–130	–105	–	III, III, IIIc
KFM01D:4	311–321	–253	–	II, II, IIc
KFM01D:2	429–438	–343	–	II, II, IIc
KFM02A:5**	411–442	–417	ZFMA2	III, III, IIIc
KFM02A:3**	490–518	–495	ZFMF1	III, III, IVc
KFM02B:4**	410–431	–407	No information	III, III, IIIc
KFM02B:2**	491–506	–484	No information	III, III, IIIc
KFM03A:4**	633.5– 650	–631	ZFMB1	III, III, IVc
KFM03A:1**	969.5–994.5	–969	–	III, III, IIIc
KFM04A:4	230–245	–200	ZFMA2	III, III, IIIc
KFM06A:5	341–362	–299	ZFMENE0060A	III, III, IIIc
KFM06A:3	738–748	–623	–	III, III, IIIc
KFM06C:5	531–540	–435	No information	III, III, IIIc
KFM06C:3	647–666		No information	III, III, IIIc
KFM07A:2	962–972	–795	ZFMNNW0100, ZFMB8	
KFM08A:6	265–280	–228	No information	III, III, IIIc
KFM08A:2	684–694	–551	DZ not mod.	III, III, IIIc
KFM08D:4	660–680	–538	–	III, III, IIIc
KFM08D:2	825–835	–663	–	III, III, IIIc
KFM10A:2	430–440	–300	–	III, III, IIIc
KFM11A:4	446–456	–390	ZFMWNW0001 (Singö def. zone)	III, III, IVc
KFM11A:2	690–710	–594	ZFMWNW0001 (Singö def. zone)	III, III, IVc
KFM12A:3**	270–280	–227	–	III, III, IIIc
HFM01:2	33.5–45.5	–37.0	ZFMA2	III, III, IIIc
HFM02:2	38–48	–39.9	ZFM1203	III, III, IIIc
HFM04:2*	57.9–65.9	–57.9	ZFM866	III, III, IIIc
HFM13:1	159–173.0	–139	ZFMENE0401A	III, III, IIIc
HFM15:1	85–95.0	–59.0	ZFMA2	III, III, IIIc
HFM16:2	54–67	–57.2	ZFMA8	III, III, IIIc
HFM19:1	168–182.0	–136	ZFMA2	III, III, IIIc
HFM21:3	22–32	–18.8	ZFM1203	III, III, IIIc
HFM27:2	46–58	–45.6	ZFM1203	III, III, IIIc
HFM32:3	26–31	–27.5	–	III, III, IIIc
KFR101:1	279.5–341.8	–240	ZFMNW0805A	III, III, IIIc
KFR102A:5	214–219	–195	–	III, III, IIIc
KFR102A:2	423–443	–389	ZFMENE3115	III, III, IIIc
KFR104:1	333–454.6	–306	–	III, III, IIIc
KFR105:1	265–306.8	–154	ZFMWNW3267	III, III, IIIc
KFR106:2	143–259	–187	ZFMNNW1034	III, III, IVc
KFR106:1	260–300.1	–261	ZFMNNW1034	III, III, IVc
KFR01:2	11.15–43.5	–71.6	ZFMWNW0001 (Singö def. zone)	III, III, IVc
KFR01:1	44.5–62.3	–94.2	ZFMWNW0001 (Singö def. zone)	III, III, IVc

*m.b.l. = metre borehole length measured along the borehole from the Top of Casing (ToC).

** Suitable local reference locations that most likely will be unaffected by the construction and operation of the repositories.

Inputs to monitoring programme for groundwater in bedrock

The proposed monitoring programme for groundwater in the bedrock is listed in Table 8-4. It includes all the boreholes, both percussion and core drilled, and all borehole sections that are included in the ongoing monitoring programme as well as two additional borehole sections in the borehole KFR01 drilled from SFR and intersecting the Singö zone (ZFMWNW0001). Sampling frequency and SKB chemical analysis class are assigned per object (cf. Section 8.3.1 and Karlsson (2017) for explanation of the analysis classes and the extent of analyses).

The following supplementary sampling campaigns are suggested to be conducted besides the regular monitoring programme.

- Redox measurements as well as gas and microbe data are often requested. However, the equipment installed in the monitored surface boreholes is not suitable for these types of investigations. Therefore, they are not suggested for the regular monitoring programme. The monitoring equipment in surface boreholes will probably be dismounted in one borehole after another for maintenance or replacement over the many years of monitoring. It is recommended that these occasions, whenever they occur, should be used for hydrogeochemical investigations with the mobile chemical unit (so called complete chemical characterisation or CCC, cf. Tullborg et al. 2010a) including the full analytical protocol, in situ pH and redox measurements as well as analyses of gases and microbes. This has already been done in borehole KFM08D during October–December 2013, and similar investigations are planned for KFM01D during 2015.
- Only two of the boreholes in the recommended monitoring programme are drilled from a tunnel system of the SFR facility (KFR01 and KFR105). The lack of standpipes makes these boreholes suitable for more extensive investigations without any dismounting of equipment. It is recommended to perform gas and microbe investigation campaigns in at least one of these boreholes (KFR01) including microbes, dissolved gas, isotopes in gas and stable noble gas isotopes. The purposes are to test new sampling procedures and obtain more data. Especially, new tools for evaluation of groundwater residence times are important.
- It should be investigated if analyses of CFC and SF6 could complement ^3H for evaluation of residence times. The ^3H activities in the atmosphere are decreasing and local emissions of ^3H from the nuclear power plant may interfere with the interpretations.

8.3.5 Summary of identified further investigation needs

Selection of additional sea water sampling locations

A sea water sampling location representing conditions expected to be hydraulically unaffected by the future construction of the spent fuel repository is probably needed upstream of the outlet from the nuclear power plant (cf. Figure 8-3) as an important reference for the assessment of environmental impacts. Furthermore, additional locations representing varying impacts from construction and operation of the repositories should also be considered. The already proposed locations (cf. Section 8.3.3) are PFM000083 (easy to reach and possible impact), PFM000065 or PFM000084 (previously sampled and located further from the construction area), and PFM102269 (at present used only for checks of tritium emissions). The focus should be on the nutrient salts (nitrate etc.) and suspended matter, which are expected as emissions to the sea due to rock-dump leakage and discharge of drainage water. The evaluation should include regional data in order to understand the Forsmark conditions in comparison with the regional gradient.

Need for sampling of additional private wells

The number and locations of relevant and accessible private wells for recurring sampling have to be checked due to the need to establish a baseline for drinking-water quality and water yield in the area, before the construction of repositories starts. Uranium analyses should be included due to the known uranium anomalies in the area and because the drinking-water quality criterion of 15µg/L is often exceeded. The regular sampling of private wells is mainly motivated by the necessity to confirm or discard impacts from SKB activities on the drinking-water quality and in the future to demonstrate the extension of the groundwater-drawdown influence area. The previous reports by Ludvigson

(2002) and Werner et al. (2010) should be considered and it should also be checked (SGUs national database of wells) if there are newly drilled wells in the area of interest after these surveys. The expected influence area including a safety zone determines which wells should be included in the monitoring programme.

Selection of local references for shallow groundwater

An extensive review of the status of the existing groundwater-monitoring wells needs to be initialised. The status of the installations, hydrological setting, type of overburden, as well as water yield and water composition should be considered in order to select additional monitoring wells to be included in the regular monitoring programme as well as the extensive sampling campaigns every fifth year. The selected monitoring wells should represent undisturbed local reference conditions, recharging conditions and conditions that may prove to be important but are not covered in the present monitoring programme (e.g. deep discharge in Gällsboträsket).

Further evaluation of hydrochemical data

The statistical evaluations presented in this report are made for each individual parameter and are mainly focused on data-quality issues. There is a need for further interpretation and modelling of the data, in order to evaluate and describe the development of the hydrochemical conditions after the final site descriptive model resulting from the site investigations. A very basic reason is that it is important to make use of the data produced without too long a delay in order to discover, for example, possible unexpected phenomena or data-quality problems. The interpretation is especially important for groundwaters in the bedrock in order to conclude if stable conditions are prevailing or not, and also to understand possible changes that may have occurred. Integrated evaluations of several parameters by multivariate methods may reveal patterns explaining the evolution of the groundwater at specific locations. The knowledge and understanding obtained may be crucial for establishing an optimised future monitoring programme.

8.4 Ecology and nature values

The SKB ecological monitoring programme at Forsmark delivers time series of data to EIA (environmental impact assessments), assessments of long-term radiological safety, and to support the forthcoming environmental monitoring programmes for planned and present facilities. Ecological monitoring is also of relevance for repository design and construction issues. This section identifies gaps related to the forthcoming needs for the EIA and safety assessments, and it also presents an updated ecological monitoring programme based on the identified gaps, earlier experience and currently existing data. The programme presented gives a brief outline of the data currently available and what further is needed, suggestions of methods to add data, and identified issues that need further evaluation.

8.4.1 Environmental impact assessment

A number of different potential disturbances have been identified as a consequence of the planned activities associated with construction and operation of repositories at Forsmark (SKB 2011a, 2014c), see the short descriptions in Sections 3.2 and 3.4. These associated disturbances have earlier been analysed based on the regulations found in The Swedish Environmental Code, and the result was presented as a preliminary environmental monitoring programme (Andersson 2013).

Based on these descriptions, potential effects on ecosystems have been used to identify suitable ecological endpoints for monitoring ecosystems at risk. At the same time, identified potential effects of disturbances must also be understood in the light of a young developing landscape, where management of the environment to a varying degree has been important for several hundreds of years. The attempt described below to match potential disturbances to effects on ecosystems aims to, as far as possible, use already available data from the site in combination with potential reference data from national monitoring programmes.

Identification of suitable ecological endpoints in an EIA

The brief description of the cases in Section 3.4 (Table 3-3) is the basis for identifying suitable endpoints to monitor. Conceptually, this approach is based on several different aspects.

1. A disturbance is introduced and its further distribution in time and space in an ecosystem will be dependent upon the media present and their state of motion (e.g. air, sea water and soil water).
2. It is important to monitor the potential disturbance (e.g. noise, introduced substance) as close as possible to the emitting source. This will determine whether there is an actual introduced disturbance from the expected source and it should also be possible to calculate the magnitude of the disturbance that is further distributed through the ecosystem.
3. The immediate effect that is expected to occur would be a suitable endpoint to monitor if an early warning indicator is needed. This effect can be either short-term or long-term and is therefore not necessarily evidence of long-term effects. An endpoint can be represented by a functional group, a species or a set of species (Figure 8-6).
4. Effects further up the food web of the ecosystem would give indications of more profound effects and indications of long-term effects (if present over time). However, it is important that the connections in the food web are empirically established to ensure that the correct responses are measured. The choice of a certain endpoint will also be affected by methodology at hand and the presence of reference estimates (see below).
5. In certain ecosystems, it will also be necessary to monitor endpoints that are of special interest (e.g. endangered species), so-called valuable endpoints.
6. Reference measurements will be a necessary, supplementing tool to identify and characterise patterns that are occurring on a regional or national scale.

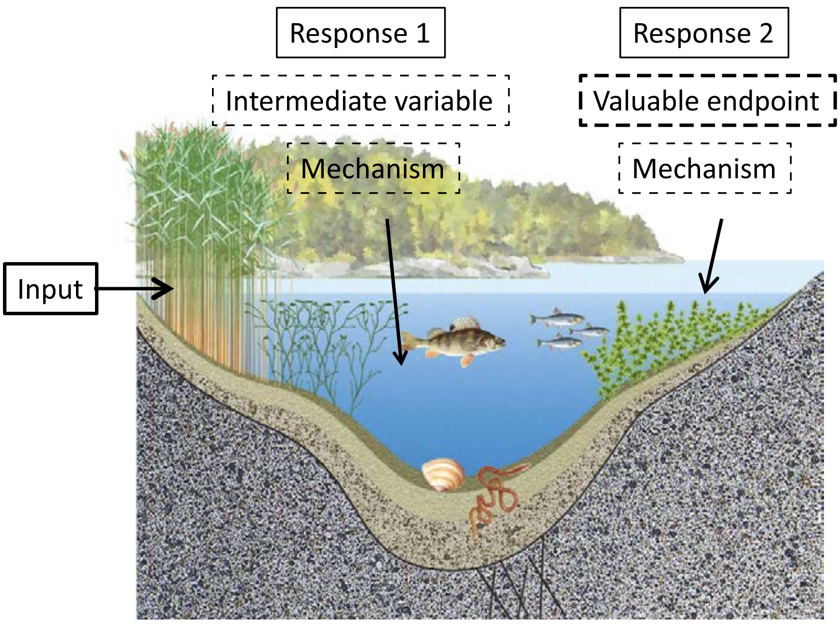

Figure 8-6. *A conceptual illustration of a shallow bay receiving a released substance, which has an effect on the ecosystem. Based on expected effects on ecosystem components, it is possible to identify several endpoints, which can represent different temporal and spatial aspects. For example, this case could represent release of nutrients where the effects are monitored by phytoplankton and benthic vegetation, representing different temporal responses, from weeks (phytoplankton) to years (benthic vegetation).*

Table 8-5 and Table 8-6 show the mapping of suggested endpoints to potential disturbances during the construction and operation phase. At least two ecological (biotic) endpoints are identified with the aim of covering two different temporal scales of the potential effect on the ecosystem (last two columns of Table 8-5 and Table 8-6). This can be conceptualised as a fast response (weeks) and a long-term response (years). A short response time may serve as an indicator or an early warning of change. The combination of actual measurements of the disturbance as close to the source as possible, measurements of the disturbance (e.g. the released substance) in the target ecosystem, endpoints representing a fast and a long term response, and the use of reference measurements will produce a set of robust information for evaluation of impacts on the target ecosystem.

For most of the identified EIA cases it is possible to predict the disturbances, but some may be more difficult to foresee. In that perspective it will be even more important to have identified well-described "cause and effect" cases to be able to distinguish other environmental changes from those caused by the identified disturbances. On the other hand, it is important to also include broader approaches, e.g. sampling functional groups, in case of unexpected disturbances or effects.

Table 8-5. Environmental impact cases identified for the construction phase of surface facilities. The abiotic fast response could be the actual introduced entity measured in the ecosystem (also in column 3); "na" stands for "not applicable".

Impact case	Disturbance		Suggested measurable ecosystem response		
	Potential disturbance	Quantification of the disturbance close to the source	Abiotic fast response (seconds-weeks)	Biotic fast response (< year)	Biotic slow response (> year)
Rock-dump drainage	Introduction of chemical elements or compounds	Measurement of the introduced entities	Measurements in sea bay	Phytoplankton, light penetration	Benthic and/ or macrofauna community
Infilling of pond	Increased turbidity	Turbidity	Measurements at a distance from source	Benthic community composition	Benthic community composition
Upfilling of land areas	Destruction of sensitive habitat/ change in hydrology	-/implication for surrounding areas	na/na	na/na	na/plant species distribution
In- and upfilling of sea bay	Increased turbidity	Turbidity	Measurements at a distance from source	Benthic community composition	Benthic community composition
Construction of bridge	Destruction of sensitive habitat	na	na	na	na
Drainage for construction of house foundations and ramp access	Introduction of chemical elements or compounds	Measurement of the introduced entities	Measurements at a distance from source	Phytoplankton	Benthic community composition
Rock crushing	Noise, dust	Noise, dust	Measurements at a distance from source	Bird and bat population decrease	Bird and bat species disappearance
Road- and boat transport	Visual disturbance, noise	Traffic and noise	Measurements at a distance from source	Population decrease of sensitive species in suggested communities	Bird species and wildlife distribution, benthic community composition
Lowering of groundwater table	Lowered groundwater table	Groundwater table	Measurements at a distance from source	Population decrease of sensitive species in wetland communities	Shrub and tree, and species distribution

Table 8-6. Environmental impact cases identified during the operation phase of surface facilities. The abiotic fast response could be the actual introduced entity measured in the ecosystem.

Impact case	Disturbance		Suggested measurable ecosystem response		
	Potential disturbance	Quantification of the disturbance close to the source	Abiotic fast (seconds-weeks)	Biotic fast response (< year)	Biotic slow response (> year)
Rock-dump drainage	See Table 8-5				
Handling of drainage from subsurface facilities	Introduction of chemical elements or compounds	Measurement of the introduced entities	Measurements at distance from source	Phytoplankton	Benthic community composition
Storm water handling	Introduction of chemical elements or compounds	Measurement of the introduced entities	Measurements at distance from source	Phytoplankton	Benthic community composition
Sewage-water handling	Introduction of chemical elements or compounds	Measurement of the introduced entities	Measurements at distance from source	Phytoplankton	Benthic community composition
Rock crushing	See Table 8-5				
Road- and boat transports	See Table 8-5				
Lowering of groundwater table	See Table 8-5				

Development and management of different habitats in the landscape

The Forsmark area is subject to continuous shoreline displacement. In combination with a flat topography this will cause a successive development of most of the different vegetation types at the coast. The very characteristic shallow and flat sea-bay bottoms in the area will slowly turn into more or less isolated bays (so called "flader") over less than a few decades. Other environments will have a successive development that occurs over tens to thousands of years, such as lakes, mires and soils. The temporal perspective of the overall monitoring programme, i.e. being able to describe and identify patterns at a specific scale, is expected to be between days and hundreds of years. It is therefore important to be able to describe the expected natural development of the site, in the absence of disturbances caused by construction and operation of the surface and underground facilities, i.e. the zero-disturbance case. For example, it is expected that ingrowth of vegetation will occur in sea bays and lakes, and that the vegetation may change on mires during a fairly short time perspective as a consequence of the onset of successional processes when the former sea bay has been isolated from the sea. At the same time, an increased successional change is expected in mires if a lowering of the groundwater table would occur (see Table 8-5).

This knowledge is also of importance to the description of landscape development for purposes of long-term safety assessment. Moreover, today there is an active management of different habitats in the Forsmark landscape, e.g. forestry and agriculture. Continuous management or changes in the management may have consequences for other habitats within the landscape, e.g. transport of elements and nutrients into sea bays as a consequence of altered agricultural practice. It will therefore be of importance to identify dependencies between development and management, and effects on objects of importance for the EIA. As an example, the area Storskäret has agricultural practise today and changes in the management may have implications for sea bays south of the area that may be affected by potential disturbances. Moreover, the landscape as a whole has been affected by forestry, hay making and grazing.

8.4.2 Long-term safety

Site data are the basis from which models are constructed aiming at describing the site and site development in long term safety assessments. Site data are used both to derive conceptual models and to underpin parameter values for the models. Consequently, time series may describe dependencies of biotic processes, transport/accumulation of elements (physical processes or chemical reactions), and landscape development processes, which may be important also in longer time perspectives. Also the time series itself is often used to define ranges of annual fluctuations in site specific properties. So far data from the present ecological monitoring programme have been used to describe biomasses and consumption by mammals, birds, reptiles, amphibians and fish, and net primary production in lakes and the sea. A mutual interest for both the EIA and the long-term safety is to be able to describe landscape changes in general but also for certain ecosystems more specifically, such as for lakes and mires.

Landscape development

The modelling of long-term radionuclide transport and accumulation for assessment of long-term safety has to handle the shoreline regression and the ongoing development of new limnic and terrestrial areas at the site. Moreover, the marine landscape is exposed to erosive processes as well as sedimentation and resuspension. These processes are most important in shaping the future landscape. Although these processes act continuously on the sea bottom, rare events such as storms or hurricanes may be most important for the redistribution of accumulated matter, thereby shaping the future terrestrial areas. It would therefore be important to describe the impact of these natural processes, and by establishing a baseline it should be possible to investigate and compare the effects of rare events on sedimentation processes in the future.

For lakes, rare events are often of less importance and they are primarily subject to continuous accumulation and redistribution of matter on the bottom. The continuous sedimentation and ingrowth of the shallow lakes and the ponds in the area are not well quantified. Vegetation change is a good predictor of changed environmental conditions and events such as seawater intrusion are expected to be present during a shorter time period (~500 yr) and become less frequent as shoreline regression proceeds. Ecosystem change is expected to be a gradual process as the shallow sea bay is turned into a narrow "flad" and further into an isolated lake. Table 8-7 lists a number of variables associated to different habitats.

Table 8-7. Properties, processes and monitoring activities related to landscape development. The monitoring activity in the last column is further described in 8.4.3 below.

Property	Process	Monitoring activity
Development of marine ecosystems	Sedimentation Ingrowth of vegetation in sea bays Change in abundance of macrophytes	Vegetation distribution and landscape development
Development of limnic ecosystems	Sedimentation Ingrowth of vegetation in lakes e.g. reed. Change in abundance of macrophytes	Vegetation distribution and landscape development
	Succession in ponds	Ponds – vegetation and benthic fauna
Development of terrestrial ecosystems	Vegetation distribution on mires	Vegetation distribution and landscape development

Carbon dynamics

^{14}C (Carbon-14, C-14) has been an important radionuclide in several safety assessments e.g. SFR (SR-PSU) and is likely to be of even greater importance in forthcoming assessments e.g. SFL (SKB 2013a). Studies of the naturally occurring ^{12}C-cycle has been one way of describing the relative importance of different processes to the transport and accumulation of C-14 in ecosystems (e.g. Aquilonius 2010, Andersson 2010, Löfgren 2010, SKB 2014e). The exchange of carbon across the water surface interface in lakes and mires is one important process that so far has not been measured at the site and for which present modelling approaches are associated with large uncertainties (e.g. SKB 2014e). This exchange is dominated by carbon dioxide, but the transport and degassing of methane is also of large importance.

8.4.3 Outline of a future monitoring programme

Wildlife monitoring

Generally, most mammal species that are part of the present monitoring programme are mobile, in the sense that they would move to other areas if the disturbance were large enough. Cederlund and Truvé (2007) pointed out that most of the planned activities, such as rock-dump development, planned constructions and new roads, for the building of a deep geological repository are close to present roads and restricted to a limited area south of the nuclear power plant. They concluded that disturbing effects on the existing wildlife would be insignificant. If specific isolated habitats that also host endangered species, such as the otter, were to be affected, it would be necessary to coordinate specific investigations accordingly. At present, it is predicted that no such isolated habitats with endangered mammals will be affected by construction or operation of repositories in Forsmark. However, it is important to be able to detect changes in the distribution of species in the area.

Wildlife statistics have been used in long-term safety assessments in order to estimate the potential magnitude of herbivory (food web characterisation) and available food for human intake (e.g. Löfgren 2010, Grolander 2013). Assessments of long-term safety require data to underpin such calculations. At the moment this monitoring programme is under revision, where the aim is to 1) be less dependent on index values, 2) establish a closer connection to other studies in terms of methodology and thereby potential reference data. It is then also of importance to make future monitoring data compatible with the earlier data set.

Hunting statistics for moose are biased in several respects (e.g. instructions to hunters to what extent sex or age category should be prioritised and the individual choice of the hunter) and it is therefore of low value according to the specific questions that are raised by long-term safety and EIA. However, it may be valuable according to other criteria, e.g. being able to discuss and plan the moose hunting in the region.

Bats are sensitive to disturbances and access to nesting and wintering localities. Moreover, there are a number of species that are classified as red listed (ArtDatabanken 2015). However, most of these species were found outside the main area affected by the planned activities associated with construction and operation. Potentially, the line-transects used to estimate bat abundances in the central less diverse area can be used as a tool to study impact of noise on the common Northern bat, if the noise is expected to affect this area. In such a case, it would be necessary to repeat the earlier inventory of at least the line transects (de Jong and Gylje 2005) in order to update the baseline description.

Bird monitoring

Birds are sensitive to different types of disturbances, such as visual disturbances and traffic-generated noise (e.g. Reijnen and Foppen, 2006). Bird monitoring may therefore be an important tool to survey effects from these disturbances in many ecosystems. The current bird-monitoring programme covers most of the terrestrial area that potentially may be affected by the construction work associated to the deep repository, such as noise from the handling of excavated rock volumes. The area monitored is large enough to also include reference areas. What is missing so far is monitoring of the coastal area around the harbour that will be subject to intensified boat traffic in the future (noise and disturbance), both in regard to the work with the deep repository as well as with the extension of the SFR. A larger costal area has been monitored during the years 2001, 2002 and 2011 (Sevastik 2013). Hence, baseline data are present today for comparison with data gathered in the future. A suitable extension of the monitoring area around the Forsmark harbour, including the near-coastal archipelago, needs to be identified for the future monitoring programme. The Natura 2000-habitat outside the SFR harbour also needs to be included in this area.

The national bird inventory will also assure that reference areas will be available for comparison. Overall, it would be relevant for an update of the list of bird species of special interest that are followed more closely in the area (see Table 7-4). This list would also have to include coastal species of specific concern, if such are identified in the coastal area. Data from the bird monitoring are also used in the analysis of long-term safety (Aquilonius 2010, Löfgren 2010). Moreover, seven species has been followed every second month since 2002 in a smaller area around SFR (Table 7-5). These were chosen based on their diet and are therefore suitable for studying effects on the food web based on potentially induced changes in basic food resources. These data may be used as an alternative endpoint for studying ecosystem effects from potential releases of substances in the shallow Asphällsfjärden sea bay.

Vegetation distribution and landscape development

Vegetation distribution

The need for a description of landscape development in terms of specific ecosystems or vegetation types is mutual to both EIA and assessments of long-term safety. For both these end-user goups, lake, mire and shallow bay ecosystems are the most important, but it could also be of importance to be able to describe other vegetation types such as different types of forests in a longer perspective. Generally, the temporal scale for changes is 10–100 years, which is well within the time frame of the Forsmark monitoring programme.

The EIA has to handle potential effects of a groundwater drawdown on different vegetation types. Changed hydrological conditions may cause wetlands and lakes to change, where shrubs and trees will colonise mires and lake ingrowth will increase. These processes occur naturally, but faster in a groundwater-drawdown scenario. Correspondingly, the distribution of macrophytes in shallow sea bays and lakes may change, due to altered nutrient status. Moreover, there are also effects from earlier management on the wetlands, such as haymaking, that may affect the future development and so will a warmer climate.

A description of natural vegetation development must by necessity be based on at least two previous points in time for comparison. The present vegetation distribution is described at one point in time by Boresjö Bronge and Wester (2003). In order to describe changes of different properties it would be important to use data as far back as possible to establish a baseline of natural changes to compare with observations in the future. Remote sensing can be used for this work, using different potential data sources. Orthophotos have been used for a long time and they are available from the Forsmark area as far back as 1965 (Lantmäteriet n d), with a spatial resolution of 0.5 m by 0.5 m. Some more recent orthophotos are in SKB's possession.

Satellite data can be found from the mid-1980s, but these data have a rather low resolution (30 m by 30 m). The Swedish national wetland inventory (VMI) has developed a remote-sensing methodology based on satellite data for wetland monitoring (Boresjö Bronge 2006) and the detailed descriptions of the wetland vegetation types. This method has also proven to be able to detect successional changes along a coast subject to shoreline displacement (Länsstyrelsen Gävleborg 2007). Highly resolved satellite data can be very expensive and are not available far back in time. A supplementary alternative is to use a drone to take photographs at specific heights on a selection of specific objects. Such an approach would also ensure that specific conditions will be fulfilled, such as time of year, weather conditions, and interval between scenes, thereby making comparisons more precise. Moreover, detailed photos would make it possible to identify changes at the species level. A methodology has to be put together to identify a suitable collection of data that can be used to answer the identified questions and combine temporal data as far back as possible, including highly resolved data (e.g. orthophotos and/or photographs obtained from drones).

Landscape development

Sedimentation and resuspension process are difficult to estimate and this can be done in several ways, both in the form of continuous monitoring using sedimentation traps or as in campaigns where different layers are dated in sediment cores. These methods all have their advantages and disadvantages. The first contributes with a high time resolution, whereas the other is more effective covering larger time intervals. Novel methods have also been introduced, such as bathymetric lidar (light detection and ranging, see also Section 7.2.2) that can be used to survey large areas and would also include the potential of monitoring benthic vegetation (e.g. Kumpumäki et al. 2015). This is a topic that is in need of further investigation to choose a suitable method of estimating sedimentation. Results from short-term estimates of vegetation change can be used to underpin descriptions of long-term development in safety assessments for ecosystems other than lakes and mires. Such work does not necessary need to be specified at this point, but would be possible to do when additional remote sensing data are in the possession of SKB.

The Sea

Shallow bays constitute important ecosystems, both in regard to biodiversity and for regeneration of pelagic fish species. One shallow bay, Asphällsfjärden, will act as recipient for different kinds of water emanating from repositories. It will therefore be very important to avoid any negative effects on the present biodiversity. Today, there are results from a set of transects and other investigations (see earlier description) already available for the specific bay and there are also a number of transects done in the area around that may act as references. The main endpoints that are suggested are for phytoplankton (measured as chlorophyll) and benthic vegetation community. Phytoplankton responds fairly fast to an increased nutrient availability, and this parameter may therefore be a first indicator for effects on the ecosystem level.

Measurements of phytoplankton (chlorophyll) are also used as an indicator of the environmental or ecological status of recipients (Naturvårdsverket 2007). Phytoplankton measurements should therefore be done in such a way that the ecological status can be assessed (e.g. measured at least three times during the summer). Benthic vegetation also has species that are sensitive to changes in the nutrient dynamics, but with a slower response time than phytoplankton and the benthic vegetation is important to the overall element dynamics in a shallow bay. This means that the response time is among years, but e.g. filamentous algae may have a fast response time and could be a complementary functional group to monitor for investigating effects of increased nutrient levels. As described earlier, a large interannual variation in the benthic community can be found and it would therefore be of importance to establish a baseline before effects could be expected.

The benthic macrofauna is an alternative endpoint, which may include effects on the ecosystem not fully covered by assessing the primary producers e.g. changes related to sediments (aerobic/anaerobic conditions). This endpoint is suggested to be included and monitored at less frequent intervals than benthic vegetation. In addition, there are possibilities to include supplementary endpoints higher up the food web, such as birds (see under the "Bird" section above). There are also extensive programmes using small detonations to estimate fish generation; this method has been applied around Forsmark as part of the present monitoring programme (see description above). This data could be a potential complementary tool for following a functional group high up in the food web.

A complicating factor in an analysis of change is that a power upgrade of the power plant started in 2013 and will continued until 2015. The upgraded power plant uses 20 % more cooling water. This means that Asphällsfjärden, which already is affected by increased currents, will undergo a successive change as a function of the increased water flow at the inlet. This also means that the investigations done in Asphällsfjärden before 2013 are partly outdated; adaptions to the new conditions after the upgrade will occur during the forthcoming years. This may suggest difficulties in disentangling potential effects from EIA cases and effects on biota from the increased water flow.

Moreover, the large and diverse datasets from the Forsmark area need to be viewed in terms of finding appropriate reference areas to the potentially affected areas (mainly Asphällsfjärden and Söderviken). For instance, comparisons between Asphällsfjärden, with the sea bays Tixelfjärden and Kallrigafjärden as potential reference areas, showed differences in bottom substrate (Borgiel 2005). It is also of importance that the use of transects for describing the benthic vegetation is further developed in terms of how the data are analysed, due to a large variation between years in shallow bays. Development of such interpretation methods will provide an important input to the monitoring effort that will be needed to establish an acceptable baseline.

Lakes

The lakes in the area are subject to an extensive monitoring programme that dates back to the start of the site investigation programme. This programme mainly relates to the determination of hydrochemical variables (see Chapter 6). Along with measurements of such variables, also a number of other variables such as chlorophyll content, turbidity and water transparency are measured; these are all important for the characterisation of lakes and such data are collected within a national monitoring programme for potential comparison. A number of descriptive investigations of biota have also been performed during the years. One EIA issue is the effects on lakes from groundwater drawdown. A relevant endpoint to monitor would be the distribution of macrophytes and ingrowth of vegetation using remote sensing, which is discussed under the section "Vegetation distribution" above.

Streams

One concern is the potential ecological effect of a groundwater drawdown on fish migration. A lower groundwater table could affect the water level in the streams during the time for migration and thereby also affect the fish migration. It is difficult to find monitored reference streams of similar size as those that are monitored in Forsmark today. Moreover, there is probably a large inter-annual variation in the fish migration. Streams with a decreasing connectance to the sea would restrict the fish migration and a decreasing discharge would also affect the distribution and abundance of hydrophilic vegetation in the streams. The inventory of stream vegetation and presence of adjacent wetlands by Carlsson et al. (2005) may be used as a long-term indicator of ecological consequences of less water in the streams. They visited several streams, including potential reference streams. Most of the migrating fish seems to be heading for Lake Bolundsfjärden, and scoping calculations suggest that the effect of lowered water levels in the streams would be insignificant.

Ponds

Threatened amphibians

The inventory of the pool frog, and the great and the lesser crested newt will continue on a yearly basis. The method by which the pool frog is monitored will be synchronised and further discussed with the County Administrative Board of Uppsala. The most important factor to further synchronise is the number of consecutive visits that is made to a specific locality after a negative observation (two to three visits in the regional monitoring and two visits in the Forsmark monitoring programme). This synchronisation will strengthen the potential for making comparisons between the few populations found in Forsmark with reference to those found in the region. During 2016, an effort was made to estimate the potential error in negative observations.

Calling males are sensitive to the water temperature and the prevailing weather conditions, and it is important to establish to what extent two visits at each pond manage to estimate the actual population size. A dedicated study in a few ponds in which visible frogs and calling males are counted each day during the mating season will provide data on how many visits that is needed to get close to the actual number of frogs in each pond. It will also give data on the best weather conditions in which to do the counting. Localities that today are empty will regularly be visited in order to understand the mobility of these amphibians, and likewise the constructed ponds will be monitored in order to further understand their habitat requirements and potential dispersal in the landscape. Furthermore, as the ability to colonise empty localities is a critical parameter it will be necessary to add some more empty localities to the present ones (only five empty of 15 visited in 2012). This can be done by adding localities east of Lake Bolundsfjärden. However, such an extension has to be evaluated in terms of already occupied localities (source) in the neighbouring area. Another approach could be to use data from the monitoring by the County Administrative Board of Uppsala to evaluate the colonisation and extinction dynamics on a five year basis as a potential reference to the Forsmark area.

Vegetation and benthic macrofauna

The ponds in the area are all of importance due to the amphibians that may be found in these. Moreover, landscape development implies that ponds naturally develop to mires. A potential groundwater drawdown would likely accelerate the pace of this development. Today, several ponds (including the constructed ponds) are well described and included in the ecological monitoring programme. The data gathered from this ongoing monitoring will serve as a baseline for the future monitoring of important habitats that potentially could be affected by a groundwater drawdown, and also as a possibility to further study the succession of ponds and associated effect on amphibians. So far, lots of data have been collected for the initial fast development of abiotic and biotic conditions of the constructed ponds and it can therefore be appropriate to decrease the sampling frequency. However, it would still be valuable to have a monitoring strategy that is able to describe effects on the biotic community from e.g. wet and dry years, apart from describing the long-term development.

Wetlands

Vegetation

At present, there is only a very general description of the vegetation communities (e.g. Boresjö Bronge and Wester 2002) or specific rich-fen indicator species (Göthberg and Wahlman 2006, Hamrén and Collinder 2010) or the fen orchid (e.g. Collinder 2013) in the wetlands that could be affected by a potential groundwater drawdown. The exception is from three wetlands, where Abrahamsson (2003) described the vascular plant and bryophyte community using a systematic and a random approach in putting out plots (size 1 m by 1 m). However, it is of importance to establish whether the permanent plots within that study are possible to locate today. On the other hand, it would be possible to use the alternative approach given in that study, according to which the 15 randomly distributed plots within a certain area can be resampled and compared. This approach would lower the potential precision of the set up, but could nevertheless be enough for the purpose of describing changes. However, the three investigated areas are quite close to or even located within the area where the potential groundwater drawdown potentially could occur. It would therefore be necessary also to establish reference plots. This information should also be coordinated with work using remote sensing (cf. above).

Fen orchid

The annual fen-orchid monitoring will continue to establish a baseline of the number of populations present in the area, and to present a description of the inter-annual population-size variation. By combining the resulting data with local meteorological data and monitoring of hydrological fluctuations in wetlands with established populations (in progress), it will be possible to describe the impact of the inter-annual meteorological and hydrological variations on the presence of the fen orchid.

The "Floraväkteriverksamheten" will continuously gather data on populations of the fen orchid that may serve as reference data. Some of the localities are visited yearly by the same persons, and this monitoring will consequently generate adequate time series that will be comparable with the populations followed around Forsmark. However, for comparison it would be desirable to have data from localities with a similar history and management to those around Forsmark, i.e. rather small near-coastal localities, without active management. Such localities could likely be found in the vicinity of the Forsmark area, and should be a sufficient distance from the area with a potential groundwater drawdown. Suitable reference populations may already be present within the ongoing monitoring, but this has to be further evaluated when up-to-date hydrological modelling of the area affected by a potential groundwater drawdown is available. This setup should be planned together with the update of vegetation distribution (see above), where a drone may be used to take highly resolved aerial photographs of the fens.

Forests

No large environmental impacts are expected to occur in forests, e.g. in terms of effects of a lowered groundwater table (Werner et al. 2010), but it would nevertheless be important to have a baseline. There are a number of investigations that have been done in forest ecosystems that can be used as a baseline for future comparisons. The most important is the one made by Abrahamsson (2003), where comprehensive data describing the vascular plant and bryophyte community were collected. However, as mentioned above it is of importance to establish whether the permanent plots within that study can be found.

On the other hand, it would be possible to use the alternative approach given in this study where the 15 randomly distributed plots within a certain area can be resampled and compared (described earlier). This approach would lower the statistical power, but could nevertheless be enough for the purpose of describing changes. Three larger areas are investigated covering a fairly large overall area that should be enough to include a gradient in distance based on the potential spatial distribution of a lowered groundwater table. Moreover, national inventories including vascular plants and bryophytes would be possible to use for describing overall changes in vegetation (e.g. the Swedish Forest Soil Inventory).

Agricultural land

The area with agricultural land, which is used both for grazing and cultivation, is found in the southeastern part of the Forsmark area, quite far from the area affected by a potential groundwater drawdown. No potential effects have been predicted for the agricultural land in Forsmark and monitoring based on such a concern is therefore of low priority. However, also for this vegetation type, Abrahamsson (2003) established vegetation plots as a baseline for potential use in a comparison (see discussion under the "Forest" section above). It should be noted that the community composition in these types of environments where different types of disturbances are maintained by man is difficult to compare over time, because changes in the disturbance regime will be the main factor to biotic changes.

Carbon dynamics

Describing and monitoring the carbon cycle is mainly related to long-term safety, where it may be used to describe pathways for organic matter and thereby all radionuclides that are incorporated into organic matter, and as an analogue for ^{14}C. A new technique (Bastviken et al. 2015) has recently been developed to enable estimates of gas exchanges across the water surface. The technique is based on continuous logging with a more cost-efficient approach compared to previous methods. The technique makes it possible to monitor CO_2 gas exchanges both in lakes and mires. A similar approach is also under development for monitoring gaseous CH_4, which also is of potential importance for forthcoming safety assessments (e.g. SFL). Based on known uncertainties, it would be appropriate to start monitor one mire object and one lake-mire object (SKB 2014e), where both the mire and the lake are monitored in the lake-mire object, in order to assess the relative importance of the objects as sources or sinks depending on horizontal transport and vertical transfer across water surfaces.

8.4.4 Additional activities in the monitoring programme

Some identified activities may be difficult to put into context of the above-mentioned categories and are treated below.

Dust

This is factor that is important in the long-term safety calculations, where dust is a carrier of certain adhesive radionuclides that may constitute a potential risk to humans and non-human biota through inhalation (e.g. SKB 2014e). Dust is also a potentially important parameter for the EIA, where dust generation during mainly the construction phase may cause problems. Today, there are no local baseline data on this parameter. There is a national monitoring programme running, and ideally site measurements should include atmospheric deposition, particles related to NO_x and SO_x, and be synchronised with the national programme (IVL 2015). Estimates of particle concentrations in the air must be included in the programme.

Noise

Noise is a type of disturbance that mainly is related to the EIA and could be a potential problem during both the construction and the operation phase. A noise measurement programme needs to be put together using information of where and when such activities are planned. Potential endpoints in such a programme could be distribution and abundance of birds in proximity of the area where noise is expected during construction and operation.

8.4.5 Summary of proposed programme

Based on the requirements from the main end users of monitoring data (environmental impact assessment and the assessment of long-term safety) experiences from the previous monitoring programme and the discussion in the previous sections a monitoring programme is suggested in Table 8-8.

Table 8-8. Recommended monitoring activities related to ecology and nature values. Activities in italics are identified as optional tools in the EIA. EIA is Environmental Impact Assessment and LTS is Long Term Safety, where the main end user is indicated for each activity. Modifications are made to the present methodology, while additions are novel parts that should be initiated.

Activity	Sub activity	Estimate	EIA	LTS	Modifications	Additions	Comment
Wildlife monitoring	Large mammals	Distribution/abundance	X	X	Revision of methodology		
	Bats	Distribution/abundance	X			Repeat earlier inventory	Optional instrument for studying effects of noise
Bird monitoring	All species	Distribution/abundance	X	X		Include coastal areas	Synchronise monitored area with area of disturbance
	Threatened bird species	Distribution/abundance/success	X		Evaluate the subset of species	Include species from coastal area	Synchronise monitored area with area of disturbance
	Food web	Distribution/abundance	X				Optional instrument for studying effects on food web. Data available.
Vegetation distribution and landscape development	Vegetation type distribution	Spatial change among vegetation types	X	X		Satellite data or orthophoto based tracking of specific vegetation types	Develop appropriate methodology including both terrestrial and benthic vegetation E.g. VMI data available for wetlands.
	Vegetation change within ecosystems	Spatial change within vegetation types	X	X		Drone photos for documenting specific vegetation types	Develop appropriate methodology for specific vegetation types e.g. lake/pond/wetland succession
	Sedimentation, resuspension and erosion in the sea	Accumulation and transport of organic and inorganic matter		X		Identify appropriate methodology e.g. green lidar	New activity
	Sedimentation in lakes	Accumulation		X		Identify appropriate methodology	New activity
Sea	Vegetation	Benthic community composition	X	X	Evaluate data and reference data		Repeat inventory
		Phytoplankton (chlorophyll)	X		More frequent sampling in space and time		
	Benthic fauna	Distribution/abundance	X		Evaluate data and reference data		Repeat inventory
Lake	Vegetation	Benthic community composition	X	X			Repeat inventory
	Carbon exchange	Transport across water-atmosphere interface		X			CO_2 and NH_4 exchange. New activity
Pond	Threatened amphibians	Distribution/abundance/success	X		Synchronise the methodology with the County AdministrativeBoard of Uppsala	Evaluate the need of adding empty localities	Modifications in methodology will provide reference areas in Northern Uppland
	Vegetation	Benthic community composition,	X	X	Evaluate a suitable subset to follow in a certain interval		Six excavated and two natural ponds are now followed
	Benthic fauna	Distribution/abundance	X		Evaluate a suitable subset to follow in a certain interval		Six excavated and two natural ponds are now followed

Activity	Sub activity	Estimate	EIA	LTS	Modifications	Additions	Comment
Wetland	Vegetation	Distribution/ abundance	X	X		Find old localities and/ or consider new localities	Synchronise with other efforts e.g. management
	Species composition		X	X		Find old localities and/ or consider new localities	Evaluate and the need for additional localities
	Fen orchid	Distribution/ abundance	X			Add some empty habitats	Managed populations studied in an experimental setup
	Carbon exchange	Transport across water-atmosphere interface		X			CO_2 and NH_4 exchange. New activity
Forest		Species distribution and abundance	X			Find old localities	Evaluate follow-up
Agricultural land		Species distribution and abundance	X			Find old localities	
Dust		Size and abundance of airborne particles	X	X		Establish monitoring	To be planned
Noise		Noise	X			Establish monitoring	To be planned

8.4.6 Establishment of a sample archive

It is recommended that SKB initiates the activities needed to establish an archive of samples representing the ecosystems at Forsmark. Samples have been collected and stored during and after the site investigations for the spent nuclear fuel repository, but it is foreseen that this must be done in a more systematic way. There are two main reasons for storing archive samples: the possibility to repeat analyses if results are questioned, and the possibility of conducting complementary determinations in the future, e.g. measure parameters not covered by the original programme. Thus, the aim is to build an archive of samples that represents all relevant media and organisms at the site at certain times or periods, such that it can be used as a reference and for complementary analyses, if needed.

Accordingly, abiotic and biotic samples need to be stored using methods that preserve the samples during at least the whole construction and operation period. These samples would need to represent relevant ecosystems in terms of dominating media, such as water and regolith, and functional groups, so that potential future needs from EIA and SA can be meet. One obvious objective is to have an adequate collection of samples representing the pre-construction (baseline) conditions. However, samples should be collected and stored also in the construction and operation stages. An investigation aiming at all relevant aspects of the sample archive should be started as soon as possible, because method development and a sufficient baseline sampling must be finished before construction activities commence.

As mentioned in Section 2.3.2, the French nuclear waste management organisation, Andra, is making a significant effort to build a sample archive at their proposed repository site (Leclerc et al. 2015). Although the needs are not necessarily the same at Forsmark, the French programme could serve as an illustration of possible solutions and what might be required.

It should be noted that the discussion of archive samples in this section applies to ecosystems in a wide sense, and not only to parameters and measurements handled within the ecological monitoring as defined in Chapter 7 of this report. Specifically, it could be expected that most of the complementary measurements consist of various types of chemical analyses, and that these could involve water samples (as in the monitoring programme) as well as solid materials (including rock) and biota.

9 Input to programme update and proposed further studies

9.1 Summary of recommendations for programme update

This chapter summarises the recommendations for updating the monitoring programme, as extracted and summarised from the preceding chapters, and provides a list of monitoring-related investigations that need to be initiated very soon. Table 9-1 to Table 9-5 describe the scientific disciplines and relevant parameter groups within each discipline. It is recommended that evaluations of presently available datasets are performed before detailed assessments of further modifications are made, except for changes that can be made directly based on the information in the tables. Hence, detailed inputs on updates of the current monitoring programme are not given for all parameters at this point; the reader is referred to the previous chapters for discussions on specific parameters or activities.

Table 9-5 presents a new discipline called "Atmosphere", which essentially includes different types of air chemistry monitoring. This discipline consists of measurements not included in the current SKB programme, and hence there is no discipline-specific chapter covering it in this report. However, parameters associated with the atmosphere have been discussed within other disciplines, such as hydrology, chemistry and ecology. Atmospheric monitoring, apart from monitoring at meteorological stations, has previously not been conducted at Forsmark. However, it is foreseen that atmospheric monitoring will have an important role in future monitoring and development of site understanding, and it is therefore introduced as a separate monitoring discipline.

Geological parameters are listed in Table 9-1, including a set of new monitoring activities. Early establishment of seismic and aseismic monitoring, in order to establish baseline data, is of most importance. Monitoring of earth currents and the global magnetic field are also included under geology. Good understanding of these parameters is needed to secure high quality data from other bedrock monitoring equipment.

Table 9-1. Summary of input to programme updates regarding monitoring of geological parameters.

Type of monitoring	Changes in current programme	External/reference	Comment
Seismic			
SNSN	No changes at present	National programme	
Local seismic network	New activity	Posiva, LKAB	Network design needed
Aseismic motions			
GNSS	New method New equipment	Earlier SKB monitoring	Online monitoring
DInSAR	New activity		Use PSInSAR methodology
Lidar	New activity		Further evaluation needed
Electrical currents and magnetic fields			
Earth currents	No changes at present		Collaboration with experts on corrosion
Global magnetic field	Monitoring during borehole surveys		

Table 9-2 presents the monitoring programme for meteorology and hydrology. The evaluation made during this work suggests that a number of new monitoring points in surface waters need to be established. Monitoring needs associated with more detailed hydrological understanding of wetlands to serve environmental impact assessment and hydrological modelling have also been identified. The need for better description of the Singö deformation zone is recognised and monitoring of temperature along boreholes in bedrock is also suggested. An overall update of relevant monitoring methods (SKB method descriptions, or similar documents), and checks and (if needed) refurbishment of field installations are also proposed.

Table 9-2. Summary of input to programme updates regarding monitoring of meteorology and hydrology.

Type of monitoring	Changes in current programme	External/reference	Comments
Meteorology			
Automatic meteorological stations	No changes at present	Surrounding SMHI stations	Parallel instrument setups at Labbomasten
Winter parameters	No changes at present	Surrounding SMHI stations	Evaluate design of snow-depth monitoring programme Need to evaluate methods for ground-frost monitoring
Hydrology			
Streams	No changes at present	Vattholma (SMHI) Forsmarksån (FKA)	Update of method description Station refurbishments needed Evaluate supplementary temp. monitoring along streams (e.g. DTS)
Lakes, ponds and the sea	Add Lake Puttan	SMHI sea-level gauge (or SKB replacement if discontinued) Cooling-water discharge (FKA)	Update of method description Further modifications require detailed evaluation Improve long-term stability of gauges
Near-surface hydrogeology	Add private wells Supplementary monitoring in wetlands and unsaturated soils	National groundwater programme (SGU)	Update of method description Improve long-term stability of wells, especially below surface waters
Bedrock hydrogeology	Boreholes along the Singö deformation zone Borehole temperature monitoring		Further modifications require more detailed evaluation

Hydrochemical data collected from 2002 until today have been evaluated and scrutinised. Although some detailed evaluations remain, an updated programme has been formulated. The hydrochemical programme is summarised in Table 9-3. The ongoing programme at Forsmark will continue as is with a few additional sampling points. Additional, more extensive sampling campaigns will ensure that a good enough site understanding is gained to adapt the programme to future needs. Furthermore, a few new parameters have also been added to the programme; these include selected isotopes and microbes. Also data from subsurface boreholes at SFR are included in the updated programme.

Table 9-3. Summary of input to programme updates regarding monitoring of hydrochemistry.

Type of monitoring	Changes in current programme	External/reference	Comment
Surface water and precipitation			
Surface water objects	Additional sampling locations and change in frequency	Reference areas added	Ponds and cooling water outlet included in the protocol Private wells
Sampling campaigns	^{14}C and ^{36}Cl		Residence time evaluation
Near-surface groundwater			
Groundwater wells	No changes at present	Reference areas decided after campaign	Optimisation of monitoring programme after campaign
Sampling campaigns	New activity		This activity is to be done at 5-year intervals
Bedrock groundwater			
Surface boreholes	No changes at present		
Sub-surface boreholes	Add two boreholes at SFR		Singö deformation zone data needed Evaluation on specific flow anomalies
Sampling campaigns during borehole equipment dismantling and maintenance	According to Tullborg et al. 2010a Microbes, gas and isotopes in SFR		Full analytical protocol during maintenance Evaluation of new tools and obtain more data Residence time of importance

On the surface, parameters describing ecological processes and nature values are monitored at Forsmark. The new programme is summarised in Table 9-4.

Table 9-4. Summary of input to programme updates regarding monitoring of ecology and nature values.

Type of monitoring	Changes in current programme	External/ reference	Comment
Wild-life monitoring			
Large mammals	Revision of method		
Bats	Optional instrument for studying effects of noise		Distribution/ abundance
Bird monitoring			
All species	Adjust monitored area to include area of disturbance	National programme	Distribution/ abundance Include coastal areas
Threatened bird species	Adjust monitored area to include area of disturbance	National programme	Distribution/ abundance/ success Include species from coastal area
Food web	Optional method for studying effects on food web		Distribution/ abundance
Vegetation and landscape development			
Large scale	New activity		Develop appropriate methodology for describing distribution and spatial change among vegetation types. Satellite data or orthophoto-based tracking of specific vegetation types
Small scale	New activity		Develop appropriate methodology for more detailed descriptions within vegetation types, e.g. photographs
Ponds			
Threatened amphibians	Synchronise the methodology with that of the County Administrative Board of Uppsala		Distribution/ abundance/ success Evaluate the need of adding empty localities/references
Vegetation	Evaluate a suitable subset to follow at appropriate intervals		Benthic community composition is followed in six excavated and two natural ponds
Benthic fauna	Evaluate a suitable subset to follow at appropriate intervals		Distribution and abundance are followed in six excavated and two natural ponds
Lake			
Vegetation	See "Vegetation and landscape development"		Benthic community composition
Sedimentation	New activity		Identify appropriate methodology to estimate accumulation
Carbon exchange	Integrate with hydrology and atmosphere monitoring		Transport across land-water-atmosphere interfaces
Sea			
Vegetation	Evaluate site data and reference data		Benthic community composition
Benthic fauna	Evaluate site data and reference data		Distribution/ abundance
Sedimentation, resuspension and erosion	New activity		Identify appropriate methodology to estimate accumulation and transport of organic and inorganic matter
Wetland			
Vegetation	See "Vegetation and landscape development"		Distribution/ abundance
Species composition	Evaluate follow-up and additional localities		
Fen orchid	Managed populations studied in an experimental setup		Distribution/ abundance
Carbon exchange	New activity		Transport across land-water-atmosphere interface
Forest	Evaluate follow-up		Species distribution and abundance

New parameters to be introduced are studies of species in sea bays and coastal areas, food web analyses, vegetation parameters and monitoring of landscape development. To serve the monitoring programme on nature values, an update of methodology is suggested for key parameters associated with ponds and wetlands close to the coast. For lakes, the need to capture changes in vegetation and sedimentation is recognised, as well as the quantification of carbon exchanges between atmosphere, lakes and land. In the sea, changes in benthic community and sediment dynamics are proposed to be monitored.

Atmospheric chemical concentrations and the related loading on the Forsmark system have been disregarded features. To be able to describe present status and processes affecting the chemistry at Forsmark, chemical data from the atmosphere are needed. Air quality and total chemistry must be monitored to describe external input and loading on the system. To differentiate natural concentrations or depositions from man-made events, a good understanding of atmospheric exchange has to be developed. Table 9-5 lists monitoring of parameters/parameter groups within the new atmosphere discipline. Note that these are not previously monitored at Forsmark, except from the monitoring of chemical concentrations in precipitation that was terminated in 2010, and that a preparatory study is required to identify and describe the specific monitoring needs (cf. below).

In the present report, focus has been on relatively intensive monitoring. There are also cases where repeated measurements can be quite sparse in time, e.g. every tenth year or even more seldom. For example, this approach could be suitable for measuring concentrations of radionuclides, environmental toxins and elements in general in soil and biota, but could also be taken for certain water sampling activities. Whether future measurements of this type should be regarded as monitoring or supplementary characterisation is to some extent a matter of taste. Due to the long intervals between sampling occasions, they are here viewed as not being part of the monitoring programme.

Table 9-5. Summary of input to programme updates regarding monitoring of atmospheric parameters.

Type of monitoring	Changes in current programme	External/reference	Comment
Air			
Air quality	New activity	National programme	Air quality as basis for assessment of pollutants and particles
Noise	Evaluate follow-up and addition of new localities		Regular monitoring to show compliance with regulations
Air chemistry	New activity		Element in/outflux at Forsmark to be used in process understanding
Air radionuclides	New activity	FKA programme	Better resolution and additional key radionuclides of importance for SKB
Precipitation and deposition			
Precipitation chemistry	Restoring old measurements	SKB	Monitoring needed as part of site understanding
Dry deposition chemistry	New activity		Monitoring needed as part of site understanding
Air-water/land fluxes			
Carbon flux	New activity		Evaluation of method needed (see Table 9-4)

9.2 Prioritised further investigations

Chapter 8 presents a number of recommendations including proposed further investigations regarding monitoring needs and how these should be fulfilled. In Chapter 8, these proposed further studies are described within the discipline-specific structure given by the present monitoring programme. This is also consistent with their further handling, i.e. most of the investigations required to provide additional information should be handled within the individual monitoring disciplines. However, some of the proposed further studies could be seen as parts of more general, multidisciplinary investigations needed to answer basic questions about the forthcoming monitoring at Forsmark.

In the following, a set of general issues that require multidisciplinary investigations is presented. The investigations outlined below are considered highly prioritised, in the sense that they concern basic issues that need to be resolved soon and/or activities that must be initiated soon in order to provide timely inputs to the ongoing repository projects at Forsmark. Furthermore, it may be noted that some of the issues/studies proposed below may not have an obvious home within the present monitoring organisation at SKB.

Establishment of baseline and reference measurements. Recommendations regarding baseline measurements and identification of possible reference measurements are provided in the present report. The associated baseline should be integrated and further analysed in a more detailed study aiming to evaluate whether all needs for baseline measurements are covered and to specify and describe the reference measurements that should be initiated. Analyses of time series data collected at Forsmark until now is an important part of this study. This study should also be coordinated with the collection of archive samples to make this effort comprehensive and cost efficient (see below).

Monitoring objects of high nature values. Further studies are required to specify the hydrological, chemical and ecological monitoring of identified lake/pond and wetland objects of high nature values, including rare/threatened species living there. Questions that need to be answered concern both general understanding and environmental impact (Section 8.4), and include both details regarding which parameters to measure and technical aspects of installations (Section 8.2).

Monitoring of environmental parameters potentially affected by construction and operation activities. Monitoring needs related to disturbances from repository construction and operation activities have been outlined in the present and earlier studies (e.g. SKB 2011a). However, there is an urgent need to proceed with the technical aspects of this monitoring, i.e. the specific parameters, methods, locations and installations. In particular, it is important to identify parameters that need baseline measurements and to initiate these measurements. Parallel to the practical needs for specific monitoring activities that are mentioned above, there is also a more general need to do a systematic inventory and reporting of monitoring activities that are directly related or occasioned by construction and operation activities.

Monitoring of atmospheric parameters. In the preceding section, a new monitoring discipline integrating different types of atmospheric chemistry monitoring was introduced (Table 9-5). Since this monitoring does not exist within the present programme and could be associated with time-consuming installations and baseline measurements, an investigation identifying parameters and methods within this discipline should be initiated as soon as possible.

Data handling and organisation of environmental monitoring. During future construction and operation of repositories at Forsmark, much faster data flows are required than those possible with present systems and procedures (e.g. Section 8.2). The environmental monitoring organisation, including technical installations and personnel, should be able to detect, evaluate and report status and potential disturbances with appropriate resolution and within sufficiently short time-frames. Specific requirements and their implications for the monitoring of different parameters in terms of data handling, communication and organisation need to be clarified.

Establishment of sample archive. In order to provide references for future evaluations of the repositories at Forsmark, a sample archive must be established that enables SKB to extract and analyse samples representing present and future states of the site. This means that abiotic and biotic samples need to be stored using methods that preserve the samples during at least the whole construction and operation period. An investigation aiming at all relevant aspects of this sample archive should be started as soon as possible.

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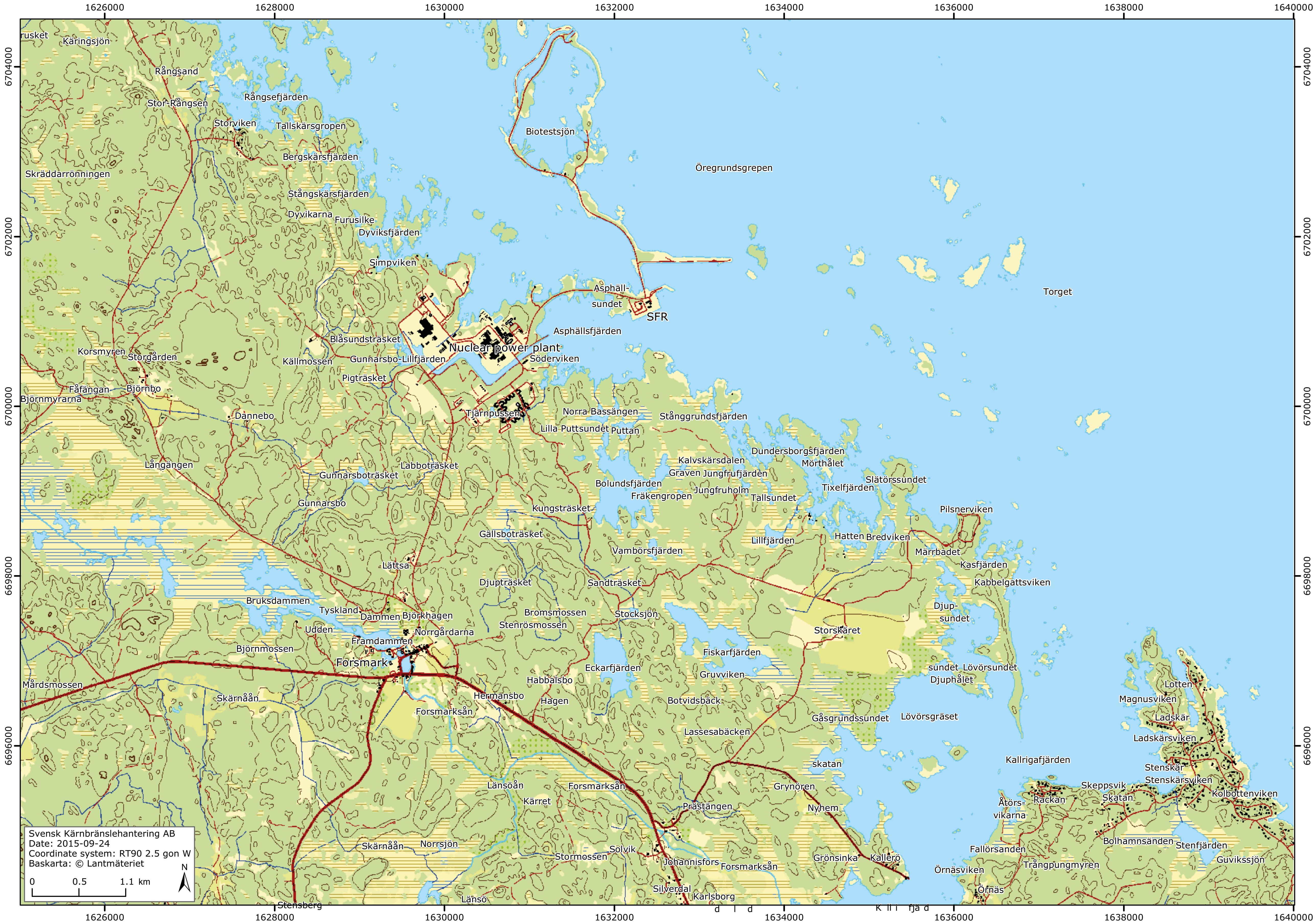
Map of Forsmark



Appendix 2

Reference to hydrochemical data in Chapter 6

All overviews and statistical evaluations of hydrochemical data in this section were compiled in an Access database. The Access database was linked to the Sicada database via seven parameter queries (p_water_chemistry1_grw, p_water_chemistry2_grw, p_water_chemistry1_suw, p_water_chemistry2_suw, p_surface_water_meas, p_precip_analys_high_acc and p_drinking_water). During the work, the content of the Access database was updated several times when more or corrected data became available. The latest update (for the present report) of the Access database was done 2015-02-24 and all compilations in this report are based on data from this date. The contents of the Access database was later compared to the traceable Sicada withdrawal 15_064_2 and the deviations identified are listed in the Table A2-1 and Table A2-2 below.

Table A2-1. Parameter values that differ between the Access database 2015-02-24 and Sicada 15_064_2.

SKB_SAMPLE_NO	Parameter	2015-02-24	Sicada 15_064_2
30346	OXYGEN (mg/l)	0.25	0.13
30372	OXYGEN (mg/l)	0.04	0.03
12880	COND (mS/m)	280	245
12879	HCO3 (mg/l)	71.1	64
12878	COND (mS/m)	135	123
12879	COND (mS/m)	1390	1300
12878	HCO3 (mg/l)	694	680
12880	HCO3 (mg/l)	366	360
30372	PH_FIELD (pH)	8.17	8.07

Table A2-2. Additional samples (SKB_SAMPLE_NO) in Sicada 15_064_2 compared to the content in the Access database 2015-02-24.

SKB_SAMPLE_NO	W_TYPE	PROJECT	IDCODE	START_DATE
13700	Sea Water	SFR	PFRSEA01	1992-06-30
16375	Sea Water	SFR-utbyggnad	PFR000125	2009-08-24
16376	Sea Water	SFR-utbyggnad	PFR000125	2009-08-31
16377	Sea Water	SFR-utbyggnad	PFR000125	2009-09-02
21600	Surface water	SFK-Bygg	PFM007762	2012-07-02
30021	Near Surface GW	SFK-Bygg	SFM000132	2013-08-08
30022	Near Surface GW	SFK-Bygg	SFM000133	2013-08-08
30023	Surface water	SFK-Bygg	PFM007442	2013-08-08
30024	Near Surface GW	SFK-Bygg	SFM000114	2013-08-08
30032	Surface water	SFK-Bygg	PFM007442	2013-08-22
30033	Surface water	SFK-Bygg	PFM007407	2013-08-22
30034	Surface water	SFK-Bygg	PFM007407	2013-08-26
30035	Surface water	SFK-Bygg	PFM007442	2013-08-26
30036	Near Surface GW	SFK-Bygg	SFM000132	2013-08-26
30063	Near Surface GW	SFK-Bygg	SFM000133	2013-09-12
30064	Near Surface GW	SFK-Bygg	SFM000114	2013-09-12
30065	Near Surface GW	SFK-Bygg	SFM000132	2013-09-10
30379	Sea Water	SFKMONIT	PFM102269	2014-11-04
30382	Sea Water	SFKMONIT	PFM102269	2014-12-01
30303	Ground Water	SFR	KFR01	2014-12-16
30304	Ground Water	SFR	KFR10	2014-12-16
30305	Ground Water	SFR	KFR08	2014-12-16
30387	Ground Water	SFR	KFR7A	2014-12-16

Appendix 3

Tables with statistical evaluations of hydrochemical data

This appendix summarises the results from the statistical evaluation of all hydrochemical data from Forsmark. The comprehensive statistical overviews reflect different aspects of data quality, general patterns of variability, representativity of chemical data and long-term temporal changes with the main purpose of evaluating data quality and inconsistencies amongst sampled objects and analysed parameters.

The evaluation is based on five major data compilations described in the list below. These compilations contribute different complementary aspects to the extensive and multidimensional hydrochemical dataset from the Forsmark area.

1. Compilation of the total number of observations per parameter and object (sampling location). This evaluation reflects the changes of the monitoring and site characterisation programmes over time.
2. Compilation of the fraction of the observations per parameter and object that fall below reporting limits. If a large part of the analyses fall below the reporting limit, this could be an indication that the analysis method is inappropriate.
3. Compilation of the coefficient of variation (CV) for all parameters and objects. This compilation shows the relative variance among parameters and objects. CV is defined as the arithmetic standard deviation divided by the arithmetic mean. The information could be used to identify objects or parameters with, for some reason, increased variation. For parameters or objects with high inherent variation, longer time series and/or more frequent sampling are needed in order to detect significant deviations.
4. Compilation of normalised means based on all data from similar objects. Independent of the absolute parameter values, this compilation shows where the mean values for individual objects are located on the total range for all similar objects for each parameter. This information could be used to identify specific objects with deviating chemistry and also to show common patterns among several parameters.
5. Compilation of the results from a regression analysis with the purpose of identifying time trends in the data. Significant trends over time could be an indication of methodological, climatic or anthropogenic factors that influence data over time. It is expected that most of the time series will show no trends if they reflect baselines under undisturbed conditions.

All available quality controlled data from the SKB Sicada database have been included in the analysis. This means that this compilation contains samples that may have been discarded due to non-representativity during previous modelling activities. The reason for including all the data is that the overall purpose of this evaluation is to describe the entire dataset with a focus on data quality issues, rather than site descriptive modelling. Many of the findings from these analyses are well known to modellers and to personnel handling data.

Table A3-1. The total number of samples per parameter and object sampled and analysed for lake water, stream water, sea water and precipitation during the period 2002 to 2014. The colour coding ranges from few (red) to many (green) observations.

	Lake Water																Small ponds and wetlands												Precipitation			Sea Water																						Stream Water							
IDCODE	PFM000074	PFM000074	PFM000087	PFM000087	PFM000097	PFM000107	PFM000107	PFM000107	PFM000117	PFM000117	PFM000117	PFM000127	PFM000127	PFM000135	PFM000135	PFM000151	PFM005864	PFM007415	PFM007416	PFM007441	PFM007442	PFM007442	PFM007443	PFM007443	PFM007444	PFM007445	PFM007446	PFM007447	PFM007448	PFM102270	PFM002457	PFM002564	PFM102271	PFM000062	PFM000062	PFM000062	PFM000063	PFM000063	PFM000063	PFM000064	PFM000064	PFM000065	PFM000082	PFM000082	PFM000082	PFM000083	PFM000083	PFM000083	PFM000084	PFM000084	PFM000084	PFM000153	PFM005865	PFM005865	PFM005865	PFM102269	PFM000066	PFM000067	PFM000068	PFM000069	PFM000070	PFM000071	PFM000072	PFM000073
CorrSec*	X	S	S	B	S	X	S	B	X	S	B	S	B	S	B	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S				X	S	B	X	S	B	S	B	S	S	X	B	S	X	B	S	X	B	S	S	i	B	S	S	S	S	S	S	S	S	S
MonitProg**	y	y	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	y	y	n	n	n	n	n	n	y	y	y	n	n	n	n	n	n	n	n	n	n	y	y	n	y	y	y	n	n	n
10B		6	3	1	3		6	1		6	1			1																				6	1	1	4	1	3	1	4	1		1											2	3	4	1	2		2	2
13C		10	5	5	4		11	4		10	4	2	2	2		1																				9	2	1	4	3	3	3	4	2		2	1		1	1		1							3	4	4	4	3	3	4	1
14C		10	5	5	4		11	4		10	4	2	2	2		1																				9	2	1	4	3	3	3	4	2		2	1		1	1		1							3	4	4	4	3	3	4	1
18O	11	40	10	7	9	14	39	11	14	37	10	3	3	5		1															1	6	45	4	11	38	3	1	9	4	8	4	10	3		2	1		1	1		1		2	2	2	1	43	11	48	43	44	4	10	4
222Rn		5					5			5				1																						5																			1	1	1										
226Ra		5					6			6				1																						6																			1	1	1				1					
228Th							1			1																										1																											1					
230Th		6	1	1	1		8	1		8	1			2																						8	1	1	2	1	1	1	2			1							1	1	1				1					
232Th		4	1	1	1		6	1		6	1			1																						6	1	1	2	1	1	1	2			1													1					
234U		6	1	1	1		8	1		8	1			2																						8	1	1	2	1	1	1	2			1							1	1	1				1					
235U		4	1	1	1		5	1		5	1			1																						5	1	1	2	1	1	1	2			1																		
235U/238U							1			1																										1																											1					
238U		6	1	1	1		8	1		8	1			2																						8	1	1	2	1	1	1	2			1							1	1	1				1					
2H	11	40	10	7	9	14	39	11	14	37	10	3	3	5		1															1	6	45	4	11	38	3	1	9	4	8	4	10	3		2	1		1	1		1		2	2	2	1	43	11	48	43	44	4	10	4
34S_SO4		10	5	3	3		10	1		7		1	1	3																						10	1	1	5	1	4	1	5	1		1							1	1	1		3	4	4	1	2		4	2
36Cl																																			1																																
37Cl		11	8	5	5		12	4		8	1	3	3	2																						11	3	1	6	2	6	3	7	2		2	1		1	1		1		1	1	1		5	6	7	4	4	2	6	3
3H	11	39	10	7	8	14	39	11	14	37	10	3	3	5		1															1	6	45	7	11	38	3	1	9	4	8	4	9	3		2	1		1	1		1		2	2	2	99	43	10	48	42	43	3	10	4
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ABS_436	7	63				8	63	14	8	62	13			2			1	8	8	12	12	14	12	14	8	14	14	14	14	1				7	64								4		3							1	1	1		90		97	95	94			
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Al	11	37	7	4	7	14	37	9	14	34	9	1	3	5			1													1	6	29		11	38	3	1	9	4	8	4	9	2		1							1	1	1		59	8	62	57	59	2	6	3
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B		1					2			1																								2																							1		1	1	1			
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Br	11	105	38	24	36	14	108	38	14	103	37	14	9	19	1	4	1	8	8	13	13	25	13	25	9	24	25	25	25	1	6	45		11	103	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	54	141	44	154	153	145	33	40	23
Ca	11	105	38	25	37	14	108	38	14	104	38	14	9	19	1	4	1	8	8	13	13	25	13	25	9	25	25	25	25	1	6	45		11	105	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	1	141	44	154	153	145	33	40	23
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Chlorofyll_field	2	83	24	11	25	2	81	23	2	80	23	6	1	17	1		1			12	12	7	12	7	8	7	7	7	7	1				2	82	4		25	9	23	7	23	8		7	1			3		2					61	1		1	1	1			1
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DIC_bio	11	105	38	25	37	14	106	38	14	104	36	14	9	19	1	4				1	1		1								1				11	104	15	1	39	21	36	19	36	11	1	10	3	1	3	5	1	5	2	1	1	1		140	44	153	153	144	33	39	23
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Dy	10	21	6	2	5	13	20	5	13	20	5		1	4			1														12		10	20	2	1	8	3	7	3	8	1		1											24	5	25	20	24		5	3
EC_field	10	92	32	20	34	12	93	32	12	90	31	11	6	18	1	4	1	8	8	13	13	23	13	23	9	23	23	23	23	1				10	93	14		34	18	33	17	32	10		9	3		1	4		3	2				78	124	39	138	135	129	28	35	21
Er	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	20	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
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K	11	105	38	25	37	14	108	38	14	104	38	14	9	19	1	4	1	8	8	13	13	25	13	25	9	25	25	25	25	1	6	45		11	105	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	1	141	44	154	153	145	33	40	23
La	10	19	5	2	4	13	19	5	13	19	5		1	3		1	1														12		10	19	2		6	3	6	3	6	1		1	1		1	1		1						24	4	24	20	23		4	2
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Lu	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	20	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
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Mo	11	37	7	4	7	14	37	9	14	34	9	1	3	5			1													1		12		11	38	3	1	9	4	8	4	9	2		1								1	1	1		59	8	62	57	60	2	6	3
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Nb		1					1			1																																	1													1		1	1	1			
Nd	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	20	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
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NO2N																																																																
NO2N_bio	11	38	11	5	9	14	38	9	14	35	8	4	2	6		1		6	6	13	13	24	13	24	9	24	24	24	24	1				11	39	5	1	10	7	11	6	11	2		1							1	1	1	1		47	10	50	49	46	6	11	5
NO3N_bio	11	27	4		4	14	28	5	14	26	5	3	1			1		6	6	13	13	24	13	24	9	24	24	24	24	1	6	17		11	29	1		1	2	3	1	2	1								1	1	1	1		37	1	38	38	36		3	
O2_bio		33	18	23	21		29	29		25	29	8	8	3	1	4				3	3		3		1	1	1	1							15	15	1	19	17	16	14	16	5		6	3		3	4		4	2			1		31	25	30	45	23	15	29	10
O2_field	10	92	32	20	34	12	93	32	12	90	31	11	6	18	1	4	1	8	8	13	13	25	13	25	9	25	25	25	25	1				10	93	14		34	18	33	17	32	10		9	3		1	4		3	2				77	124	39	138	135	130	28	35	21
ORP_field	9	85	24	11	25	10	83	23	10	82	23	6	1	17	1		1	8	8	13	13	21	13	21	9	21	21	21	21	1				9	82	3		24	8	22	6	23	9		8	1			3		2					78	117	27	125	123	122	22	26	16
P_bio	11	104	37	24	36	14	106	37	14	104	36	13	9	19	1	4	1	7	7	13	13	24	13	24	9	24	24	24	24	1	6	29		11	103	15	1	39	20	36	18	35	12	1	11	3	1	3	5	1	5	2	1	2	2		141	43	154	152	145	33	40	23
Pb	10	37	7	3	5	12	35	8	12	34	9	1	2	5			1													1		12		10	38	3	1	9	4	8	4	9	2		1								1	1	1		57	7	60	55	58	1	6	3
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pH_field	10	92	32	20	34	12	93	32	12	90	31	11	6	18	1	4	1	8	8	13	13	23	13	23	9	23	23	23	23	1				10	93	14		34	18	33	17	32	10		9	3		1	4		3	2				78	125	39	139	136	131	28	35	21
Pheo_bio	11	99	38	25	36	14	103	38	14	102	37	14	9	19	1	4				1										1				11	100	16	1	40	21	37	17	35	12	1	11	3	1	3	5	1	5	2	2	1	1		13	17	16	17	10	11	13	8
PO4P_bio	11	104	38	25	37	14	107	38	14	105	37	14	9	19	1	4		7	7	13	13	24	13	24	9	24	24	24	24	1				11	104	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2		141	44	155	153	145	33	40	23
POC_bio	10	104	37	23	35	13	105	37	13	104	35	13	8	19	1	4															1				10	99	14	1	39	19	36	18	35	12		11	3	1	3	5	1	5	2	1	1	1		137	41	151	150	142	32	39	22
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S_2-		1	1	1	1		1	1																											1																				1		1				2	
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Se		3					3			2	1																								3																							2		2	2	2			
Si	11	105	38	25	37	14	108	38	14	104	38	14	9	19	1	4	1	8	8	13	13	25	13	25	9	25	25	25	25	1		18		11	105	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	1	141	44	154	152	144	33	40	23
SiO2_bio	11	104	38	25	37	14	107	38	14	105	37	14	9	19	1	4		7	7	2	2	19	2	19	1	18	18	18	18	1				11	104	16	1	39	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2		141	44	155	152	145	33	40	23
Sm	9	21	7	3	6	11	21	6	11	21	6		1	4		1	1														12		9	20	2	1	8	3	7	3	8	2		2	1		1	1		1						24	5	24	19	23		5	3
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SO4S	11	105	38	25	37	13	108	38	14	104	38	14	9	19	1	4	1	8	8	13	13	25	13	25	8	23	24	25	25	1	6	45		11	105	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	1	141	44	154	153	145	33	40	23
Sr	11	105	38	25	37	14	108	38	14	104	38	14	9	19	1	4	1	8	8	13	13	25	13	25	9	25	25	25	25	1		18		11	105	16	1	40	21	37	19	36	12	1	11	3	1	3	5	1	5	2	2	2	2	1	141	44	154	153	144	33	40	23
Susp	11	38				14	39	9	14	38	9																						11	43																							78		82	81	79			
Tb	10	21	6	2	5	13	20	5	13	20	5		1	4			1														12		10	20	2	1	8	3	7	3	8	1		1											24	5	25	20	24		5	3
Th	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	21	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
Tl	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	21	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
Tm	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	20	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
TOC_bio	11	105	38	25	36	14	107	38	14	104	36	14	9	19	1	4		7	7	13	13	24	13	24	9	24	24	24	24	1				11	103	16	1	39	21	37	19	36	11	1	10	3	1	3	5	1	5	2	1	1	1		139	44	154	153	145	33	39	23
turbidity	9	84	25	12	25	10	82	23	10	80	23	6	1	17	1		1	8	8	12	12	21	12	21	8	21	21	21	21	1				9	83	5		26	10	24	8	24	8		7	1			3		2					62	16		17	17	17			1
U	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	21	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
V	11	37	7	3	5	14	35	8	14	34	9	1	2	5			1													1		12		11	38	3	1	9	4	8	4	9	2		1								1	1	1		58	7	61	56	59	1	6	3
Y	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	21	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
Yb	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	20	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3
Zn	11	37	7	4	7	14	37	9	14	34	9	1	3	5			1													1		12		11	38	3	1	9	4	8	4	9	2		1								1	1	1		59	8	62	57	60	2	6	3
Zr	10	21	7	3	6	13	21	6	13	21	6		1	4		1	1														12		10	21	2	1	8	3	7	3	8	2		2	1		1	1		1						25	5	25	20	24		5	3

* S=surface, B=bottom, i=intermediary, x= no info.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-2. The percentage of the total number of observations that falls below reporting limit for all objects and parameters for lake water, stream water, sea water and precipitation during the period 2002–2014. The colour coding ranges from few (green) to many (red) observations below reporting limits.

Lake Water

IDCODE	PFM000074	PFM000074	PFM000087	PFM000087	PFM000097	PFM000107	PFM000107	PFM000107	PFM000117	PFM000117	PFM000117	PFM000127	PFM000127	PFM000135	PFM000135	PFM000151	PFM005864
CorrSec	X	S	S	B	S	X	S	B	X	S	B	S	B	S	B	S	S
MonitProg	y	y	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n
10B		0	0	0	0		0	0		0	0			0			
13C		0	0	0	0		0	0		0	0	0	0	0		0	
14C		0	0	0	0		0	0		0	0	0	0	0		0	
18O	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	
222Rn		0					20			60				100			
226Ra		80					83			83				100			
228Th							0			0							
230Th		17	100	100	100		25	100		38	0			100			
232Th		0	100	100	100		17	100		17	100			100			
234U		0	0	100	0		13	100		13	0			50			
235U		0	100	100	100		20	100		20	100			100			
235U/238U							0			0							
238U		0	0	100	0		13	100		13	0			50			
2H	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	
34S_SO4		0	20	33	0		0	0		0		0	0	33			
36Cl																	
37Cl		0	0	0	0		0	0		0	0	0	0	0			
3H	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	
87Sr		0	0	0	0		0	0		0	0	0	0	0			
ABS_436	0	0				0	0	0	0	0	0			0			0
ABS_bio	0	0				0	0	0	0	0	0			0			0
Al	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
As		0	0	0	0		25	0		25	0	0	0	0			
B		0					0			0							
Ba	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Br	0	10	13	38	6	0	3	3	0	8	24	0	22	11	0	75	100
Ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	45	57	43	67	20	21	34	38	36	47	67	0	0	40			100
Ce	0	0	0	0	0	0	0	0	0	14	0		0	0		0	0
ChlA	9	8	13	0	14	0	7	13	7	2	8	0	0	5	0	25	
ChlC	91	74	87	83	89	21	59	82	36	42	68	64	100	53	100	50	
Chlorofyll_field	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
COND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	9	0	0	0	0	0	0	0	0	3	0	0	0	0			0
Cs	100	95	71	67	67	92	71	67	92	90	83		100	100		0	100
Cu	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
DIC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
DOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Dy	10	10	0	0	0	0	5	0	15	45	0		100	0			0
EC_field	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Er	10	5	14	0	17	15	14	0	23	52	0		100	25		0	0
Eu	90	76	71	33	50	54	62	50	69	90	83		100	100		0	100
F	0	14	9	5	9	0	8	12	0	32	24	31	13	33	100	0	100
Fe	0	4	0	0	0	0	0	0	0	11	0	0	0	0		0	0
Gd	0	5	17	0	0	0	5	0	23	55	0		100	0			0
HCO3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	30	43	14	0	17	15	43	0	23	57	33		100	25		0	0
Hg	91	70	86	0	60	79	74	63	93	88	89	100	100	80			100
Ho	60	71	57	0	33	46	57	0	54	81	50		100	75		0	0
I	9	4	3	0	0	7	5	11	7	6	7	0	0	0	0		
In		100	50	0	50		50	0		75	0					0	
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0	0	11	0		0	0		0	0
Li	18	70	53	28	43	14	56	43	14	68	58	7	0	39	0	0	0
light	0	1	0	0	0	0	0	5	0	1	5	0	0	0			
Lu	90	86	57	33	50	69	76	33	69	81	83		100	100		0	100
Mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mn	0	8	0	0	0	0	8	0	0	2	0	0	0	20		0	0
Mo	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nb		0					0			0							
Nd	0	0	0	0	0	0	0	0	0	0	0		0	0		0	0
NH4N_bio	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Ni	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
NO23N_bio	0	3	3	0	3	0	2	0	0	0	0	7	0	0	0	0	
NO2N_bio	0	8	9	0	11	7	16	0	0	11	13	25	0	17		0	
NO3N_bio	9	11	75		75	7	11	20	0	4	0	100	100			100	
O2_bio		3	0	26	14		3	21		4	21	0	0	33	100	0	
O2_field	0	0	0	5	3	0	0	0	0	0	0	0	0	0	0	0	0
ORP_field	0	25	17	55	40	0	5	35	0	6	39	0	0	24	100		100
P_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pb	0	0	0	0	0	0	0	0	8	12	0	0	0	0			0
pH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pH_field	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pheo_bio	55	29	29	20	39	7	42	39	29	42	22	50	44	16	0	50	
PO4P_bio	45	36	18	20	14	21	21	26	14	15	22	14	0	5	0	0	
POC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
PON_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
POP_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pr	10	10	14	0	0	0	5	0	23	52	0		100	0		0	0
Rb	0	0	0	0	0	0	0	0	0	0	0		0	0		0	0
S_2-		100	100	100	100		100	100									
salinity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
Sb	0	0	0	0	0	0	0	0	0	0	0		0	0			0
Sc	100	90	71	67	67	83	81	83	83	90	83		100	100		0	100
Se		0					0			0	0						
Si	0	0	0	0	3	0	1	0	0	0	0	0	0	5	0	0	0
SiO2_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Sm	11	14	14	0	0	0	5	0	18	57	0		100	0		0	0
SO4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SO4S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Susp	18	82				0	72	67	0	71	67						
Tb	90	86	67	50	60	69	85	40	62	95	80		100	100			100
Th	50	76	71	33	50	31	62	17	23	81	33		100	100		0	0
Tl	100	90	71	67	67	100	81	83	100	86	83		100	100		0	100
Tm	90	90	71	33	50	69	76	33	69	90	83		100	100		0	100
TOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
turbidity	0	58	72	50	36	0	72	65	0	79	74	50	100	41	0		100
U	0	0	0	0	0	0	0	0	0	0	0		0	0		0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
Y	0	0	0	0	0	0	0	0	0	0	0		0	0		0	0
Yb	10	5	0	0	0	8	19	0	23	48	0		100	25		0	0
Zn	0	0	0	0	0	0	0	0	0	3	0	0	0	0			0
Zr	0	0	0	0	0	0	0	0	0	0	0		0	0		0	0

Small ponds and wetlands / Precipitation

IDCODE	PFM007415	PFM007416	PFM007441	PFM007442	PFM007442	PFM007443	PFM007443	PFM007444	PFM007445	PFM007446	PFM007447	PFM007448	PFM102270	PFM002457	PFM002564	PFM102271
CorrSec	S	S	S	S	S	S	S	S	S	S	S	S	S			
MonitProg	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
10B																
13C																
14C																
18O													0	0	0	0
222Rn																
226Ra																
228Th																
230Th																
232Th																
234U																
235U																
235U/238U																
238U																
2H													0	0	0	0
34S_SO4																
36Cl																
37Cl																
3H													0	0	0	0
87Sr																
ABS_436	0	0	0	0	0	0	0	0	0	0	0	0	0			
ABS_bio	0	0	0	0	0	0	0	0	0	0	0	0	0			
Al													0	50	52	
As																
B																
Ba													0		0	
Br	63	100	85	92	96	92	100	89	38	32	96	100	100	100	62	
Ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	
Cd													0		0	
Ce															0	
ChlA			0										0			
ChlC			0										100			
Chlorofyll_field			0	0	0	0	14	0	14	14	14	14	0			
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	
Co													0		17	
COND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	
Cr													0		0	
Cs															92	
Cu													0		0	
DIC_bio			0	0		0							0			
DOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Dy															83	
EC_field	0	0	0	0	0	0	0	0	0	0	0	0	0			
Er															100	
Eu															100	
F	0	0	0	0	0	0	4	0	0	0	0	0	0		100	
Fe	0	0	0	0	0	0	0	44	0	0	0	0	0	67	60	
Gd															100	
HCO3	0	0	0	0	0	0	0	0	0	0	0	0	0	100	98	
Hf															100	
Hg													0		83	
Ho															100	
I													0		42	
In																
K	0	0	0	0	0	0	0	0	0	0	0	0	0	17	62	
La															17	
Li	25	100	85	100	96	100	96	89	68	28	88	68	100		56	
light			0	0		0		0	0	0	0	0	0			
Lu															100	
Mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	
Mn	13	13	31	0	0	15	36	56	0	0	40	28	0		22	
Mo													0		50	
N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0		0	
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Nb																
Nd															25	
NH4N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0			
Ni													0		0	
NO23N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0			
NO2N_bio	0	0	15	15	4	8	13	22	4	0	4	0	0			
NO3N_bio	0	0	0	15	4	0	0	0	0	0	4	0	0	0	0	
O2_bio			0	0		33		0	0	0	0					
O2_field	0	0	0	0	0	0	0	0	0	0	0	0	0			
ORP_field	0	0	31	31	14	38	19	44	29	19	0	0	0			
P_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	50	7	
Pb													0		0	
pH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
pH_field	0	0	0	0	0	0	0	0	0	0	0	0	0			
Pheo_bio			0										100			
PO4P_bio	0	14	62	77	38	62	33	89	38	29	33	38	0			
POC_bio													0			
PON_bio													0			
POP_bio													0			
Pr															67	
Rb															0	
S_2-																
salinity			0	0	0	0	0	0	0	0	0	0	0			
Sb															0	
Sc															100	
Se																
Si	0	0	0	0	0	0	0	0	0	4	0	0	0		89	
SiO2_bio	0	0	0	0	0	0	0	0	0	0	0	0	0			
Sm															83	
SO4	0	0	0	0	0	0	0	0	0	0	0	0	0		6	
SO4S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	
Sr	0	0	0	0	0	0	0	0	0	0	0	0	0		56	
Susp																
Tb															100	
Th															100	
Tl															83	
Tm															100	
TOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0			
turbidity	0	0	75	92	5	50	0	100	0	0	5	0	0			
U															0	
V													0		0	
Y															33	
Yb															100	
Zn													0		0	
Zr															92	

Sea Water

IDCODE	PFM000062	PFM000062	PFM000062	PFM000063	PFM000063	PFM000063	PFM000064	PFM000064	PFM000065	PFM000082	PFM000082	PFM000082	PFM000083	PFM000083	PFM000083	PFM000084	PFM000084	PFM000084	PFM000153	PFM005865	PFM005865	PFM005865	PFM102269
CorrSec	X	S	B	X	S	B	S	B	S	S	X	B	S	X	B	S	X	B	S	S	i	B	S
MonitProg	y	y	y	n	n	n	n	n	n	y	y	y	n	n	n	n	n	n	n	n	n	n	y
10B		0	0	0	0	0	0	0	0	0		0											
13C		0	0	0	0	0	0	0	0	0		0	0		0	0		0					
14C		0	0	0	0	0	0	0	0	0		0	0		0	0		0					
18O	0	0	0	0	0	0	0	0	0	0		0	0		0	0		0		0	0	0	0
222Rn		40																		0	100	100	
226Ra		67																		100	100	100	
228Th		0																					
230Th		25	100	100	100	100	100	0	100			100								100	0	0	
232Th		33	100	100	100	100	100	100	100			100											
234U		0	100	100	50	100	100	0	100			100								0	0	0	
235U		20	100	100	100	100	100	100	100			100											
235U/238U		0																					
238U		0	100	100	50	100	100	0	100			100								0	0	0	
2H	0	0	0	0	0	0	0	0	0	0		0	0		0	0		0		0	0	0	0
34S_SO4		0	0	0	0	0	0	0	0	0		0								0	0	0	
36Cl		0																					
37Cl		0	0	0	0	0	0	0	0	0		0	0		0	0		0		0	0	0	
3H	0	0	0	0	0	0	0	0	0	0		0	0		0	0		0		0	0	0	0
87Sr		0	0	0	0	0	0	0	0	0		0								0	0	0	
ABS_436	0	0								0		0								0	0	0	
ABS_bio	0	0								0		0								0	0	0	
Al	9	3	0	0	0	0	0	0	0	0		0								0	0	0	
As		40	50		50	50	50	50	50														
B		0																					
Ba	0	0	0	0	0	0	0	0	0	0		0	0		0	0		0		0	0	0	
Br	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0
Ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	82	58	33	0	78	50	50	50	56	50		100								0	0	0	
Ce	40	45	0	0	13	33	14	0	13	50		50	0		0	0		0					
ChlA	9	1	0	0	3	0	0	0	0	8	0	9	0	0	0	0	0	0	0	0	0	0	
ChlC	27	32	88	100	73	62	46	44	60	33	100	18	33	100	0	0	100	0	0	0	0	0	
Chlorofyll_field	0	0	0		0	0	0	0	0	0		0	0			0		0					7
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Co	55	50	0	100	44	75	13	0	11	50		100								0	0	0	
COND	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	27	13	0	0	11	0	25	0	0	0		0								0	0	0	
Cs	67	81	0	100	63	33	57	33	63	50		50	0		0	0		0					
Cu	0	13	0	0	44	25	13	25	11	0		0								0	0	0	
DIC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
DOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Dy	90	90	100	100	88	100	57	67	63	100		100											
EC_field	0	0	0		0	0	0	0	0	0		0	0		0	0		0	0				0
Er	90	95	100	100	88	100	71	100	63	50		50	0		0	0		0					
Eu	100	100	100	100	100	100	71	100	63	50		50	0		100	0		0					
F	0	24	100	100	90	92	94	92	86	44		57	100		100	67		100		0	0	0	0
Fe	9	21	20	0	0	17	0	0	0	50		60	0		0	0		50		0	0	0	100
Gd	90	90	100	100	88	100	57	67	63	100		100											
HCO3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	100	90	50	100	75	67	57	67	50	50		50	0		0	0		0					
Hg	100	92	100	100	100	100	88	100	89	50		100								100	100	100	
Ho	100	95	100	100	100	100	71	100	63	50		50	0		0	0		0					
I	27	12	0		0	0	0	0	0	13		14	0		0	0		0		0	0	0	0
In		60	0		33	0	33	0	33	0		0	0		0	0		0					
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La	70	53	0		17	33	17	0	17	0		0	0		0	0		0					
Li	0	1	6	0	0	0	3	0	6	0		0	0		0	0		0	0	0	0	0	0
light	0	0	0		0	0	0	0	0	0		0	0			0		0					9
Lu	100	90	100	100	100	100	71	100	75	50		50	0		0	0		0					
Mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mn	0	17	25	0	0	17	0	0	0	67		20	0		100	0		0		0	0	0	100
Mo	0	0	0	0	0	0	0	0	0	0		0								0	0	0	
N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nb										100													
Nd	70	55	0	100	13	33	14	0	13	50		50	0		0	0		0					
NH4N_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Ni	0	5	0	0	11	25	0	0	0	0		0								0	0	0	
NO23N_bio	27	3	0	0	5	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	
NO2N_bio	18	10	20	0	10	29	9	17	0	0		0							100	0	0	0	
NO3N_bio	64	31	100		0	100	67	100	50	0									100	0	0	0	
O2_bio		0	0	0	0	0	0	0	0	0		0	0		0	0		0	0			0	
O2_field	0	0	0		0	0	0	0	0	0		0	0		0	0		0	0				0
ORP_field	0	0	0		0	0	0	0	0	11		13	0			0		0					6
P_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pb	60	63	33	100	67	25	38	75	33	0		0								0	0	0	
pH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pH_field	0	0	0		0	0	0	0	0	0		0	0		0	0		0	0				0
Pheo_bio	9	15	69	0	28	33	11	0	11	33	100	27	67	100	33	0	100	0	0	50	0	0	
PO4P_bio	36	19	19	0	13	10	5	5	6	8	0	0	67	0	100	0	0	0	0	0	0	0	
POC_bio	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	
PON_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
POP_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pr	90	90	100	100	88	100	29	33	38	50		50	0		0	0		0					
Rb	0	0	0	0	0	0	0	0	0	0		0	0		0	0		0					
S_2-			0																				
salinity	0	0	0		0	0	0	0	0	0		0	0		0	0		0	0				0
Sb	90	76	0	0	38	33	29	33	13	0		0											
Sc	89	90	50	100	88	100	57	33	75	50		50	0		0	0		0					
Se		0																					
Si	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SiO2_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Sm	89	90	100	100	88	100	57	67	63	50		50	0		0	0		0					
SO4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SO4S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Susp	0	44																					
Tb	100	100	100	100	100	100	71	100	63	100		100											
Th	90	100	100	100	100	100	86	100	63	100		100	0		100	0		0					
Tl	90	90	0	100	75	33	71	33	63	50		50	0		0	0		0					
Tm	100	100	100	100	100	100	86	100	75	50		50	0		100	0		0					
TOC_bio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
turbidity	0	43	60		15	20	0	0	0	50		57	0			0		50					45
U	10	0	0	0	0	0	0	0	0	0		0	0		0	0		0					
V	0	0	0	0	0	0	0	0	0	0		0								0	0	0	
Y	0	5	0	0	13	0	0	0	0	0		0	0		0	0		0					
Yb	100	95	100	100	88	100	71	100	63	50		50	0		0	0		0					
Zn	0	24	0	0	22	0	13	0	11	0		0								0	0	0	
Zr	70	71	50	0	50	67	29	33	25	0		0	0		0	0		0					

Stream Water

IDCODE	PFM000066	PFM000067	PFM000068	PFM000069	PFM000070	PFM000071	PFM000072	PFM000073	PFM004306
CorrSec	S	S	S	S	S	S	S	S	S
MonitProg	y	n	y	y	y	n	n	n	n
10B	0	0	0	0	0		0	0	
13C	0	0	0	0	0	0	0	0	
14C	0	0	0	0	0	0	0	0	
18O	0	0	0	0	0	0	0	0	
222Rn									
226Ra			0						0
228Th			0						0
230Th			0						0
232Th			0						0
234U			0						0
235U									
235U/238U			0						0
238U			0						0
2H	0	0	0	0	0	0	0	0	
34S_SO4	0	0	0	0	0		25	100	
36Cl									
37Cl	0	0	0	0	0	0	0	0	
3H	0	0	0	0	0	0	0	0	
87Sr	0	0	0	0	0		0	0	
ABS_436	0		0	0	0				
ABS_bio	0		0	0	0				
Al	0	0	0	0	0	0	0	0	
As	0	33	0	0	0		50	0	
B	0		0	0	0				
Ba	0	0	0	0	0	0	0	0	
Br	9	7	9	8	6	30	13	26	
Ca	0	0	0	0	0	0	0	0	
Cd	57	14	21	34	29	0	33	0	
Ce	0	0	0	0	0		0	0	
ChlA	38	12	44	41	9	64	23	0	
ChlC	92	76	94	94	80	91	77	75	
Chlorofyll_field	0		0	0	0			0	
Cl	0	0	0	0	0	0	0	0	
Co	0	0	0	0	0	0	0	0	
COND	0	0	0	0	0	0	0	0	
Cr	0	0	0	0	2	0	0	0	
Cs	88	80	96	100	96		80	67	
Cu	0	0	2	2	2	0	0	0	
DIC_bio	0	0	0	0	0	0	0	0	
DOC_bio	0	0	0	0	0	0	0	0	
Dy	0	0	0	0	0		0	0	
EC_field	0	0	0	0	0	0	0	0	
Er	0	0	0	0	4		20	33	
Eu	68	60	56	65	75		80	67	
F	21	31	6	5	32	18	27	0	
Fe	0	0	0	0	2	0	0	0	
Gd	0	0	0	0	0		20	0	
HCO3	0	0	0	0	0	0	0	0	
Hf	12	40	0	0	38		40	0	
Hg	81	71	43	52	73	100	67	100	
Ho	28	60	0	5	67		60	67	
I	3	0	5	3	12	4	0	13	
In	50	100	100		100		100		
K	0	0	0	1	2	0	0	0	
La	0	0	0	0	0		0	0	
Li	62	51	62	58	65	71	37	5	
light	100		100	0	0				
Lu	76	60	52	65	83		100	67	
Mg	0	0	0	0	0	0	0	0	
Mn	5	0	0	2	2	11	0	0	
Mo	0	0	0	4	3	0	0	0	
N_bio	0	0	0	0	0	0	0	0	
Na	0	0	0	0	0	0	0	0	
Nb	0		0	0	0				
Nd	0	0	0	0	0		0	0	
NH4N_bio	1	0	0	2	1	6	3	4	
Ni	0	0	0	0	0	0	0	0	
NO23N_bio	1	0	0	0	0	0	0	0	
NO2N_bio	4	0	2	4	2	0	9	0	
NO3N_bio	8	0	0	0	0		33		
O2_bio	0	0	3	2	9	0	14	0	
O2_field	0	0	0	0	0	0	0	0	
ORP_field	9	11	6	11	7	9	35	13	
P_bio	0	0	0	0	0	0	0	0	
Pb	2	0	2	0	2	100	0	0	
pH	0	0	0	0	0	0	0	0	
pH_field	0	0	0	0	0	0	0	0	
Pheo_bio	62	47	50	53	50	64	38	0	
PO4P_bio	24	14	19	18	28	3	8	0	
POC_bio	0	0	0	0	0	0	0	0	
PON_bio	0	0	0	0	0	0	0	0	
POP_bio	0	0	0	0	0	0	0	0	
Pr	0	0	0	0	0		0	33	
Rb	0	0	0	0	0		0	0	
S_2-	100		100				100		
salinity	0	0	0	0	0	0	0	0	
Sb	0	0	0	0	0		0	0	
Sc	79	60	83	84	83		80	67	
Se	100		100	100	100				
Si	0	0	0	0	0	0	0	0	
SiO2_bio	0	0	0	0	0	0	0	0	
Sm	0	0	0	0	0		0	33	
SO4	0	0	0	0	1	0	0	0	
SO4S	0	0	0	0	0	0	0	0	
Sr	0	0	0	0	0	0	0	0	
Susp	44		41	43	44				
Tb	79	60	40	35	75		80	67	
Th	24	60	4	15	58		80	100	
Tl	88	80	88	95	96		80	67	
Tm	76	60	64	65	83		100	67	
TOC_bio	0	0	0	0	0	0	0	0	
turbidity	6		6	6	6			0	
U	0	0	0	0	0		0	0	
V	0	0	0	0	0	0	0	0	
Y	0	0	0	0	0		0	0	
Yb	0	0	0	0	4		20	0	
Zn	2	0	2	2	2	0	0	0	
Zr	0	0	0	0	0		0	0	

* S=surface, B=bottom, i=intermediary, x= no info.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-3. The coefficient of variation (CV) expressed in percent for all objects and parameters with at least 5 observations representing a time period longer than one year for lake water, stream water, sea water and precipitation. The CV is defined as the ratio between the arithmetic standard deviation and the arithmetic mean. The colour coding ranges from low (green) to high (red) variability.

	Lake Water																				
IDCODE	PFM000074	PFM000087	PFM000087	PFM000097	PFM000107	PFM000107	PFM000117	PFM000117	PFM000127	PFM000127	PFM000135	PFM007441	PFM007442	PFM007442	PFM007443	PFM007443	PFM007444	PFM007445	PFM007446	PFM007447	PFM007448
CorrSec*	S	S	B	S	S	B	S	B	S	B	S	S	S	S	S	S	S	S	S	S	S
MonitProg**	y	n	n	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n
10B	1				1		1														
13C	29				38		69														
14C	1				2		3														
18O	19	17	17	28	31	18	21	14													
222Rn																					
226Ra																					
230Th					77																
232Th																					
234U	12				11		17														
235U																					
238U	12				10		10														
2H	13	13	14	17	19	12	12	9													
34S_SO4	89				38		42														
37Cl	163	112			1174		158														
3H	14	14	16	20	13	17	18	17													
87Sr	0				0		0														
ABS_436	239				243	67	250	43				72	31	173	25	25	69	24	20	30	38
ABS_bio	28				65	68	55	50				72	31	44	26	25	69	24	20	30	38
Al	155	174		54	207	114	174	116													
As	62				43		15														
B																					
Ba	16	39		45	26	31	24	24													
Br	34	60	33	73	118	154	33	68	27	28	25							56	26		
Ca	19	22	32	52	28	26	22	18	15	9	47	45	29	24	46	38	38	24	28	34	20
Cd	78				133		69														
Ce	63	52		63	77	28	101	56													
ChlA	123	80	75	68	77	99	54	69	73	77	132										
ChlC	92				54	53	49	61			99										
Chlorofyll_field	191	35	46	64	54	55	47	39	45		67	84	46	48	58	59	92	48	47	37	43
Cl	57	46	22	81	134	159	19	23	21	24	26	42	35	52	32	39	21	81	48	34	26
Co	46	81		38	33	68	42	19													
COND	19	15	27	60	82	108	20	15	13	10	29	40	28	22	41	31	27	43	31	29	15
Cr	46	31		256	141	36	48	44													
Cs					84																
Cu	66	78			46	50	38	27													
DIC_bio	27	38	56	58	43	47	32	43	35	55	51										
DOC_bio	20	19	29	28	26	32	15	25	16	25	22	38	23	22	18	23	33	20	21	20	19
Dy	53	59			89		60														
EC_field	20	14	27	97	82	124	18	17	8	9	29	44	26	24	42	29	30	47	26	26	21
Er	53	37			75	28	51	41													
Eu					66																
F	30	32	33	98	19	19	29	38	42	24	10	21	15	22	20	21	9	22	24	20	20
Fe	88	97	93	111	82	68	158	53				157	151	140	148	138		93	69	212	126
Gd	59				87		58														
HCO3	19	20	30	37	28	24	21	17	16	14	44	48	34	25	46	40	33	33	48	39	30
Hf	60	53			114	43	39														
Hg	31				34																
Ho	26				64	27															
I	47	48	40	44	36	35	36	23	27	25	46										
K	30	18	30	45	66	103	13	12	7	10	20	29	32	39	31	43	28	40	33	34	21
La	61				79		99														
Li	50	51	67	30	50	72	61	13	15	19	33							20	21	19	10
light	133	163		117	125	246	150	153	110		141										
Lu																					
Mg	18	14	17	51	89	127	11	10	8	11	21	41	25	22	23	23	18	51	35	27	15
Mn	175	268	154	95	124	81	156	78				97	126	161	150	115		109	90	105	115
Mo	34	40		33	34	43	19	14													
N_bio	21	18	27	21	17	24	19	25	20	20	42	42	26	41	67	52	20	24	20	26	23
Na	40	20	21	72	126	154	13	11	19	20	25	46	19	40	19	26	18	86	50	28	29
Nd	61	60		64	84	28	98	49													
NH4N_bio	319	197	137	258	154	96	128	71	120	152	162	153	182	150	257	187	139	194	167	81	94
Ni	46	31		42	47	37	43	33													
NO23N_bio	184	186	207	195	173	160	123	104	143	76	301	129	117	140	132	147	96	215	271	129	127
NO2N_bio	105	96		77	83	54	71	50				101	49	48	109	68	61	147	189	71	84
NO3N_bio	168				150		126					130	104	145	134	151	97	220	278	128	128
O2_bio	67	32	46	40	60	68	61	72	6	7											
O2_field	47	36	77	51	37	82	30	92	8	8	56	64	66	98	68	49	51	70	72	94	79
ORP_field	60	58		44	56	56	63	44	19		59	79	72	31	69	28		25	29	37	35
P_bio	35	32	31	25	26	22	26	14	33	21	35	21	46	62	74	65	81	41	33	71	50
Pb	91	76			79	72	97	86													
pH	5	6	6	10	8	7	6	6	5	2	10	7	6	7	9	7	8	6	6	7	5
pH_field	5	7	7	11	8	8	6	6	6	4	11	8	7	7	10	7	8	6	6	8	5
Pheo_bio	110	66	79	151	80	123	67	60	83		165										
PO4P_bio	62	67	46	59	47	54	53	51	35	36	55			42		61		44	53	75	49
POC_bio	97	49	34	39	291	52	35	26	74	50	134										
PON_bio	90	46	38	30	72	49	38	26	78	38	125										
POP_bio	57	43	39	29	47	29	31	29	51	28	70										
Pr	58	43		63	81	28	62	51													
Rb	22	22		20	24	14	12	13													
S_2-																					
salinity	20	18	31	115	91	141	18	18	9		29	45	25	38	42	12	31	39	8	20	32
Sb	26	28		17	23		17														
Sc																					
Si	31	51	40	130	106	72	58	35	75	71	101	109	38	43	53	63	31	49	50	46	44
SiO2_bio	29	49	40	136	105	70	56	36	72	69	106			45		69		54	53	53	48
Sm	55	47		67	85	30	56	46													
SO4	67	58	218	51	88	130	31	34	11	9	32	30	117	116	70	127	19	88	88	105	118
SO4S	60	48	73	50	85	130	26	28	10	11	28	28	91	99	51	99	14	89	83	94	107
Sr	17	76	17	42	65	86	12	11	10	13	28	41	27	21	32	23	22	33	27	26	16
Susp	76				48		24														
Tb																					
Th					62																
Tl																					
Tm																					
TOC_bio	21	17	28	27	25	31	16	21	17	19	21	39	22	21	18	24	32	19	21	19	19
turbidity	216			340										48		109		275	176	178	36
U	43	26		33	36	18	19	12													
V	29	39			41	31	25	14													
Y	52	48		64	75	27	81	46													
Yb	52	46		65	72	28	50	40													
Zn	100	67		59	126	92	66	72													
Zr	54	48		41	66	15	63	42													

	Precipitation	Sea Water										Stream Water							
IDCODE	PFM002564	PFM000062	PFM000062	PFM000063	PFM000063	PFM000064	PFM000064	PFM000065	PFM000082	PFM000082	PFM102269	PFM000066	PFM000067	PFM000068	PFM000069	PFM000070	PFM000071	PFM000072	PFM000073
CorrSec*		S	B	S	B	S	B	S	S	B	S	S	S	S	S	S	S	S	S
MonitProg**	n	y	y	n	n	n	n	n	y	y	y	y	n	y	y	y	n	n	n
10B		8																	
13C		59																	
14C		3																	
18O	25	8		3		16		12				13	27	11	11	22		20	
222Rn																			
226Ra																			
230Th		115																	
232Th																			
234U		103																	
235U																			
238U		121																	
2H	23	7		3		12		11				11	18	10	10	18		11	
34S_SO4		6																	
37Cl		330		300		4914		106					770	356				115	
3H	26	18		12		13		15			206	15	22	15	13	16		9	
87Sr		0																	
ABS_436		336										215		216	211	241			
ABS_bio		71										35		37	36	43			
Al	215	263		138		187		225				173	50	96	178	222		81	
As		44																	
B																			
Ba	77	8		10		8		11				16	32	22	17	33		39	
Br	176	12	13	14	10	33	18	39	18	13	7	38	69	45	40	65	123	76	58
Ca	75	5	5	6	6	11	5	12	6	7		17	19	17	17	23	11	23	14
Cd	88	84										58	52	66	36	71			
Ce	83	73		133		123		177				39		45	36	107			
ChlA		78	50	53	61	79	54	108	82	61		137	133	59	52	63		101	188
ChlC		95		55	45	125	50	140	84	69									
Chlorofyll_field		41		48	60	111	41	72	77	41	112								
Cl	68	4	4	12	4	32	15	41	10	2	4	34	71	56	41	37	83	59	21
Co	61	152				54		108				50	39	76	40	82		62	
COND	41	3	3	10	3	32	18	34	4	3	4	15	37	20	16	19	11	27	11
Cr	197	156		44		63		116				35	41	27	29	62		32	
Cs																			
Cu	57	261				56		65				48	31	63	57	42		34	
DIC_bio		26	54	47	55	47	54	41	25	41		27	48	27	28	28	29	44	33
DOC_bio	65	17	35	58	30	61	58	69	37	38		20	24	19	22	22	19	24	30
Dy												38		34	40	87			
EC_field		10	14	14	15	30	18	38	13	14	9	18	32	24	19	66	10	36	18
Er												38		34	41	81			
Eu												24		25	24	30			
F		17									11	20	24	24	19	15	25	38	27
Fe	64	87		118		102		196				69	67	67	106	99	143	118	
Gd												39		35	39	88			
HCO3		4	5	33	35	21	36	15	12	7	3	17	18	19	19	24	12	25	15
Hf												53		71	41	47			
Hg												21		41	51	39			
Ho												27		33	40	51			
I	37	74	26	20	31	27	24	17	22	30		56	39	48	91	36	72	53	93
K	96	6	4	11	4	30	14	38	11	5		21	32	28	93	30	33	35	16
La	71	68										33		40	32	97			
Li		16	32	17	19	29	24	31	15	12		152	30	40	39	51	53	26	19
light		108		92	85	104		103	180		123								
Lu												56		25	42	35			
Mg	51	4	5	12	5	32	17	40	12	4		16	38	26	21	19	10	35	14
Mn	96	132		67		65		91				146	137	116	130	203	105	102	
Mo	83	15		18		25		31				66	28	63	61	32		37	
N_bio		32	6	54	24	76	49	81	68	16		20	25	47	19	26	29	32	78
Na	68	5	4	11	4	32	17	41	11	3		21	62	46	36	20	14	52	20
Nd	63	54		114		128		159				36		36	36	93			
NH4N_bio		88	73	179	132	175	136	155	88	184		135	143	194	186	105	100	244	225
Ni	128	35		15		48		65				22	33	23	25	31		46	
NO23N_bio		149	141	225	142	210	175	204	70	39		204	130	520	212	127	136	411	108
NO2N_bio		113		94		115		106				108	65	85	169	61	21	101	
NO3N_bio	54	119										131		105	210	135			
O2_bio		14	15	11	23	10	10	11		3		59	40	44	73	51	36	66	20
O2_field		16	15	13	30	16	24	15	6	24	16	50	35	48	46	38	27	84	16
ORP_field		50		35	37	40	61	42	49	54	56	49	42	46	53	48	33	36	51
P_bio	130	30	15	25	29	35	37	30	42	45		49	56	89	59	120	78	99	79
Pb	87	128						179				106	39	80	88	162		66	
pH	9	2	1	3	4	5	5	5	4	2	2	3	6	3	4	3	3	5	3
pH_field		3	2	3	4	6	7	5	2	3	3	3	7	2	3	4	2	3	2
Pheo_bio		72		66	56	57	53	91	79	77			198	80	33			43	153
PO4P_bio		106	71	97	57	95	56	111	68	68		85	64	241	196	120	89	176	104
POC_bio		38	38	48	54	62	49	45	86	51		63	70	56	57	45	97	73	99
PON_bio		35	33	45	51	57	54	41	99	52		55	63	51	53	49	82	71	101
POP_bio		34	26	41	46	50	48	37	111	49		61	71	124	50	55	117	89	136
Pr												34		37	36	95			
Rb	72	10		6		36		36				21		31	27	31			
S_2-																			
salinity		11	15	15	16	32	19	40	14	15	10	20	26	24	19	87	12	37	36
Sb	79							18				52		28	25	27			
Sc																36			
Si		48	48	102	71	139	115	119	79	38		33	95	26	26	44	24	50	50
SiO2_bio		57	39	93	65	137	114	118	28	40		30	96	25	24	42	28	51	61
Sm												40		37	39	91			
SO4	58	6	5	12	5	28	12	35	12	7	15	104	28	96	56	135	114	74	30
SO4S	60	10	5	10	4	28	13	35	14	8		90	26	89	51	117	97	66	30
Sr		7	3	11	3	29	13	37	11	7		16	20	22	17	21	11	27	15
Susp		49										231		262	69	80			
Tb														27	33	39			
Th												270		344	361	155			
Tl																			
Tm												29		22	30	35			
TOC_bio		16	31	59	75	61	56	72	27	36		20	23	17	21	23	17	17	25
turbidity		71		73		98	135	131			124	213		166	244	218			
U	83	13		19		55		49				45		42	57	61			
V	68	73		51		61		122				35	41	30	28	49		53	
Y	51	276		63		129		134				32		30	33	79			
Yb												39		33	43	80			
Zn	54	153		45		89		107				52	93	84	91	250		134	
Zr		147						193				59		36	41	63			

* S=surface, B=bottom, i=intermediary, x= no info.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-4. Normalised means for all surface water objects and parameters for lake water, stream water, sea water and precipitation. The normalisation is made per parameter based on all chemical data from the surface water in the Forsmark area, including lake water, stream water, precipitation and sea water. The scaling is made per parameter by subtracting the overall mean for all objects, from the individual means for each object, followed by a division by the standard deviation for all objects. This scales the values per parameter to overall zero mean and a unit variance of 1 (the colour coding in the compilation ranges between –2 and 2, from red to yellow to green, i.e. from low to high values).

	Lake Water																												
IDCODE	PFM000074	PFM000074	PFM000087	PFM000087	PFM000097	PFM000107	PFM000107	PFM000107	PFM000117	PFM000117	PFM000117	PFM000127	PFM000127	PFM000135	PFM000135	PFM000151	PFM005864	PFM007415	PFM007416	PFM007441	PFM007442	PFM007442	PFM007443	PFM007443	PFM007444	PFM007445	PFM007446	PFM007447	PFM007448	PFM102270
CorrSec*	X	S	S	B	S	X	S	B	X	S	B	S	B	S	B	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
MonitProg**	y	y	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
10B		0.5	0.3	0.2	0.3		0.3	2.6		0.4	0.2			0.3																
13C		-0.2	-0.7	-0.8	-0.4		0.2	0.0		0.7	0.2	0.1	0.1	1.4		-1.3														
14C		1.3	0.6	0.6	0.4		0.0	0.5		0.1	1.0	0.0	-0.2	-0.2		-0.2														
18O	-0.8	-0.2	-0.3	-0.2	0.5	0.0	0.7	0.2	0.1	1.0	0.7	2.1	1.6	0.6		-1.1														-1.1
222Rn		-0.3					0.6			-0.5																				
226Ra		1.7					-0.5			-0.7																				
228Th							-0.5			-0.5																				
230Th		-0.3					-0.3			-0.3	2.1																			
232Th		0.3					-0.3			-0.4																				
234U		-0.4	1.7		1.7		0.3			-0.5	1.2			-0.5																
235U		-0.1					1.5			-0.3																				
235U/238U							0.0			0.0																				
238U		-0.4	1.8		1.8		0.2			-0.5	1.3			-0.5																
2H	-0.8	-0.2	-0.4	-0.2	0.2	0.0	0.6	0.2	0.1	0.8	0.5	1.7	1.6	0.5		-1.4														-1.2
34S_SO4		-0.5	-0.8	-0.6	-0.5		-0.5	-0.6		-0.9		-1.2	-0.8	-1.2																
36Cl																														
37Cl		0.5	0.2	0.4	-0.4		-0.2	-0.1		0.5	-0.3	0.2	-0.4	0.1																
3H	-0.2	-0.1	0.0	0.0	0.0	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1		-0.1														-0.1
87Sr		0.7	0.9	0.8	0.7		0.4	0.3		1.0	0.8	0.4	0.4	0.5																
ABS_436	-0.2	-0.1				-0.3	-0.2	-0.2	-0.3	-0.2	-0.2			-0.4			0.0	-0.1	0.0	-0.2	0.0	0.3	-0.1	-0.1	-0.3	0.0	0.1	0.0	-0.1	-0.2
ABS_bio	0.0	-0.2				-0.3	-0.5	-0.1	-0.4	-0.7	-0.2			-1.3			1.3	0.8	1.5	0.3	1.3	1.1	0.6	0.9	-0.5	1.3	2.6	1.4	1.1	0.4
Al	-0.3	0.0	-0.2	-0.3	-0.2	0.0	0.0	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.1		-0.2														0.0
As		-0.5	0.1	-0.4	0.8		-0.4	-0.6		-0.7	-0.8	-0.6	-0.4	-0.4																
B		-0.5					-0.4			-0.5																				
Ba	0.6	0.7	1.3	2.7	0.0	-0.2	-0.2	0.6	-0.4	-0.9	-0.1	-0.7	-0.4	-0.1		-0.3	-1.0													-0.7
Br	-0.6	-0.6	-0.6	-0.6	-0.5	-0.5	-0.5	-0.4	-0.6	-0.6	-0.6	-0.5	-0.5	-0.5	-0.5	-0.6		-0.5		-0.6	-0.5	-0.5	-0.5		-0.6	-0.5	-0.5	-0.5		
Ca	0.2	0.5	0.1	0.9	-0.7	-0.5	-0.5	0.1	-0.6	-0.8	-0.3	-1.4	-1.3	-0.6	0.8	-0.1	-1.4	0.8	-0.1	-0.2	-0.1	-0.5	0.3	0.1	-0.8	-0.1	-0.1	0.4	0.4	-0.6
Cd	-0.2	-0.2	-0.2	0.2	-0.3	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3															-0.1
Ce	-0.3	-0.4	-0.4	-0.2	0.0	0.4	-0.1	0.2	0.3	-0.4	-0.3		-0.5	-0.4		-0.3	-0.1													
ChlA	-0.7	-0.2	-0.3	-0.2	-0.4	0.0	-0.2	-0.4	-0.2	-0.1	-0.4	1.6	0.9	0.4	-0.7	0.2				6.7										-0.7
ChlC	-0.1	-0.1	-0.1	0.0	-0.3	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2	0.1		0.0		0.1				17.1										
Chlorofyll_field	2.9	0.5	0.0	0.4	0.0	-0.1	-0.2	0.1	0.6	-0.2	0.2	-0.1	-0.3	-0.1	0.8		0.1			0.0	0.6	1.3	0.5	0.7	-0.3	1.0	1.2	2.0	1.2	0.4
Cl	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5
Co	-0.4	-0.5	-0.4	0.6	-0.1	0.0	-0.1	0.3	0.2	-0.6	-0.5	0.0	0.3	0.1			-0.3													-0.2
COND	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.4	-0.2	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.5	-0.5
Cr	-0.1	-0.1	-0.1	0.3	3.2	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	0.3	-0.1			0.0													0.0
Cs		-0.6	-0.6	-0.7	-0.6	0.0	0.2	-0.3	0.0	-0.6	-0.6					-0.7														
Cu	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.2	-0.3	-0.3	-0.4			-0.2													0.4
DIC_bio	0.5	0.8	0.2	0.5	-0.5	0.2	-0.3	0.1	0.1	-0.3	0.0	-0.9	-1.0	0.2	1.9	-0.6				-0.1	0.1		0.4							0.1
DOC_bio	0.2	0.1	-0.2	0.0	0.1	0.7	0.1	0.2	0.7	0.2	0.3	0.0	-0.1	0.2	1.2	-0.6		1.4	1.9	1.0	1.2	1.3	1.5	1.8	0.5	1.3	2.5	1.3	1.3	0.1
Dy	-0.3	-0.4	-0.5	0.2	-0.2	0.1	-0.1	0.3	0.2	-0.6	-0.3			-0.7			-0.2													
EC_field	-0.5	-0.5	-0.5	-0.5	-0.3	-0.5	-0.4	-0.2	-0.6	-0.6	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.6	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.5	-0.6
Er	-0.3	-0.5	-0.4	0.2	0.0	0.3	-0.2	0.3	0.2	-0.5	-0.2			-0.6		-0.2	-0.3													
Eu	-0.3	-0.2	-0.7	-0.5	-0.5	-0.1	0.0	-0.2	0.1	-0.7	-0.5					-0.6														
F	-0.3	-0.2	0.2	0.6	0.2	-0.1	-0.2	0.0	-0.5	-0.6	-0.4	0.7	0.4	-0.7		-1.6		3.2	0.1	0.7	0.2	0.2	0.1	0.5	0.7	1.0	0.8	0.9	0.9	-0.7
Fe	-0.3	-0.4	-0.3	-0.2	0.0	0.3	-0.3	0.1	-0.2	-0.5	-0.4	-0.5	-0.5	-0.1		-0.4	0.6	0.4	-0.1	1.1	0.7	0.3	0.2	-0.1	-0.3	0.1	0.8	0.8	0.6	-0.2
Gd	-0.4	-0.4	-0.5	-0.1	-0.2	0.1	-0.2	0.2	0.2	-0.5	-0.3			-0.6			-0.1													
HCO3	0.7	0.9	0.6	1.3	-0.4	0.0	-0.3	0.2	-0.1	-0.3	0.2	-0.7	-0.6	0.2	1.4	0.2	-1.1	1.5	0.2	0.2	0.2	-0.1	0.5	0.4	-0.1	0.5	0.2	0.5	0.5	-0.4
Hf	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2			-0.2		-0.2	-0.2													
Hg	0.7	-0.1	-0.9	0.0	3.0	-0.4	0.2	0.0	-0.5	-0.1	-0.5			-0.3																-0.6
Ho	-0.3	-0.4	-0.5	-0.3	-0.4	0.3	0.1	-0.2	0.2	-0.5	-0.3			-0.6		-0.5	-0.6													
I	0.3	-0.2	-0.5	-0.1	-0.5	0.3	-0.1	-0.1	0.5	-0.4	-0.3	1.5	0.9	1.1	2.4															0.0
In			-1.2	-1.3	-1.1		-1.9	-0.3		-0.8	-0.8					0.2														
K	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.3	-0.5	-0.5	-0.3	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5
La	-0.4	-0.4	-0.5	-0.2	0.2	0.5	0.0	0.5	0.2	-0.6	-0.2		-0.7	-0.5		-0.3	0.0													
Li	-0.8	-0.8	-0.7	-0.7	-0.6	-0.8	-0.6	-0.5	-0.9	-0.8	-0.9	-0.6	-0.5	-0.5	-0.3	-0.8	-0.9	-0.4		-0.5		-0.6		-0.6	-0.5	-0.4	-0.3	-0.5	-0.5	
light	-0.3	-0.3	-0.3	-0.5	0.2	-0.1	-0.2	-0.6	-0.3	0.1	-0.7	-0.2	-0.7	-0.2						-0.6	-0.6		-0.7		-0.7	2.0	4.5	1.1	0.6	0.5
Lu	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	0.4	-0.2	-0.1	-0.1	-0.2					-0.3														
Mg	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5
Mn	-0.1	-0.2	0.5	1.7	-0.3	0.1	-0.2	0.3	0.4	-0.3	0.6	-0.4	-0.4	0.4		-0.4	0.0	0.6	-0.3	0.5	0.7	0.0	0.2	-0.1	0.2	-0.2	-0.1	-0.3	-0.1	0.0
Mo	-0.4	-0.5	-0.2	-0.5	0.0	-0.2	0.0	-0.2	-0.7	-0.8	-0.9	-0.1	0.2	-0.3			-0.7													0.0
N_bio	-0.3	-0.2	-0.3	0.0	0.1	0.3	0.1	0.4	0.8	0.6	1.2	1.2	1.0	1.4	2.2	-0.7		0.4	0.4	1.3	0.1	0.0	1.3	0.8	0.8	0.3	1.2	0.1	0.3	0.0
Na	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.4	-0.2	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.5	-0.5
Nb		0.3					0.6			-1.4																				
Nd	-0.3	-0.3	-0.4	-0.1	0.0	0.3	-0.1	0.4	0.2	-0.5	-0.2		-0.7	-0.5		-0.2	0.0													
NH4N_bio	-0.2	-0.3	-0.3	0.1	-0.3	0.3	-0.2	0.6	1.5	0.5	2.3	-0.2	-0.2	1.0	2.9	-0.4		-0.2	-0.3	1.6	0.0	-0.2	1.6	0.1	0.5	-0.2	-0.2	-0.4	-0.3	-0.2
Ni	-0.4	-0.4	-0.5	1.0	-0.4	-0.2	-0.3	-0.2	-0.5	-0.8	-0.7	-1.0	0.1	-0.7			-0.4													0.3
NO23N_bio	-0.2	-0.1	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2		-0.1	0.0	-0.1	-0.2	-0.2	-0.1	-0.2	-0.1	-0.2	-0.1	-0.1	0.1	0.3
NO2N_bio	-0.2	-0.3	-0.1	0.0	-0.1	-0.1	-0.3	-0.1	0.0	-0.3	-0.1	-0.1	-0.1	0.0		0.4		0.0	0.3	-0.1	-0.4	-0.4	-0.2	-0.4	-0.4	-0.3	-0.1	-0.2	-0.2	1.3
NO3N_bio	-0.3	-0.2	-0.4		-0.4	-0.2	-0.2	-0.2	-0.2	-0.3	-0.2							-0.2	0.1	-0.2	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2	0.3	1.1
O2_bio		-0.6	0.5	0.2	0.5		-0.1	-0.2		0.0	-0.3	1.0	1.0	-1.6		0.0				-1.2	-1.0		-1.1		-0.8	-0.4	-1.1	-0.7		
O2_field	-0.5	-0.3	0.4	-0.4	0.3	0.4	0.3	-0.7	0.4	0.4	-0.8	0.9	0.9	0.2	-1.7	-0.1	0.5	-0.5	-0.1	-0.2	-0.5	-0.1	0.0	0.0	0.2	-0.6	-0.6	0.1	0.1	0.5
ORP_field	0.3	-0.3	0.2	0.1	-0.6	0.6	0.2	0.0	0.5	0.1	0.0	0.2	0.7	0.0				0.4	0.0	-0.3	-0.1	0.4	-0.2	0.2	-0.3	0.7	0.6	0.2	0.4	0.1
P_bio	-0.4	-0.4	-0.3	-0.2	-0.1	-0.1	-0.2	-0.2	0.3	-0.4	-0.4	0.4	0.4	0.2	0.3	-0.3	-0.5	0.0	0.0	-0.3	-0.3	-0.3	-0.1	-0.3	-0.2	0.2	0.4	-0.2	-0.3	-0.1
Pb	-0.3	-0.3	-0.4	-0.3	0.0	-0.2	0.1	-0.1	-0.3	-0.3	-0.3	0.2	0.1	0.0			-0.1													-0.1
pH	-0.1	-0.1	0.4	0.1	1.0	0.6	0.8	0.0	0.6	0.8	0.2	1.3	1.5	0.6	-0.9	0.1	0.0	0.1	0.1	0.2	-0.4	-0.1	0.3	0.4	0.4	-0.3	-0.4	0.1	0.2	-0.7
pH_field	-0.5	-0.3	0.2	-0.2	1.1	1.1	1.0	-0.1	0.9	1.0	0.1	1.8	1.8	0.9	-1.2	-0.4	0.5	0.1	0.2	0.2	-0.7	-0.3	0.4	0.5	0.5	-0.7	-0.9	-0.1	0.0	0.1
Pheo_bio	-0.4	-0.1	-0.1	0.2	0.0	-0.3	-0.3	-0.2	-0.4	-0.2	-0.2	0.6	0.2	0.3	-0.3	0.0				14.5										
PO4P_bio	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	-0.2	0.4	-0.2	-0.2	-0.1	-0.1	-0.2	-0.3	-0.2		-0.1	-0.1	-0.2	-0.3	-0.2	-0.2	-0.2	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2
POC_bio	-0.4	-0.2	-0.2	-0.2	0.0	0.2	0.4	-0.1	0.2	0.1	0.1	2.4	1.5	1.0	0.5	-0.2														-0.2
PON_bio	-0.6	-0.3	-0.3	-0.1	0.0	0.1	0.2	-0.1	0.4	0.2	0.0	3.6	2.3	1.6	1.0	-0.3														-0.1
POP_bio	-0.5	-0.4	-0.3	-0.1	-0.1	-0.1	-0.2	-0.2	0.2	-0.4	-0.3	1.0	0.7	0.5	0.4	-0.2														0.1
Pr	-0.4	-0.4	-0.4	-0.3	-0.1	0.2	-0.2	0.2	0.2	-0.4	-0.3			-0.5		-0.3	-0.1													
Rb	-0.6	-0.6	-0.5	-0.3	-0.4	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5		-0.3	-0.3		-0.6	-0.5													
S_2-																														
salinity	-0.6	-0.6	-0.6	-0.6	-0.4	-0.6	-0.5	-0.3	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.5		-0.6			-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.6
Sb	-0.9	-0.9	-0.5	0.2	0.3	0.1	0.5	-0.3	-0.1	0.0	-0.3		1.7	0.9			-0.3													
Sc		-0.2	-0.4	-0.4	-0.4	0.0	-0.2	-0.4	0.1	-0.3	-0.4					-0.4														
Se		-0.3					0.5			1.2	-0.1																			
Si	0.9	0.9	0.5	1.2	-0.8	0.1	-0.6	-0.3	0.0	-0.5	-0.1	-0.8	-0.8	-0.6	1.0	0.0	-0.3	0.6	-0.3	-0.3	0.7	0.4	0.9	0.7	0.7	0.5	1.6	0.5	1.1	0.2
SiO2_bio	1.0	0.9	0.7	1.4	-0.8	0.1	-0.6	-0.3	0.0	-0.5	0.0	-0.8	-0.8	-0.5	1.3	0.0		0.7	-0.4	-0.6	0.4	0.5	0.2	1.0	1.5	0.5	1.5	0.5	1.1	0.2
Sm	-0.3	-0.4	-0.4	-0.2	-0.1	0.0	-0.2	0.2	0.0	-0.4	-0.3			-0.6		-0.3	-0.1													
SO4	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.4	-0.3	-0.6	-0.5	-0.5	-0.5	-0.5	-0.4	-0.3	-0.6	-0.6	-0.5	-0.5	-0.5	-0.6	-0.5	-0.6	-0.6	-0.5	-0.4	-0.2	-0.5	-0.4	-0.5
SO4S	-0.5	-0.5	-0.5	-0.4	-0.4	-0.5	-0.4	-0.3	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.3	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.1	-0.5	-0.4	-0.5
Sr	-0.5	-0.5	-0.4	-0.4	-0.4	-0.5	-0.4	-0.2	-0.5	-0.6	-0.5	-0.5	-0.5	-0.4	-0.3	-0.5	-0.6	-0.2	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5	-0.4	-0.5
Susp	-0.3	-0.1				-0.1	0.0	-0.2	-0.2	0.0	-0.1																			
Tb	-0.2	-0.3	-0.5	0.1	-0.2	0.1	0.1	0.0	-0.1	-1.0	-0.5																			
Th	0.2	-0.2	-0.2	-0.2	-0.2	0.1	-0.2	-0.2	0.0	-0.2	-0.2					-0.2	-0.2													
Tl		-0.6	-0.7	-0.8	-0.7		-0.4	-0.7		-0.7	-0.8					-0.8														
Tm	-0.2	-0.6	-0.7	-0.2	-0.4	0.3	0.6	-0.2	0.0	-0.8	-0.4					-0.7														
TOC_bio	0.1	0.1	-0.3	-0.1	0.1	0.7	0.0	0.1	0.7	0.1	0.3	0.0	0.0	0.1	1.1	-0.7		1.4	1.9	1.0	1.2	1.4	1.6	1.8	0.5	1.3	2.5	1.3	1.3	0.1
turbidity	-0.1	0.0	-0.1	0.3	1.3	-0.1	0.0	-0.1	-0.1	-0.1	-0.1	-0.1		0.0	-0.1			-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1		0.0	0.0	-0.1	-0.1	
U	-0.2	-0.1	0.5	1.0	0.2	0.1	0.1	0.2	-0.3	-0.3	-0.3		-0.2	-0.2		0.0	-0.5													
V	-0.2	-0.1	0.0	-0.3	0.4	0.2	0.2	-0.1	0.0	-0.1	-0.2	0.8	0.7	0.1			0.0													0.0
Y	-0.2	-0.2	-0.2	0.4	0.2	0.3	-0.1	0.6	0.1	-0.5	0.1		-0.8	-0.4		0.0	-0.1													
Yb	-0.3	-0.5	-0.4	0.4	-0.2	0.2	-0.2	0.3	0.3	-0.5	-0.2			-0.6		-0.2	-0.4													
Zn	-0.1	-0.2	-0.3	-0.2	-0.1	-0.1	-0.2	-0.1	0.0	-0.2	-0.3	-0.4	-0.2	-0.3			-0.1													-0.1
Zr	-0.2	-0.3	-0.1	0.3	0.0	0.0	-0.2	0.1	0.0	-0.3	0.0		-0.6	-0.3		-0.2	-0.2													

	Precipitation			Sea Water																							Stream Water								
IDCODE	PFM002457	PFM002564	PFM102271	PFM000062	PFM000062	PFM000062	PFM000063	PFM000063	PFM000063	PFM000064	PFM000064	PFM000065	PFM000082	PFM000082	PFM000082	PFM000083	PFM000083	PFM000083	PFM000084	PFM000084	PFM000084	PFM000153	PFM005865	PFM005865	PFM005865	PFM102269	PFM000066	PFM000067	PFM000068	PFM000069	PFM000070	PFM000071	PFM000072	PFM000073	PFM004306
CorrSec*				X	S	B	X	S	B	S	B	S	S	X	B	S	X	B	S	X	B	S	S	i	B	S	S	S	S	S	S	S	S	S	S
MonitProg**	n	n	n	y	y	y	n	n	n	n	n	n	y	y	y	n	n	n	n	n	n	n	n	n	n	y	y	n	y	y	y	n	n	n	n
10B					-0.2	-2.3	0.4	-0.3	-2.3	-0.6	-2.3	-0.4	0.3		0.4												0.4	-0.5	-0.2	-2.1	0.4		0.3	0.6	
13C					1.3	1.1	1.2	0.8	0.8	0.0	0.0	0.1	1.4		1.4	1.1		1.1	-1.6		-1.3						-1.0	-0.1	-1.1	-1.5	-0.5	-1.7	-1.6	-1.1	
14C					-0.9	-0.4	-0.1	-0.4	-0.4	-0.5	-0.6	-0.6	-0.4		-0.3	-0.1		-0.1	-2.4		-3.4						0.2	0.2	0.7	1.1	1.0	-3.2	-0.1	-2.2	
18O	-1.4	-0.9	-0.2	0.3	0.6	0.6	0.5	0.6	0.6	0.3	0.7	0.2	0.6		0.6	0.6		0.6	-0.6		-0.6		0.6	0.6	0.6	0.6	-0.7	0.7	-0.5	-0.8	0.2	-1.0	0.6	-1.1	
222Rn					0.1																	0.0											
226Ra					0.3																								-0.6						-0.4
228Th					-0.6																								1.8						-0.1
230Th					-0.2						4.6												-0.3	-0.3				-0.2						-0.3
232Th					0.5																								1.5						-0.8
234U					-0.6			1.2			3.7												-0.8	-0.8	-0.8				-0.1						1.7
235U					-1.0																														
235U/238U					0.0																								0.0						0.0
238U					-0.5			1.3			3.7												-0.8	-0.7	-0.8				-0.1						1.6
2H	-1.5	-0.9	-0.2	0.6	0.8	0.7	0.6	0.7	0.7	0.4	0.7	0.2	0.7		0.6	0.6		0.6	-0.8		-0.8		0.7	0.8	0.7	1.0	-0.6	0.5	-0.4	-0.7	0.2	-1.0	0.4	-1.1	
34S_SO4					1.2	1.4	1.2	1.2	1.3	1.2	1.3	1.1	1.2		1.2								1.3	1.3	1.4		-0.7	-0.4	-1.0	-0.3	-0.9		-1.0		
36Cl																																			
37Cl					0.0	-0.5	0.3	-0.7	-0.4	-0.3	-0.1	-0.7	0.1		-0.3	-0.1		-0.1	0.2		0.4		-1.2	-1.0	-1.0		1.0	-0.2	-0.5	-0.1	0.7	3.0	0.3	-1.0	
3H	-0.1	-0.1	-0.1	-0.2	-0.1	0.1	0.3	0.2	0.2	0.0	0.1	0.0	0.0		0.3	0.2		0.1	-0.1		-0.1		-0.1	0.0	-0.1	0.5	-0.1	0.0	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	
87Sr					-1.4	-1.4	-1.4	-1.4	-1.4	-1.3	-1.2	-1.3	-1.4		-1.4								-1.4	-1.4	-1.4		0.8	0.4	0.8	0.4	0.9		0.4	1.7	
ABS_436				-0.4	-0.4								-0.4		-0.4								-0.4	-0.4	-0.4		0.1		0.3	0.3	0.1				
ABS_bio				-1.4	-1.4								-1.4		-1.4								-1.4	-1.5	-1.5		-0.1		0.5	0.5	-0.3				
Al	0.3	1.1		-0.3	0.1	-0.4	-0.4	-0.2	-0.3	0.8	-0.2	0.7	-0.3		-0.3								-0.3	0.3	0.0		-0.1	-0.3	0.0	0.1	0.1	-0.2	-0.3	-0.3	
As					0.8	3.0		1.0	1.7	1.2	1.9	1.4															-0.1	-0.5	-0.9	-0.9	-0.6		-0.4	0.3	
B					1.9																						-0.5		-0.5	-0.5	-0.5				
Ba		-2.8		-0.6	-0.6	-0.6	0.0	-0.5	-0.2	-0.1	-0.2	-0.2	-0.5		-0.6	-0.7		-0.8	-0.8		-0.8		-0.6	-0.6	-0.6		0.5	0.0	0.2	0.6	-0.4	1.1	1.3	3.0	
Br		-0.6		2.0	2.0	1.9	1.9	1.7	1.8	1.3	1.6	1.2	1.8	1.8	1.9	1.7	1.3	1.8	0.0	1.0	1.5	1.3	1.9	2.0	2.0	1.9	-0.6	-0.5	-0.5	-0.5	-0.6	-0.6	-0.5	-0.6	
Ca	-2.9	-2.9		0.8	0.9	0.6	0.7	0.7	0.7	0.6	0.6	0.5	0.9	0.6	0.9	0.6	0.3	0.6	0.0	0.1	0.3	0.5	0.9	1.0	1.0	1.0	0.4	-0.7	0.0	0.3	-0.7	0.9	-0.8	3.1	
Cd		0.7		0.6	1.1	6.8	0.6	-0.1	0.5	0.4	0.9	1.7	0.9										2.9	3.9	1.6		-0.3	-0.2	-0.2	-0.3	-0.2	-0.2	-0.2	0.0	
Ce		-0.4		-0.5	-0.4	-0.5	-0.5	-0.4	-0.5	0.8	-0.2	2.1	-0.3		-0.2	-0.1		-0.3	4.0		4.5						-0.2	-0.1	0.6	0.2	-0.1		-0.3	-0.4	
ChlA				-0.1	-0.1	-0.2	-0.5	0.0	0.2	1.0	0.7	0.7	0.3	0.1	0.1	0.5	-0.2	1.4	0.5	-0.7	0.4	1.3	-0.1	0.0	0.9		-0.3	1.0	-0.5	-0.6	-0.2	-0.7	-0.3	0.3	
ChlC				-0.1	-0.2	0.1		-0.1	0.0	0.6	0.1	0.5	0.2		0.0	0.5		0.5	0.1		0.1	0.2	-0.2	-0.1	0.1		-0.5	0.4	-0.4	-0.5	-0.2	-0.4	-0.2	-0.2	
Chlorofyll_field				-0.1	-0.5	-0.3		-0.4	-0.3	0.1	-0.1	-0.1	-0.4		-0.5	-0.2			0.5		-0.6					-0.5	0.1		0.3	0.3	0.1				-0.2
Cl	-0.5	-0.5		2.1	2.2	2.1	2.1	2.0	2.1	1.6	1.8	1.5	2.1	2.1	2.2	2.0	1.5	2.1	0.2	1.1	1.5	1.4	2.2	2.2	2.3	2.2	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Co		-0.7		-0.8	-0.4	-0.7		-0.4	-0.1	1.5	0.5	2.1	-0.4										-0.7	-0.5	-0.4		0.1	-0.1	0.4	0.1	-0.1	0.3	1.0	1.2	
COND	-0.6	-0.6		2.2	2.2	2.2		2.1	2.2	1.6	1.8	1.6	2.2	2.1	2.2	2.1	1.5	2.1	0.2	1.1	1.5	1.5	2.3	2.4	2.4	2.2	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	
Cr		0.1		-0.1	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.2	-0.1		-0.1								0.0	0.1	-0.1		-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.1	
Cs		0.2		1.8	0.9	-0.3		-0.1	-0.2	0.0	-0.4	0.9	0.0		0.0	0.1		-0.1	0.0		0.2						-0.3	-0.7	-0.5		-0.6		-0.6	-0.6	
Cu		0.2		0.0	0.6	0.2	0.4	0.0	0.4	0.4	0.0	0.6	1.3		0.4								0.7	0.1	0.1		0.0	-0.1	0.1	0.0	-0.2	1.8	-0.4	1.2	
DIC_bio				-0.8	-1.0	-1.3	-1.3	-1.2	-1.2	-1.0	-1.2	-0.9	-1.1	-1.1	-1.2	-1.5	-0.8	-1.4	-0.9	-0.9	-1.2	-1.9	-0.9	-0.8	-0.9		0.9	-0.5	0.5	0.8	0.0	0.7	-0.2	1.5	
DOC_bio	-1.7	-1.8		-1.5	-1.6	-1.7	-1.8	-1.5	-1.6	-1.2	-1.3	-1.1	-1.6	-1.6	-1.7	-1.6	-1.1	-1.6	-0.7	-1.1	-1.4	-1.4	-1.5	-1.6	-1.6		0.1	-0.1	0.5	0.4	0.3	-0.6	-0.1	-1.1	
Dy		-0.9		-0.9	-0.4			-0.3		1.9	-0.9	4.4															-0.1	-0.3	0.5	0.4	-0.2		-0.7	-0.8	
EC_field				2.1	2.1	1.8		1.9	1.8	1.4	1.6	1.3	1.9		1.9	2.0		2.1	0.2		1.1	1.4				2.1	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	
Er				-1.0	0.0			-0.6		2.3		3.7	-0.9		-0.9	-0.7		-0.9	3.0		3.3						-0.1	-0.5	0.5	0.4	-0.2		-0.8	-0.9	
Eu										1.4		2.9	-0.9		-0.9	-0.8			1.8		1.9						-0.3	-0.4	0.0	0.0	-0.1		-0.8	-0.3	
F				1.1	0.3			-0.2	6.9	-1.2	-2.7	-1.3	0.7		0.6				-1.5				0.1	0.1	0.3	0.2	-0.5	-0.2	-0.1	0.1	-0.6	-0.6	-0.5	1.2	
Fe	-0.1	-0.6		-0.6	-0.6	-0.6	-0.6	-0.5	-0.4	-0.1	-0.4	0.1	-0.5		-0.5	-0.1		-0.4	1.4		2.3		-0.6	-0.6	-0.6		-0.1	-0.3	0.4	0.3	-0.3	0.1	0.5	-0.4	
Gd				-0.8	-0.4			-0.1		1.9	-0.8	4.7															-0.1	-0.3	0.5	0.4	-0.2		-0.6	-0.7	
HCO3		-2.4		-1.2	-1.2	-1.2	-1.1	-1.1	-1.1	-1.0	-0.9	-1.0	-1.1	-1.2	-1.1	-1.2	-1.1	-1.2	-0.9	-1.0	-1.1	-1.0	-1.2	-1.1	-1.1	-1.2	0.7	-0.3	0.2	0.5	-0.3	1.4	-0.1	3.8	
Hf					3.0	3.1		2.2	4.1	2.2	6.6	2.0	-0.2		-0.2	-0.2		-0.2	-0.1		-0.1						-0.2	-0.2	-0.2	-0.2	-0.2		-0.2	-0.2	
Hg		0.1			0.9					-0.8		-0.9	-0.2														-0.6	-0.4	0.0	0.2	-0.2		0.1		
Ho					2.3					1.7		3.4	-0.9		-0.9	-0.8		-1.0	2.2		2.5						-0.3	-0.3	0.0	0.0	0.1		-0.9	-1.0	
I		-1.4		1.2	0.9	0.2		0.3	0.3	0.3	0.6	0.3	0.4		0.3	-0.5		-0.3	-0.5		-0.1		0.9	1.1	1.2	1.5	-0.2	-0.4	-0.1	0.2	-0.4	-0.4	0.0	-0.9	
In					1.5	0.2		0.2	0.2	0.8	0.8	0.5	0.2		0.2	0.1		0.1	0.0		1.3						-0.8								
K	-0.6	-0.6		2.5	2.4	2.2	2.3	2.1	2.2	1.7	1.9	1.6	2.2	2.1	2.3	2.1	1.4	2.1	0.8	1.1	1.5	1.5	2.5	2.5	2.6	2.6	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.4	-0.2	
La		-0.7		-0.6	-0.6	-0.8		-0.7	-0.8	0.9	-0.3	0.9	-0.4		-0.2	-0.2		-0.5	5.6		6.1						-0.2	0.0	0.8	0.5	-0.1		-0.4	-0.7	
Li		-0.9		1.5	1.4	1.3	1.9	1.3	1.5	1.0	1.3	1.0	1.3		1.4	1.4		1.5	0.4		0.7	0.9	1.7	1.8	1.7	1.4	-0.8	-0.7	-0.8	-0.7	-0.9	-0.8	-0.5	0.1	
light				0.5	0.5	-0.6		0.6	-0.6	0.4	-0.5	0.1	0.2		-0.7	-0.5			-0.2		-0.7					0.1									
Lu					4.9					0.2		0.2	-0.3		-0.3	-0.3		-0.3	-0.1		-0.1						-0.2	-0.2	-0.2	-0.1	-0.2			-0.3	
Mg	-0.5	-0.5		2.3	2.3	2.3	2.3	2.2	2.3	1.7	2.0	1.6	2.2	2.2	2.3	2.2	1.5	2.2	0.8	1.1	1.5	1.5	2.4	2.4	2.4	2.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.4	-0.3	
Mn		-0.4		-0.5	-0.4	-0.5	-0.3	-0.4	-0.3	-0.2	-0.2	-0.2	-0.5		-0.4	-0.4			0.5		0.1		-0.4	-0.3	-0.2		0.1	-0.2	0.0	0.0	0.5	-0.1	0.0	-0.1	
Mo		-1.1		1.5	1.8	1.9	1.4	1.8	1.9	1.7	1.8	1.2	1.6		1.8								1.6	1.9	1.8		-0.4	0.5	-0.2	0.0	-0.8	0.5	-0.6	1.8	
N_bio		-0.4		-1.4	-1.3	-1.4	-1.1	-1.2	-1.2	-0.4	-0.6	-0.6	-1.1	-1.2	-1.3	-1.3	-0.6	-1.3	0.5	-0.3	-0.8	-0.9	-1.4	-1.4	-1.3		-0.3	0.2	0.1	-0.2	0.4	-0.5	0.5	2.6	
Na	-0.5	-0.5		2.4	2.3	2.3	2.3	2.2	2.3	1.7	2.0	1.6	2.2	2.2	2.3	2.2	1.5	2.2	0.8	1.1	1.5	1.5	2.4	2.5	2.5	2.3	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	
Nb																										0.3		0.5	1.1	-1.4				
Nd		-0.7		-0.6	-0.6	-0.7		-0.5	-0.8	0.7	-0.4	1.8	-0.4		-0.3	-0.2		-0.5	4.0		4.5						-0.1	-0.1	0.7	0.5	-0.1		-0.4	-0.6	
NH4N_bio				-0.4	-0.4	-0.4	-0.1	-0.4	-0.3	-0.3	-0.2	-0.3	-0.4	-0.4	-0.3	-0.4	-0.3	-0.4	-0.2	-0.2	-0.3	-0.4	-0.4	-0.4	-0.4		-0.3	-0.2	-0.1	-0.3	0.6	-0.3	0.2	-0.2	
Ni		0.9		0.4	0.7	0.7	0.6	0.3	1.3	2.0	1.2	2.3	1.3		-0.1								7.7	0.9	0.6		-0.1	-0.4	0.1	0.1	-0.5	0.5	-0.4	1.4	
NO23N_bio				-0.1	-0.1	-0.2	0.1	0.0	0.0	0.4	0.1	0.4	0.0	0.1	0.0	-0.1	0.6	-0.1	1.7	1.1	0.3	0.1	-0.2	-0.2	-0.2		-0.1	-0.1	0.1	-0.1	-0.1	0.1	0.1	4.9	
NO2N_bio				-0.1	0.0	0.2	1.1	0.3	0.5	1.4	0.8	1.2	0.4		0.7								-0.4	-0.5	-0.4		0.0	-0.2	0.2	0.2	0.0	-0.2	0.6	4.7	
NO3N_bio	4.0	3.5		0.1	-0.1			-0.4		-0.4		-0.4	0.2										-0.4	-0.4	-0.4		-0.2	-0.4	0.1	-0.1	-0.1		0.0		
O2_bio					0.9	0.9	0.7	0.9	0.7	0.8	0.8	0.8	1.4		1.4	1.4		1.5	0.9		1.1	0.9			0.6		-0.9	0.2	-0.7	-1.1	-0.3	-0.1	-1.0	0.5	
O2_field				0.7	0.9	0.8		0.7	0.4	0.6	0.5	0.6	1.3		0.9	1.3		1.2	0.7		0.9	0.8				0.8	-0.6	0.2	-0.3	-0.7	-0.1	-0.1	-1.4	0.3	
ORP_field				0.9	0.5	0.5		0.6	0.2	0.4	0.2	0.3	0.6		0.3	0.4			0.6		-0.2					0.1	-0.2	-0.5	-0.3	-0.4	-0.1	-0.1	-0.3	-0.5	
P_bio	-0.4	0.8		-0.1	-0.2	-0.3	-0.3	-0.1	0.0	0.6	0.5	0.3	0.0	-0.2	-0.1	-0.1	0.1	-0.2	1.2	0.6	0.4	0.3	-0.4	-0.3	0.4		-0.2	0.0	0.0	0.0	-0.2	0.8	1.7	3.8	
Pb		1.8		0.5	2.4	1.0		0.2	0.9	0.2	0.3	1.0	0.1		0.7								1.8	1.1	0.8		-0.3	0.0	-0.2	-0.2	-0.1		0.2	0.0	
pH	-3.7	-4.0		0.5	0.5	0.6	0.1	0.4	0.2	0.4	0.2	0.4	0.4	0.2	0.3	0.5	0.2	0.5	0.1	-0.1	0.2	0.8	0.7	0.1	0.0	0.4	-0.3	0.4	-0.4	-0.5	-0.3	0.0	-0.5	0.5	
pH_field				0.8	0.5	0.7		0.4	0.2	0.5	0.3	0.5	0.5		0.4	0.9		1.2	-0.1		0.2	1.1				0.4	-0.7	0.3	-0.8	-0.9	-0.5	-0.5	-1.1	0.2	
Pheo_bio				-0.2	-0.2	0.0	-0.2	0.0	0.2	0.3	0.2	0.4	0.0		0.0	0.2		0.3	0.0		0.0	0.0	-0.5	-0.4	-0.2		-0.3	1.8	-0.1	0.0	-0.3	0.1	-0.1	0.6	
PO4P_bio				0.0	-0.1	-0.2	0.2	-0.2	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	0.1	-0.2	-0.1		0.2	0.5	0.0	-0.2	-0.3	-0.2	-0.2		-0.2	-0.2	0.0	0.0	-0.2	1.1	1.6	3.3	
POC_bio				-0.2	-0.2	-0.2	-0.4	-0.1	-0.1	0.6	0.2	0.3	-0.2		-0.3	0.0	-0.2	0.0	0.4	-0.3	0.1	0.2	-0.2	-0.2	0.4		-0.3	0.2	-0.1	-0.2	0.0	-0.2	0.3	0.0	
PON_bio				-0.3	-0.3	-0.3	-0.7	0.1	0.1	1.4	1.1	0.7	-0.2	-0.6	-0.5	0.1	-0.2	0.1	0.9	-0.3	0.2	0.6	-0.2	-0.1	0.8		-0.5	0.4	-0.3	-0.4	-0.2	-0.4	0.9	0.2	
POP_bio				-0.1	-0.1	-0.2	-0.5	0.2	0.3	1.4	1.2	0.9	0.1	-0.3	-0.1	0.2	0.2	0.3	2.1	0.5	0.9	1.5	-0.4	0.1	0.7		-0.3	0.1	-0.1	-0.2	-0.3	0.5	1.5	2.2	
Pr		-0.6		-0.5	-0.3			0.0		0.9	-0.6	2.8	-0.5		-0.4	-0.3		-0.5	3.5		3.9						-0.2	-0.2	0.5	0.2	-0.2		-0.5	-0.5	
Rb		-0.9		1.9	2.0	2.2	2.1	2.0	2.1	1.4	1.7	1.3	2.0		2.0	2.0		1.9	-0.3		-0.2						-0.5	-0.4	-0.5	-0.5	-0.6		-0.4	-0.6	
S_2-																																			
salinity				1.9	1.9	1.6		1.7	1.6	1.2	1.4	1.2	1.7		1.7	1.7		1.8	0.1		0.9	1.1				1.9	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.5	-0.5	
Sb		0.1		-0.3	1.7	1.4	0.1	0.9	1.1	1.0	1.4	0.9	0.1		-0.2												-0.3	0.6	-0.1	-0.4	-0.2		-0.3	1.0	
Sc				7.1	-0.4	1.0		-0.4		0.0	-0.4	0.6	-0.4		-0.3	-0.4		-0.5	0.3		0.2						-0.1	-0.2	0.0	0.0	0.0		-0.5	-0.4	
Se					-0.9																														
Si		-1.3		-1.1	-1.1	-1.2	-1.0	-1.1	-1.1	-0.9	-1.0	-0.9	-1.0	-1.1	-1.1	-1.1	-0.7	-1.2	-0.3	-0.5	-0.7	-1.1	-1.2	-1.2	-1.2	-1.2	0.6	-0.8	0.7	1.0	-0.2	0.2	-0.6	-0.2	
SiO2_bio				-1.1	-1.1	-1.2	-1.0	-1.1	-1.1	-0.9	-1.0	-0.9	-1.1	-1.0	-1.1	-1.1	-0.6	-1.2	-0.1	-0.4	-0.8	-1.1	-1.2	-1.2	-1.2		0.6	-0.7	0.7	1.0	-0.2	0.3	-0.6	0.0	
Sm		-0.8		-0.7	-0.4			0.0		1.8	-0.8	4.3	-0.6		-0.6	-0.4		-0.6	3.5		3.9						-0.1	-0.3	0.5	0.4	-0.2		-0.6	-0.7	
SO4		-0.6		2.1	2.1	2.0	2.1	2.0	2.0	1.5	1.7	1.5	2.0	1.7	2.1	1.8	1.2	2.1	0.2	0.8	1.4	1.2	2.2	2.3	2.3	2.1	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.4	-0.2	
SO4S	-0.6	-0.6		2.5	2.4	2.1	2.2	2.1	2.1	1.7	1.8	1.6	2.3	2.1	2.3	2.0	1.4	2.1	0.8	1.1	1.4	1.5	2.4	2.4	2.5	2.6	-0.5	-0.4	-0.4	-0.4	-0.5	-0.5	-0.4	-0.1	
Sr		-0.7		2.4	2.4	2.1	2.2	2.1	2.1	1.7	1.8	1.6	2.2	2.1	2.3	2.1	1.4	2.1	0.8	1.1	1.4	1.4	2.4	2.5	2.5	2.2	-0.5	-0.4	-0.4	-0.4	-0.6	-0.5	-0.4	-0.1	
Susp				0.0	0.3																						0.0		0.3	-0.1	-0.2				
Tb										1.4		2.9															-0.3	-0.2	0.0	-0.2	-0.1		-1.1	-1.0	
Th				0.8						-0.1		0.0				-0.2			0.0		0.0						-0.1	-0.2	0.0	0.4	0.0		-0.2		
Tl		-0.4		2.5	0.6	2.0		1.1	1.3	1.1	2.0	0.8	-0.5		-0.5	-0.5		-0.6	-0.5		-0.5						-0.7	-0.7	-0.4	-0.4	-0.8		-0.8	-0.5	
Tm										1.4		3.5	-1.0		-1.0	-0.9			1.0		1.2						-0.3	-0.5	0.0	0.0	0.0			-1.0	
TOC_bio				-1.5	-1.6	-1.7	-1.7	-1.6	-1.6	-1.3	-1.4	-1.2	-1.7	-1.7	-1.7	-1.6	-1.3	-1.6	-0.8	-1.2	-1.4	-1.4	-1.6	-1.6	-1.6		0.1	-0.1	0.5	0.4	0.3	-0.7	-0.1	-1.2	
turbidity				-0.1	-0.1	0.0		-0.1	-0.1	0.0	0.0	0.0	-0.1		-0.1	-0.1			0.0		-0.1					-0.1	-0.1		-0.1	-0.1	0.0				
U		-0.7		-0.5	-0.5	-0.5	-0.4	-0.5	-0.5	-0.2	-0.3	-0.2	-0.4		-0.4	-0.4		-0.5	0.2		0.2						-0.1	0.2	0.4	0.9	-0.4		-0.5	8.7	
V		-0.2		-0.4	-0.2	-0.4	-0.4	-0.1	-0.1	0.5	0.4	0.8	10.0		-0.5								-0.4	-0.3	-0.4		-0.1	0.4	0.0	-0.1	-0.1	0.3	0.3	0.6	
Y		-0.9		-0.7	-0.3	-0.9	-0.7	-0.6	-0.7	0.5	-0.3	1.2	-0.6		-0.6	-0.4		-0.5	3.4		3.6						0.1	-0.1	0.6	0.6	0.0		-0.5	-0.6	
Yb					0.1			-0.6		2.4		3.4	-0.9		-0.8	-0.8		-1.0	2.7		2.9						-0.1	-0.4	0.5	0.5	-0.2		-0.8	-0.9	
Zn		0.7		0.1	0.0	0.1	0.2	-0.1	4.3	0.3	0.3	0.4	-0.2		-0.2								3.1	0.3	0.2		-0.1	-0.1	0.0	-0.1	0.2	-0.3	0.4	0.0	
Zr		-0.8		-0.2	0.9	-0.8	-0.4	-0.5	-0.7	0.0	-0.3	2.0	-0.4		-0.6	-0.6		-0.7	0.9		0.9						0.1	-0.3	0.3	0.3	-0.2		-0.4	0.2	

* S=surface, B=bottom, i=intermediary, x= no info.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-5. Regression analysis of times series consisting of at least 10 sampling occasions ranging over a period of at least 4 years for lake water, stream water, sea water and precipitation. The numbers in the table represent the probabilities for the hypothesis that there is no time-trend in data, i.e. p values between –0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign (and colour) of the probabilities represents the direction of the trends (orange – increasing, blue – decreasing).

	Lake Water					Precipitation	Sea Water		Stream Water			
IDCODE	PFM000074	PFM000107	PFM000107	PFM000117	PFM000117	PFM002564	PFM000062	PFM102269	PFM000066	PFM000068	PFM000069	PFM000070
CorrSec*	S	S	B	S	B	a	S	S	S	S	S	S
MonitProg**	y	y	y	y	y	n	y	y	y	y	y	y
10B												
13C	0.05	0.38		0.07								
14C	-0.33	-0.01		0.00								
18O	-0.84	0.91	-0.22	0.84	-0.42	0.14	-0.44		-0.36	-0.03	-0.02	0.00
230Th												
232Th												
234U												
235U												
238U												
2H	0.85	0.91	-0.46	0.42	0.48	0.20	0.76		-0.82	-0.39	-0.15	-0.01
34S_SO4	-0.83	-0.37					-0.24					
37Cl	0.24	0.58					0.41					
3H	0.00	0.00	-0.03	0.00	-0.06	-0.71	0.00	-0.31	0.00	0.00	0.00	0.00
87Sr	0.54											
ABS_436	0.02	0.02	0.02	0.02	0.12		0.04		0.25	0.23	0.24	-0.83
ABS_bio	0.04	0.06	0.01	0.03	0.02		0.36		0.12	0.48	0.23	0.05
Al	0.86	0.40		-0.46		-0.91	0.10		0.82	0.20	-0.67	0.12
As												
B												
Ba	-0.87	-0.57	0.21	0.42	0.15	-0.38	-0.37		0.36	-0.91	-0.35	0.08
Br	0.01	0.42	0.41	0.35	-0.65	-0.06	0.02	-0.01	0.01	0.70	-0.63	-0.23
Ca	0.03	0.03	0.00	0.07	0.00	0.99	0.02		0.08	0.63	0.40	0.12
Cd	0.40	-0.44		0.85		-0.21	-0.73		0.83	0.76	0.53	0.00
Ce	0.64	-0.85		-0.66		-0.01	0.55		0.04	0.35	0.47	0.59
ChlA	0.07	-0.51	0.00	0.11	-0.22		0.06				-0.14	
ChlC	0.39	0.04		0.00	0.19		0.29					
Chlorofyll_field	0.85	-0.98	0.51	0.77	0.53		0.94	-0.22				
Cl	0.07	0.44	0.34	0.00	0.00	-0.22	0.04	-0.02	-0.19	-0.19	-0.05	-0.56
Co	0.14	0.42		0.05		-0.85	0.31		0.88	0.36	-0.82	0.35
COND	0.09	0.50	0.50	0.15	0.01	-0.11	0.88	0.00	0.51	-0.85	-0.81	-0.98
Cr	0.32	0.46		0.60		0.35	-0.86		0.08	0.22	0.27	0.01
Cs												
Cu	-0.91	0.65		-0.56		0.70	-0.06		0.89	0.57	0.41	0.95
DIC_bio	0.00	0.00	0.00	0.00	0.00		0.00		0.00	0.00	0.00	0.00
DOC_bio	0.00	0.00	0.00	0.00	0.00	0.23	0.00		0.00	0.00	0.00	0.00
Dy	0.22	0.71		0.56					0.09	0.64	0.59	-0.92
EC_field	0.00	0.33	0.47	0.00	0.00		0.00	0.00	0.68	-0.74	0.36	-0.33
Er	0.16	0.55		-0.57					0.08	0.59	0.56	-0.97
Eu										-0.98		
F	-0.71	0.00	0.88	-0.35	-0.69		0.08	0.00	-0.67	-0.12	0.38	-0.60
Fe	-0.91	0.64	0.05	0.82	0.14	-0.02	-0.04		0.21	0.11	0.25	0.29
Gd	0.23	0.60							0.07	0.66	0.59	-0.92
HCO3	0.16	0.76	0.00	0.13	0.00		0.00	-0.04	0.01	0.48	0.40	0.04
Hf	-0.38	-0.17							-0.36	-0.04	0.34	-0.25
Hg	0.98								0.33	-0.99	-0.49	0.00
Ho									0.11	0.66	0.62	0.04
I	0.00	0.83	0.86	0.26	-0.45		0.55		0.00	0.00	0.15	0.00
K	0.00	0.27	0.24	0.00	0.01	0.00	0.00		0.06	0.03	0.53	0.02
La	0.40	-0.79		-0.38		-0.02			0.14	0.38	0.55	0.97
Li	0.97	0.37	0.05	0.25	-0.66		0.22		-0.08	-0.01	0.00	0.74
light	-0.87	0.25	-0.13	0.87	-0.17		-0.46	0.00				
Lu										0.13		
Mg	0.01	0.31	0.29	0.00	0.00	0.23	-0.14		0.03	-0.81	0.80	0.48
Mn	-0.18	-0.80	0.07	-0.16	0.33	-0.43	-0.27		-0.66	0.29	0.56	0.37
Mo	-0.37	-0.60		-0.05			-0.11		0.51	0.11	0.01	0.00
N_bio	0.09	0.00	0.00	0.06	0.00		-0.33		0.14	0.88	0.64	0.06
Na	0.03	0.45	0.33	0.00	0.10	-0.08	-0.33		-0.17	-0.34	-0.50	-0.04
Nd	0.29	0.82		-0.61					0.09	0.56	0.52	0.86
NH4N_bio	0.35	0.03	0.00	0.43	0.00		0.56		0.35	0.18	-0.42	0.03
Ni	0.03	0.04		0.01		-0.04	0.01		0.05	0.07	0.23	0.23
NO23N_bio	0.24	-0.83	0.76	-0.48	0.71		0.03		-0.08	-0.78	0.84	0.18
NO2N_bio	-0.78	-0.46		-0.47			-0.05		-0.06	-0.64	0.52	-0.21
NO3N_bio	0.97	0.92		0.85		0.78	0.16		-0.34	-0.82	-0.73	0.65
O2_bio	0.00	0.00	0.00	0.00	0.00		-0.75		-0.01	-0.11	-0.01	-0.70
O2_field	0.90	0.60	-0.03	0.21	-0.01		0.20	0.01	0.06	0.16	0.17	0.86
ORP_field	0.99	0.03	0.62	0.01	0.55		0.14	-0.74	0.29	0.00	0.06	0.21
P_bio	0.36	0.21	0.92	0.71	0.28	-0.66	0.00		0.03	0.54	-0.69	-0.79
Pb	-0.41	-0.01		-0.03		-0.06	-0.05		0.41	0.32	-0.96	0.02
pH	-0.71	-0.51	0.00	-0.62	0.00	-0.54	-0.01	-0.44	-0.44	-0.04	-0.09	0.13
pH_field	0.55	-0.77	0.00	-0.73	0.00		-0.28	0.00	0.22	-0.79	0.50	0.01
Pheo_bio	0.32	-0.65	-0.05	-0.33	-0.13		-0.20					
PO4P_bio	-0.73	0.49	-0.01	-0.23	-0.01		0.00		0.66	0.93	-0.24	-0.65
POC_bio	0.33	0.67	-0.33	-0.60	-0.55		-0.73		0.09	0.74	0.58	0.69
PON_bio	0.65	-0.39	-0.09	-0.19	-0.15		-0.39		-0.99	-0.38	-0.28	-0.37
POP_bio	0.91	-0.09	-0.66	-0.44	-0.34		-0.92		-0.56	0.63	-0.48	-0.19
Pr	0.36	0.95		-0.55					0.16	0.73	0.64	0.84
Rb	0.06	0.96		0.21		0.90	-0.26		0.78	-0.72	-0.66	-0.35
S_2-												
salinity	0.00	0.10	0.37	0.00	0.00		0.00	0.00	0.73	-0.61	0.52	-0.56
Sb	0.82	0.94		-0.53		-0.09			0.20	0.47	0.95	0.45
Sc												
Si	0.00	0.09	0.00	0.01	0.00		0.00		0.00	0.00	0.00	0.00
SiO2_bio	0.01	0.17	0.00	0.15	0.00		0.03		0.00	0.00	0.01	0.00
Sm	0.27	0.77							0.05	0.78	0.46	0.75
SO4	-0.15	0.37	0.38	-0.80	0.30	-0.51	0.41	0.00	-0.02	-0.26	-0.12	-0.01
SO4S	-0.20	0.26	0.29	0.78	0.20	-0.98	0.00		-0.02	-0.44	-0.64	0.00
Sr	0.17	0.06	0.12	0.04	0.01		0.01		0.10	-0.71	0.86	0.01
Susp		-0.09		-0.63			-0.34		-0.01	-0.62	0.00	0.00
Tb										-0.23	0.66	
Th									0.53	0.49	0.59	0.64
Tm												
TOC_bio	0.00	0.00	0.00	0.00	0.00		0.00		0.00	0.00	0.00	0.00
turbidity	-0.30						-0.02	-0.03	0.30	-0.89	0.28	0.40
U	-0.93	0.58		0.00		-0.91	-0.07		-0.35	0.69	0.16	-0.38
V	-0.20	-0.64		-0.10		-0.08	-0.78		-0.13	-0.04	0.49	0.22
Y	0.26	0.81		-0.71			0.36		0.08	0.68	0.61	-0.87
Yb	0.12	0.40		-0.86					0.08	0.66	0.59	-0.94
Zn	0.52	-0.36		-0.58		-0.60	-0.09		0.67	0.22	0.74	0.04
Zr	0.95	-0.77		-0.30					0.20	0.48	0.04	0.54

* S=surface, B=bottom, i=intermediary, x= no info.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-6. The total number of samples per parameter and object sampled and analysed for near surface groundwater in monitoring wells and private wells during the period 2002 to 2014. The colour coding ranges from few (red) to many (green) observations.

Private wells (drilled or dug wells)

IDCODE	PFM000001	PFM000002	PFM000003	PFM000004	PFM000005	PFM000006	PFM000007	PFM000008	PFM000009	PFM000010	PFM000011	PFM000012	PFM000013	PFM000014	PFM000015	PFM000016	PFM000017	PFM000018	PFM000019	PFM000020	PFM000021	PFM000022	PFM000023	PFM000024	PFM000025	PFM000038	PFM000039	PFM002942	PFM004179	PFM004504	PFM004778	PFM006382
CorrSECUP*										0																						3.7
CorrSECLOW*	4.1									6																	60.0					4.1
MonitProg**	y	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y
10B	3						3	3	3																	1	3	3	2	1	3	
13C																														1		
14C																														1		
18O	3						3	3	3	1																1	4	3	2	1	3	
222Rn																														1		
226Ra																														1		
230Th																														1		
232Th																																
234U																														1		
235U																																
235U/238U																																
238U																														1		
2H	3						3	3	3	1																1	4	3	2	1	3	
34S_SO4																												1		1		
36Cl																																
37Cl																														1		
3H	3						3	3	3	1																1	4	3	2	1	3	
87Sr																														1		
Al	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	1		
As																													1	1		
B																																
Ba																													1	1		
Br	3						3	3	3	2																1	4	3	2	1	3	
Ca	12	1	1	1	1	1	6	6	12	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	3	2	1	3	7
Cd																													1	1		
Ce																													1	1		
Cl	12	1	1	1	1	1	6	6	12	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	3	2	1	3	7
Co																													1	1		
COND	12	1	1	1	1	1	6	6	12	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	3	2	1	3	7
Cr																													1	1		
Cs																													1	1		
Cu	9	1	1	1	1	1	3	3	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2		1	1		7
DIC_bio	3						3	3	3	1																1	4	3	1	1	3	
DOC_bio	3						3	3	3	1																1	4	3	1	1	3	
Dy																													1	1		
EC_field	3						3	3	3																	1	3	1	2	1	2	
Er																													1	1		
Eu																													1	1		
F	12	1	1	1	1	1	6	6	12	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	3	2	1	3	7
Fe	9	1	1	1	1	1	3	3	9	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2		1	1		7
Fe_2+																																
Fe_tot																																
Gd																													1	1		
HCO3	12	1	1	1	1	1	6	6	12	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	3	2	1	3	7
Hf																													1	1		
Hg																													1	1		
Ho																													1	1		
I										2																	1		1	1		
In																																
K	11	1	1	1	1	1	5	5	11	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	3	2	1	3	7
La																													1	1		
Li	3						3	3	3	2																1	4	3	2	1	3	
Lu																													1	1		
Mg	12	1	1	1	1	1	6	6	12	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	3	2	1	3	7
Mn	9	1	1	1	1	1	3	3	9	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2		1	1		7
Mo																													1	1		
N_bio	2						2	2	2	1																1	3	2	1	1	2	
Na	11	1	1	1	1	1	5	5	11	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	3	2	1	3	7
Nb																																
Nd																													1	1		
NH4N	9	1	1	1	1	1	3	3	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2					7
NH4N_bio	3						3	3	3	1																1	4	3	1	1	3	
Ni																													1	1		
NO23N_bio	3						3	3	3	1																1	4	3	1	1	3	
NO2N	9	1	1	1	1	1	3	3	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2					7
NO2N_bio	3						3	3	3	1																1	4	3	1	1	3	
NO3N	8	1	1	1	1	1	2	2	8	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1					7
NO3N_bio																																
O2_bio																																
O2_field	3						3	3	3																	1	3	1	2	1	2	
ORP_field	2						2	2	2																	1	2	1	2	1	1	
P																																
P_bio	2						2	2	2	1																1	3	2	1	1	2	
Pb																													1	1		
pH	12	1	1	1	1	1	6	6	12	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	3	2	1	3	7
pH_field	3						3	3	3																	1	3	1	2	1	2	
PO4P	9	1	1	1	1	1	3	3	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		2					7
PO4P_bio	3						3	3	3	1																1	4	3	1	1	3	
PO4P_hlysis_bio																																
POC_bio																																
PON_bio																																
POP_bio																																
Pr																													1	1		
Rb																													1	1		
S_2-																																
salinity	3						2	3	3																	1	3	1	2	1	2	
Sb																													1	1		
Sc																													1	1		
Se																																
Si	3						3	3	3	2																1	4	3	2	1	3	
SiO2_bio	3						3	3	3	1																1	4	3	1	1	3	
Sm																													1	1		
SO4	12	1	1	1	1	1	6	6	12	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	3	2	1	3	7
SO4S	3						3	3	3	2																1	4	3	2	1	3	
Sr	3						3	3	3	2																1	4	3	2	1	3	
Tb																													1	1		
Th																													1	1		
Tl																													1	1		
Tm																													1	1		
TOC_bio	3						3	3	3	1																1	4	3	1	1	3	
U																													1	1		
V																													1	1		
Y																													1	1		
Yb																													1	1		
Zn	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	1		
Zr																													1	1		

Monitor wells

IDCODE	SFM0001	SFM0002	SFM0003	SFM0005	SFM0006	SFM0008	SFM0009	SFM0010	SFM0011	SFM0012	SFM0013	SFM0014	SFM0015	SFM0016	SFM0017	SFM0018	SFM0019	SFM0020	SFM0021	SFM0022	SFM0023	SFM0024	SFM0025	SFM0026	SFM0027	SFM0028	SFM0029	SFM0030	SFM0031	SFM0032	SFM0034	SFM0036
CorrSECUP*	3.8	4.2	9.0	2.2	3.2	5.1	2.0	1.0	3.5	5.4	4.5	2.0	6.3	7.5	4.0	4.5	4.5	3.0	2.0	5.3	3.3	2.7	6.1	16.0	7.0	7.0	7.0	4.0	3.5	1.9	2.0	2.0
CorrSECLOW*	5.0	5.2	11.0	3.2	4.2	6.1	3.0	2.0	4.5	6.4	5.5	3.0	7.3	8.5	5.0	5.5	5.5	4.0	3.0	5.8	5.4	3.2	7.1	17.0	8.0	8.0	8.0	5.0	4.5	4.0	3.0	3.0
MonitProg**	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	n	y	n	n
10B	19	11	11	7	6	9	8			8			8							3	11	2	7		8		8		8	17		
13C	13	9	9	5	5	6	5			8			8							3	6	2	6		6		5		6	11		
14C	11	7	7	3	3	4	4			6			6							2	3	2	4		4		3		4	7		
18O	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	3	44	3	9	1	9	1	8	1	8	48	1	1
222Rn	7	4	4	1	1	3	2			1			1												2		2		2	5		
226Ra	7	4	4	1	1	3	2			1			1												2		2		2	5		
230Th	6	3	3	1	1	2	1			1			1												1		1		1	4		
232Th	5	2	2	1	1	1				1			1																	3		
234U	6	3	3	1	1	2	1			1			1												1		1		1	4		
235U	5	2	2	1	1	1				1			1																	3		
235U/238U																																
238U	6	3	3	1	1	2	1			1			1												1		1		1	4		
2H	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	3	44	3	9	1	9	1	8	1	8	48	1	1
34S_SO4	13	10	10	6	6	9	8			9										3	8	2	8		8		8		8	11		
36Cl																																
37Cl	15	12	11	7	6	9	8			8			7							3	7	1	7		8		8		8	11		
3H	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	3	40	3	9	1	9	1	8	1	8	48	1	1
87Sr	12	9	9	5	4	8	8			8			7							3	8	2	8		8		8		8	11		
Al	31	8	8	5	4	6	6			1			1								1		1		6		6		6	29		
As	8	4	4	1	2	2	2			1			1								1		1		2		2		2	6		
B	4																															
Ba	32	9	9	5	4	6	6			1			1								1		1		6		6		6	29		
Br	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	46	3	9	1	9	1	8	1	8	48	1	1
Ca	50	12	12	7	6	9	9	1	1	9	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Cd	32	8	8	5	4	6	6			1			1								1		1		6		6		6	29		
Ce	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Cl	50	12	12	7	6	9	9		1	10	1	1	9	1	1	1	1	1		4	48	3	9	1	9	1	8	1	8	48	1	1
Co	31	8	8	5	4	6	6			1			1								1		1		6		6		6	29		
COND	48	10	10	6	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	48	3	9	1	9	1	8	1	8	48	1	1
Cr	31	7	8	5	4	6	6			1			1								1		1		6		6		6	29		
Cs	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Cu	32	7	8	5	4	6	6			1			1								1		1		6		6		6	29		
DIC_bio	48	11	11	6	6	9	8			9			8							3	42	2	8		8		7		8	45		
DOC_bio	49	12	12	6	6	9	8			9			8							3	40	2	8		8		7		8	45		
Dy	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
EC_field	46	11	11	5	5	7	8			8			7							2	44	1	8		7		8		8	45		
Er	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Eu	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
F	50	12	12	7	6	9	9		1	8	1	1	9	1	1	1	1	1		4	46	2	6	1	9	1	8	1	8	47	1	1
Fe	43	9	9	6	5	7	6			1			1							1	2				6		6		6	38		
Fe_2+	25	7	7	5	4	7	6																		5		6		6	25		
Fe_tot	25	7	5	5	4	7	6																		5		6		6	25		
Gd	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
HCO3	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	48	3	9	1	9	1	8	1	8	48	1	1
Hf	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Hg	32	9	9	5	4	6	6			1			1								1		1		6		6		6	29		
Ho	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
I	42	11	11	7	5	7	8	1	1	7	1	1	7	1	1	1	1	1	1	3	32	2	6	1	7	1	6	1	6	39	1	1
In	7	2	2	1	1	2	2																		2		2		2	7		
K	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
La	27	7	7	4	3	6	6			1			1								1		1		6		6		6	26		
Li	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Lu	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Mg	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Mn	43	9	10	6	5	7	6			1			1							1	5				6		6		6	39		
Mo	31	8	8	5	4	6	6			1			1								1		1		6		6		6	29		
N_bio	48	11	11	6	6	8	7			8			7							3	41	1	7		7		6		7	44		
Na	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Nb	1																				1									1		
Nd	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
NH4N																																
NH4N_bio	49	12	12	7	6	9	8			9			8							3	42	2	8		8		7		8	45		
Ni	29	6	8	5	4	6	6			1			1								1		1		6		6		6	29		
NO23N_bio	48	11	11	7	6	9	8			9			8							3	41	2	8		8		7		8	44		
NO2N																																
NO2N_bio	41	9	9	6	5	8	8			8			7							3	39	2	7		8		7		8	40		
NO3N																																
NO3N_bio	34	2	2	1	1	2	2			2			2								32	1	2		2		2		2	34		
O2_bio	6	5	5	3	3	2	1			2			2								1		1		1		1		1	2		
O2_field	43	8	9	5	5	7	7			9			7							3	42	1	8		7		8		8	43		
ORP_field	42	7	7	4	3	5	5			6			5							2	40	1	5		6		6		6	42		
P	2																													2		
P_bio	48	11	11	6	6	8	7			7			7							2	41	1	7		7		6		7	44		
Pb	31	8	8	5	4	6	6			1			1								1		1		6		6		6	29		
pH	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	48	3	9	1	9	1	8	1	8	48	1	1
pH_field	46	11	11	5	5	7	8			8			7							2	44	1	8		7		8		8	45		
PO4P	1																															
PO4P_bio	49	12	12	7	6	9	8			9			8							3	41	2	8		8		7		8	45		
PO4P_hlysis_bio	27																				25									27		
POC_bio	3	3	2	1	1																											
PON_bio	3	3	2	1	1																											
POP_bio	3	2	3	1	1																											
Pr	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Rb	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
S_2-	27	4	8	5	5	5	5			1			1								4				4		5		4	25		
salinity	37	8	9	5	5	7	8			9			7							3	35	1	8		7		8		8	37		
Sb	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Sc	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Se	1																													1		
Si	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	45	3	9	1	9	1	8	1	8	48	1	1
SiO2_bio	49	12	12	7	6	9	8			9			8							3	42	2	8		8		7		8	45		
Sm	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
SO4	50	12	12	7	6	9	9		1	10	1	1	9	1	1	1	1	1		4	46	3	9	1	9	1	8	1	8	48	1	1
SO4S	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Sr	50	12	12	7	6	9	9	1	1	10	1	1	9	1	1	1	1	1	1	4	44	3	9	1	9	1	8	1	8	48	1	1
Tb	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Th	29	7	7	4	4	6	6			1			1								2		1		6		6		6	28		
Tl	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Tm	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
TOC_bio	49	12	12	7	6	9	8			9			8							3	42	2	8		8		7		8	45		
U	29	7	7	4	4	6	6			1			1								2		1		6		6		6	28		
V	32	9	8	5	4	6	6			1			1								1		1		6		6		6	29		
Y	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Yb	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		
Zn	31	6	8	5	4	6	6			1			1								1		1		6		6		6	29		
Zr	27	7	7	4	4	6	6			1			1								1		1		6		6		6	26		

IDCODE	SFM0037	SFM0049	SFM0051	SFM0053	SFM0056	SFM0057	SFM0059	SFM0060	SFM0061	SFM0062	SFM0063	SFM0065	SFM0074	SFM0077	SFM0078	SFM0079	SFM0080	SFM0081	SFM0083	SFM0084	SFM0087	SFM0090	SFM0091	SFM0094	SFM0095	SFM0102	SFM0103
CorrSECUP*	1.1	2.9	4.3	6.0	6.0	3.5	4.9	6.6	6.0	3.3	3.2	4.5	2.0	6.0	3.5	4.7	8.6	4.9		3.7	2.0	3.1	1.9	2.2	5.0	2.1	4.9
CorrSECLOW*	3.0	5.0	5.2	6.2	6.2	4.6	5.9	7.6	8.1	3.7	3.7	4.9	4.7	7.0	4.5	5.7	9.6	5.3	2.7	4.1	2.3	5.6	2.3	7.7	6.0	2.3	7.4
MonitProg**	n	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
10B	16	12	18	6	6	7	1	5	3	2	1		11						3		2				2	3	
13C	9	7	8	8		6		5													1				1		
14C	7	5	6	6		4		3													1				1		
18O	46	44	45	8	8	7	1	5	2	3	2	1	11	2	2	2	2	6	6	7	7		7		7	6	
222Rn	5	4				2		1													1				1		
226Ra	5	4				2		1													1				1		
230Th	4	4				1		1													1				1		
232Th	3	3																			1				1		
234U	4	4				1		1													1				1		
235U	3	3																			1				1		
235U/238U			3																								
238U	4	4				1		1													1				1		
2H	46	44	45	8	8	7	1	5	2	3	2	1	11	2	2	2	2	6	6	7	7		7		7	6	
34S_SO4	11	3				7		5													1				1		
36Cl																											
37Cl	11	7	7	7	1	6		5													1				1		
3H	46	44	45	8	8	7	1	5	3	2	1		11	2	2	2	2	6	6	7	7		7		7	6	
87Sr	11	7	8	8	1	7		5													1				1		
Al	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
As	6	6	13	4	4	2		2						1	1	1	1		1		3				3	2	
B	4	4	7											1	1	1	1		1		3				3	2	
Ba	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Br	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Ca	46	44	45	8	8	7	1	5	3	3	2	1	10	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Cd	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Ce	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Cl	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	8	3	9	3	8	6	2
Co	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
COND	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Cr	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Cs	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Cu	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
DIC_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
DOC_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
Dy	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
EC_field	45	41				7		4						2	2	2	2	6		7	7		7		7		
Er	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Eu	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
F	45	44	45	8	8	6	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Fe	38	37	42	5	5	6		4		3		1		1	1	1	1		3		5				5	4	
Fe_2+	24	21	30	6		6		4						1	1	1	1		1		4				5		
Fe_tot	24	21	30	6		6		4						1	1	1	1		1		4				5		
Gd	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
HCO3	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	8	9	3	9	3	8	2	2
Hf	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Hg	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Ho	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
I	37	36	32	3	4	5	1	5	3	3	2	1	11	1	1	1	1	3	3	4	5		4		5	4	
In	7	7	13	4	4	2		2											1		3				3	2	
K	46	44	45	8	7	6	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
La	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Li	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Lu	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Mg	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Mn	39	37	43	6	6	6		4		3		1		1	1	1	1		3		5				5	4	
Mo	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
N_bio	44	41				6		5						2	2	2	2	6	5	7	7		7		7	6	
Na	46	44	45	8	7	6	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Nb	1	1	1																								
Nd	25	24	38	6	6	6		4						1	1	1	1		3		4				5	4	
NH4N																											
NH4N_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
Ni	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
NO23N_bio	45	40				7		5						2	2	2	2	6	5	7	7		7		7	6	
NO2N																											
NO2N_bio	41	36				7		5						1	1	1	1	5	5	6	6		6		6	5	
NO3N																											
NO3N_bio	35	33				1		1						1	1	1	1	5	5	6	6		6		6	5	
O2_bio	3	2				1		1																			
O2_field	43	39				7		4						2	2	2	2	6		7	7		7		7		
ORP_field	41	40	1			5		3						2	2	2	2	6		7	7		7		7		
P	2	2	10											1	1	1	1				1				1		
P_bio	43	41	7			6		5						2	2	2	2	6	5	7	7		7		7	6	
Pb	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
pH	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
pH_field	45	41				7		4						2	2	2	2	6		7	7		7		7		
PO4P																											
PO4P_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
PO4P_hlysis_bio	27	27																2	2	2	2		2		2	2	
POC_bio																											
PON_bio																											
POP_bio																											
Pr	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Rb	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
S_2-	23	22				5		2						1	1	1	1				4				5		
salinity	38	32				7		4						2	2	2	2	6		7	7		7		7		
Sb	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Sc	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Se	1	1	1																								
Si	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
SiO2_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
Sm	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
SO4	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
SO4S	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	5	9	3	3	5	3	8	6	2
Sr	46	44	45	8	8	7	1	5	3	3	2	1	11	2	2	2	2	6	6	9	9	3	9	3	8	6	2
Tb	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Th	27	26	40	6	6	6		4						1	1	1	1		3		5				5	4	
Tl	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Tm	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
TOC_bio	45	41				7		5						2	2	2	2	6	5	7	7		7		7	6	
U	27	26	40	6	6	6		4						1	1	1	1		3		5				5	4	
V	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Y	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Yb	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	
Zn	28	27	43	6	6	6		4						1	1	1	1		3		5				5	4	
Zr	25	24	38	6	6	6		4						1	1	1	1		3		5				5	4	

*corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-7. The percentage of the total number of observations that falls below the reporting limit for all objects and parameters for near surface groundwater in monitoring wells and private wells during the period 2002–2014. The colour coding ranges from few (green) to many (red) observations below reporting limits.

Private wells

IDCODE	PFM000001	PFM000002	PFM000003	PFM000004	PFM000005	PFM000006	PFM000007	PFM000008	PFM000009	PFM000010	PFM000011	PFM000012	PFM000013	PFM000014	PFM000015	PFM000016	PFM000017	PFM000018	PFM000019	PFM000020	PFM000021	PFM000022	PFM000023	PFM000024	PFM000025	PFM000038	PFM000039	PFM002942	PFM004179	PFM004504	PFM004778	PFM006382
CorrSECUP*										0																						4
CorrSECLOW*	4									6																	60					4
MonitProg**	y	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y
10B	0						0	0	0																	0	0	0	0	0	0	
13C																														0		
14C																														0		
18O	0						0	0	0	0																0	0	0	0	0	0	
222Rn																														0		
226Ra																														0		
230Th																														0		
232Th	[illegible]
234U	[illegible]
235U	[illegible]
235U/238U	[illegible]
238U	[illegible]
2H	[illegible]
34S_SO4	[illegible]
36Cl	[illegible]
37Cl	[illegible]
3H	[illegible]
87Sr	[illegible]
ABS_436	[illegible]
ABS_bio	[illegible]
Al	[illegible]
As	[illegible]
B	[illegible]
Ba	[illegible]
Br	[illegible]
Ca	[illegible]
Cd	[illegible]
Ce	[illegible]
Cl	[illegible]
Co	[illegible]
COND	[illegible]
Cr	[illegible]
Cs	[illegible]
Cu	[illegible]
DIC_bio	[illegible]
DOC_bio	[illegible]
Dy	[illegible]
EC_field	[illegible]
Er	[illegible]
Eu	[illegible]
F	[illegible]
Fe	[illegible]
Fe_2+	[illegible]
Fe_tot	[illegible]
Gd	[illegible]
HCO3	[illegible]
Hf	[illegible]
Hg	[illegible]
Ho	[illegible]
I	[illegible]
In	[illegible]
K	[illegible]
La	[illegible]
Li	[illegible]
Lu	[illegible]
Mg	[illegible]
Mn	[illegible]
Mo	[illegible]
N_bio	[illegible]
Na	[illegible]
Nb	[illegible]
Nd	[illegible]
NH4N	[illegible]
NH4N_bio	[illegible]
Ni	[illegible]
NO23N_bio	[illegible]
NO2N	[illegible]
NO2N_bio	[illegible]
NO3N	[illegible]
NO3N_bio	[illegible]
O2_bio	[illegible]
O2_field	[illegible]
P	[illegible]
P_bio	[illegible]
Pb	[illegible]
pH	[illegible]
pH_field	[illegible]
PO4P	[illegible]
PO4P_bio	[illegible]
PO4P_hlysis_bio	[illegible]
POC_bio	[illegible]
PON_bio	[illegible]
POP_bio	[illegible]
Pr	[illegible]
Rb	[illegible]
S_2-	[illegible]
salinity	[illegible]
Sb	[illegible]
Sc	[illegible]
Se	[illegible]
Si	[illegible]
SiO2_bio	[illegible]
Sm	[illegible]
SO4	[illegible]
SO4S	[illegible]
Sr	[illegible]
Tb	[illegible]
Th	[illegible]
Tl	[illegible]
Tm	[illegible]
TOC_bio	[illegible]
U	[illegible]
V	[illegible]
Y	[illegible]
Yb	[illegible]
Zn	[illegible]
Zr	[illegible]

Monitor wells

IDCODE	SFM0001	SFM0002	SFM0003	SFM0005	SFM0006	SFM0008	SFM0009	SFM0010	SFM0011	SFM0012	SFM0013	SFM0014	SFM0015	SFM0016	SFM0017	SFM0018	SFM0019	SFM0020	SFM0021	SFM0022	SFM0023	SFM0024	SFM0025	SFM0026	SFM0027	SFM0028	SFM0029	SFM0030	SFM0031	SFM0032	SFM0034	SFM0036	SFM0037	SFM0049	SFM0051	SFM0053	SFM0056	SFM0057	SFM0059	SFM0060	SFM0061	SFM0062	SFM0063	SFM0065	SFM0074	SFM0077	SFM0078	SFM0079	SFM0080	SFM0081	SFM0083	SFM0084	SFM0087	SFM0090	SFM0091	SFM0094	SFM0095	SFM0102	SFM0103
CorrSECUP*	3.8	4.2	9.0	2.2	3.2	5.1	2.0	1.0	3.5	5.4	4.5	2.0	6.3	7.5	4.0	4.5	4.5	3.0	2.0	5.3	3.3	2.7	6.1	16.0	7.0	7.0	7.0	4.0	3.5	1.9	2.0	2.0	1.1	2.9	4.3	6.0	6.0	3.5	4.9	6.6	6.0	3.3	3.2	4.5	2.0	6.0	3.5	4.7	8.6	4.9		3.7	2.0	3.1	1.9	2.2	5.0	2.1	4.9
CorrSECLOW*	5.0	5.2	11.0	3.2	4.2	6.1	3.0	2.0	4.5	6.4	5.5	3.0	7.3	8.5	5.0	5.5	5.5	4.0	3.0	5.8	5.4	3.2	7.1	17.0	8.0	8.0	8.0	5.0	4.5	4.0	3.0	3.0	3.0	5.0	5.2	6.2	6.2	4.6	5.9	7.6	8.1	3.7	3.7	4.9	4.7	7.0	4.5	5.7	9.6	5.3	2.7	4.1	2.3	5.6	2.3	7.7	6.0	2.3	7.4
MonitProg**	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	n	y	n	n	n	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
10B	0	0	0	0	0	0	0			0			0							0	0	0	0		0		0		0	0			0	0	0	0	0	0	0	0	0	0	0		0						0		0				0	0	
13C	0	0	0	0	0	0	0			0			0							0	0	0	0		0		0		0	0			0	0	0	0		0		0													0				0		
14C	0	0	0	0	0	0	0			0			0							0	0	0	0		0		0		0	0			0	0	0	0		0		0													0				0		
18O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0		0	0	
222Rn	0	0	0	0	0	0	0			0			0												0		0		0	0			0	0				0		0													0				0		
226Ra	0	0	75	0	100	0	0			0			0												0		0		0	0			20	75				0		100													0				0		
230Th	33	67	100	100	100	100	0			100			100												100		100		0	0			0	0				0		100													0				0		
232Th	[illegible]
234U	[illegible]
235U	[illegible]
235U/238U	[illegible]
238U	[illegible]
2H	[illegible]
34S_SO4	[illegible]
36Cl	[illegible]
37Cl	[illegible]
3H	[illegible]
87Sr	[illegible]
ABS_436	[illegible]
ABS_bio	[illegible]
Al	[illegible]
As	[illegible]
B	[illegible]
Ba	[illegible]
Br	[illegible]
Ca	[illegible]
Cd	[illegible]
Ce	[illegible]
Cl	[illegible]
Co	[illegible]
COND	[illegible]
Cr	[illegible]
Cs	[illegible]
Cu	[illegible]
DIC_bio	[illegible]
DOC_bio	[illegible]
Dy	[illegible]
EC_field	[illegible]
Er	[illegible]
Eu	[illegible]
F	[illegible]
Fe	[illegible]
Fe_2+	[illegible]
Fe_tot	[illegible]
Gd	[illegible]
HCO3	[illegible]
Hf	[illegible]
Hg	[illegible]
Ho	[illegible]
I	[illegible]
In	[illegible]
K	[illegible]
La	[illegible]
Li	[illegible]
Lu	[illegible]
Mg	[illegible]
Mn	[illegible]
Mo	[illegible]
N_bio	[illegible]
Na	[illegible]
Nb	[illegible]
Nd	[illegible]
NH4N	[illegible]
NH4N_bio	[illegible]
Ni	[illegible]
NO23N_bio	[illegible]
NO2N	[illegible]
NO2N_bio	[illegible]
NO3N	[illegible]
NO3N_bio	[illegible]
O2_bio	[illegible]
O2_field	[illegible]
P	[illegible]
P_bio	[illegible]
Pb	[illegible]
pH	[illegible]
pH_field	[illegible]
PO4P	[illegible]
PO4P_bio	[illegible]
PO4P_hlysis_bio	[illegible]
POC_bio	[illegible]
PON_bio	[illegible]
POP_bio	[illegible]
Pr	[illegible]
Rb	[illegible]
S_2-	[illegible]
salinity	[illegible]
Sb	[illegible]
Sc	[illegible]
Se	[illegible]
Si	[illegible]
SiO2_bio	[illegible]
Sm	[illegible]
SO4	[illegible]
SO4S	[illegible]
Sr	[illegible]
Tb	[illegible]
Th	[illegible]
Tl	[illegible]
Tm	[illegible]
TOC_bio	[illegible]
U	[illegible]
V	[illegible]
Y	[illegible]
Yb	[illegible]
Zn	[illegible]
Zr	[illegible]

*corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-8. The coefficient of variation (CV) expressed in percent for all objects and parameters with at least 5 observations representing a time period longer than one year for near surface groundwater in monitoring wells and private wells. The CV is defined as the ration between the arithmetic standard deviation and the arithmetic mean. The colour coding ranges from low (green) to high (red) variability.

	Monitor wells																											
IDCODE	SFM0001	SFM0002	SFM0003	SFM0005	SFM0006	SFM0008	SFM0009	SFM0012	SFM0015	SFM0023	SFM0025	SFM0027	SFM0029	SFM0031	SFM0032	SFM0037	SFM0049	SFM0051	SFM0053	SFM0056	SFM0057	SFM0081	SFM0083	SFM0084	SFM0087	SFM0091	SFM0095	SFM0102
CorrSECUP*	3.8	4.2	9.0	2.2	3.2	5.1	2.0	5.4	6.3	3.3	6.1	7.0	7.0	3.5	1.9	1.1	2.9	4.3	6.0	6.0	3.5	4.9		3.7	2.0	1.9	5.0	2.1
CorrSECLOW*	5.0	5.2	11.0	3.2	4.2	6.1	3.0	6.4	7.3	5.4	7.1	8.0	8.0	4.5	4.0	3.0	5.0	5.2	6.2	6.2	4.6	5.3	2.7	4.1	2.3	2.3	6.0	2.3
MonitProg**	y	n	n	n	n	n	n	n	n	y	n	n	n	n	y	n	y	y	n	n	n	n	n	n	n	n	n	n
10B	5	7	7	3	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	0							
13C	7	8	11			8		72	7	87	13	3		10	35	7	9	8	23		9							
14C	4	1	9					14	1						6	5		1	3									
18O	6	2	3	5	2	2	2	2	2	4	2	1	2	4	5	9	11	4	2	3	4	1	16	2	1	2	2	1
222Rn	44																											
226Ra	100																											
234U	24																											
238U	32																											
2H	6	5	5	5	4	4	3	4	3	5	2	3	2	3	5	10	8	4	2	2	5	3	10	2	2	5	4	2
34S_SO4	61	45	59					16		32	17	49									32							
37Cl	142	72	124	4205	190	2524	566	110	23	124	61	65	270	965	1966	85	409	289	106		106							
3H	17	10	22	4	14	11	6	119	30	52	36	12	10	11	19	16	15	18	36		12	25	8	15	8	9	10	6
87Sr	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0		0							
Al	58	76	111			82	62					111	111	83	147	156	205	121	65	158	47							
As	18														25			37										
B																		11										
Ba	25	13	22			21	19					17	6	9	19	30	17	9	11	96	35							
Br	37	47	57	97		84	70	28	27	27	31	38	69	88	53	50	34	27		23	65	11	42	32	20	30	25	15
Ca	13	19	15	14	11	14	12	8	23	22	20	15	6	7	16	19	11	6	7	32	34	7	22	35	4	15	15	15
Cd	105	30	61			42	34					63	37	68	82	131	90	139			41							
Ce	39	26	27			55	54					69	14	39	65	38	29	99	72	171	33							
Cl	38	56	26	56	40	68	38	3	9	19	23	3	49	18	38	82	18	42	31	40	59	1	48	25	26	30	9	4
Co	48	64	20			32	57					61	31	26	102	78	110	102	51	45	30							
COND	28	13	4	12	15	19	11	3	40	12	17	5	5	3	13	35	9	5	5	30	39	1	37	13	6	13	5	2
Cr	32	35	47			37	23					28	15	29	30	19	26	170	56	89	34							
Cs	59											37						54										
Cu	425	55				30	8						36	30	52	195	109	195	87	91	62							
DIC_bio	19	14	11	13	16	18	22	24	6	53	27	7	16	21	10	28	17				23	21		25	5	6	9	33
DOC_bio	23	9	9	15	10	21	12	12	5	51	7	13	8	23	12	26	19				25	45		14	4	11	37	4
Dy	42	23	39			56	45					38	15	40	39	30	25	56			35							
EC_field	30	19	5			17	15	3	2	26	3	2	6	4	19	34	31				38	1		7	2	9	4	
Er	43	17	33			53	41					29	18	39	32	29	24	37			30							
Eu	46	31					43						19	44	51	39	31	100	58		30							
F	23	23	15		45	37	31		40	25		27	12	26	9	20	18	11	19			9	3	34	17	13	14	
Fe	23	35	75	47		32	120					75	15	89	19	44	40	31			35							
Fe_2+	30	44	44			30							39	80	18	35	28	23	22		188							
Fe_tot	30	44	43			32	44						39	82	17	35	27	24	22		180							
Gd	41	33	42			50	44					56	17	36	42	31	26	69			30							
HCO3	19	5	3	16	11	10	10	7	3	32	7	11	4	4	11	29	11	5	6	6	16	8	19	18	5	7	12	
Hf	30	23				55	32					29	17		26	38	70	45	46		22							
Hg																25												
Ho	43	20				55	43						16	39	34	28	25	46			32							
I	595	40	88	94		77	45	66	28	67	20	48	40	54	556	533	496	24										
K	23	17	7	9	7	9	16	3	23	22	12	5	6	6	13	43	23	13	8	24	28	7	36	25	6	8	28	17
La	48	47	54			23	35					67	21	34	52	40	28	97	73	187	17							
Li	26	25	14			24	38	5	18	11	13	21	27	10	24	39	68	22	35	29		10	133	17	8	10	83	
Lu	39	13					36						17	37	27	28	24	227			25							
Mg	27	15	6	14	24	11	12	3	19	20	17	10	7	10	13	40	10	5	5	20	37	4	36	36	7	12	35	17
Mn	14	45	29	113		29	94					16	14	10	17	29	47	8	5	33	45							
Mo	38	22	10			22	21					114	20	18	55	81	60	30	25	28	26							
N_bio	13	5	8	12	24	14	28	3	11	23	2	8	7	11	12	31	18				38	12		10	6	15	12	9
Na	35	44	13	19	44	57	14	3	22	22	19	6	36	15	23	69	13	35	25	43	45	4	49	37	4	12	18	88
Nd	45	40	45			50	49					72	18	42	50	37	28	87	70	186	34							
NH4N_bio	24	62	10	119	106	52	101	5	10	24	3	18	47	15	35	170	58				63	2		22	58	17	24	22
Ni	42	51	59			14	25					36	36	11	44	53	49	147	43	81	26							
NO23N_bio	328	193	144	76	61	83	108			253		121	104	146	160	449	142				150					68	172	94
NO2N_bio	84	97	92	59		132	93		133	213		91	99	70	99	98	69				159							
NO3N_bio	56									211					115	388	120										60	
O2_field	99	91	98			96	83	126	65	122	122	50	95	48	101	82	89				79	121		34	84	47	52	
P_bio	14	132	285	18	45	41	102	118	51	348	33	5	19	118	11	194	27	32			35	224		113	6	10	24	14
Pb	70	52	54				62					54	87		66	143	102	103	64	125	56							
pH	2	2	2	4	3	1	2	2	2	5	2	2	1	2	3	2	2	2	2	3	2	3	3	4	1	1	1	2
pH_field	3	3	2			1	2	2	2	5	2	1	1	1	4	4	4				3	2		3	1	2	1	
PO4P_bio	27	40	54	17	124	33	38	132	107	92	122	37	53	46	50	106	43				40			94	6	97	41	14
PO4P_hlysis_bio	17									98					18	135	43											
Pr	45	37	47			48	48					67	16	44	52	38	29	96	70		32							
Rb	25	18	5			36	30					20	16	10	17	41	26	47	27	12	32							
S_2-	32														124	178	49											
salinity	27	12	4			17	17	2	4	9	3	3	6	5	22	33	36				42	1		8	2	9	5	
Sb	24	98	39			22	10					72	18	26	37	40	41	109		44	22							
Sc	38	18													14	31	27	64			35							
Si	11	15	15	12	6	8	11	18	22	53	16	13	11	11	13	21	20	10	9	20	10	42	41	24	8	8	66	5
SiO2_bio	12	24	22	16	6	8	11	10	6	63	9	11	5	5	11	20	20				12	30		28	9	11	16	3
Sm	45	31	43			52	46					69	18	43	50	35	26	80			37							
SO4	29	36	17	29	25	16	58	5	118	25	13	4	6	4	94	55	134	17	6	33	33	3	86	38	46	81	123	
SO4S	29	18	14	29	26	16	54	5	58	26	15	5	8	7	96	53	91	16	8	33	26	6		44			113	31
Sr	22	16	6	12	24	12	12	7	22	23	22	18	5	9	16	34	11	6	7	24	37	6	28	27	8	14	61	47
Tb	41	23													43	30	27	68			36							
Th	49	44													33	43	37	97			54							
Tl															115													
Tm	42	19					40						15	38	30	27	25	60			28							
TOC_bio	22	7	12	16	8	20	12	16	5	66	11	5	5	4	12	26	19				25	24		15	4	10	36	7
U	20	19	10			16	13					45	36	12	29	53	75	24	30	41	37							
V	20	31	11			61	25					27	12	8	21	32	37	28	42	95	30							
Y	41	26	40			55	43					35	16	37	21	30	28	44	65	167	30							
Yb	43	18	27			55	39					23	16	35	29	29	23	146			27							
Zn	402	70	66				29					54	73	33	86	121	242	122	49	89	75							
Zr	22	33	16			67	41					24	19	12	20	37	39	30	23	123	30							

*corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-9. Normalised means for all surface water objects and parameters for near surface groundwater in monitoring wells and private wells. The normalisation is made per parameter based on all chemical data from the surface water in the Forsmark area, including lake water, stream water, precipitation and sea water. The scaling is made per parameter by subtracting the overall mean for all objects, from the individual means for each object, followed by a division by the standard deviation for all objects. This scales the values per parameter to overall zero mean and a unit variance of 1 (the colour coding in the compilation ranges between –2 and 2, from red to yellow to green, i.e. from low to high values).

IDCODE	PFM000001	PFM000002	PFM000003	PFM000004	PFM000005	PFM000006	PFM000007	PFM000008	PFM000009	PFM000010	PFM000011	PFM000012	PFM000013	PFM000014	PFM000015	PFM000016	PFM000017	PFM000018	PFM000019	PFM000020	PFM000021	PFM000022	PFM000023	PFM000024	PFM000025	PFM000038	PFM000039	PFM002942	PFM004179	PFM004504	PFM004778	PFM006382
	Private wells																															
CorrSECUP*										0.0																						3.7
CorrSECLOW*	4.1									6.0																	60					4.1
MonitProg**	y	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y
10B	0.0						0.0	-0.1	-0.7																	-0.3	-0.4	0.1	0.3	0.6	0.3	
13C																														0.0		
14C																														-0.2		
18O	-0.6						-1.2	-0.1	-0.5	0.1																-0.9	0.5	-0.6	-0.8	-0.1	-1.3	
222Rn																														-0.1		
226Ra																														-0.2		

*corrSECUP=upper section limit, corrSECLOW=lower section limit.
** Included in the current monitoring programme (Y=yes, N=no).

Table A3-10. Regression analysis of times series consisting of at least 10 sampling occasions ranging over a period of at least 4 years for near surface groundwater in monitoring wells and private wells. The numbers in the table represent the probabilities for the hypothesis that there is no time-trend in data, i.e. p values between –0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign (and colour) of the probabilities represents the direction of the trends (orange – increasing, blue – decreasing).

	Monitor wells					
IDCODE	SFM0001	SFM0023	SFM0032	SFM0037	SFM0049	SFM0051
CorrSECUP*	3.8	3.32	1.94	1.1	2.9	4.32
CorrSECLOW*	4.95	5.42	4	3	5	5.18
MonitProg**	y	y	y	n	y	y
10B	0.18	0.96	-0.63	0.77	-0.69	0.46
13C	0.16		-0.34			
14C	-0.48					
18O	-0.02	-0.75	-0.05	-0.60	-0.09	-0.88
2H	-0.99	0.37	0.88	0.83	-0.26	0.41
34S_SO4	-0.82					
37Cl	0.47		0.47	-0.75		
3H	0.00	0.65	0.00	0.00	-0.01	0.00
87Sr	-0.01		0.73	-0.21		
Al	-0.47		-0.73	-0.17	-0.43	0.00
As						0.02
B						
Ba	-0.17		0.26	-0.20	0.73	-0.04
Br	-0.44	0.00	0.00	-0.01	0.92	-0.66
Ca	-0.59	0.00	0.02	-0.01	-0.49	-0.11
Cd	-0.23		0.72	0.22		-0.26
Ce	0.72		0.72	-0.92	-0.10	0.00
Cl	-0.03	0.00	0.00	-0.02	0.03	0.00
Co	0.00		-0.51	0.06	-0.14	0.00
COND	-0.05	0.00	0.00	0.00	0.47	0.00
Cr	-0.88		-0.85	-0.56	-0.06	-0.50
Cs						-0.62
Cu	-0.53		-0.20	0.78	-0.67	-0.27
DIC_bio	0.57	0.01	0.03	-0.01	-0.95	
DOC_bio	0.00	0.00	0.10	0.00	0.00	
Dy	0.26		1.00	0.96	-0.18	0.00
EC_field	-0.67	0.00	0.00	0.00	0.14	
Er	0.11		0.65	0.90	-0.34	0.00
Eu	-0.69		-0.10	-0.17	-0.04	-0.07
F	0.10	-0.01	0.11	-0.12	0.00	0.05
Fe	0.00		0.17	-0.01	0.02	0.00
Fe_2+	0.00		0.87	-0.27	0.70	-0.54
Fe_tot	0.00		0.83	-0.24	0.79	-0.54
Gd	0.80		-0.53	-0.61	-0.08	0.00
HCO3	-0.50	-0.46	0.74	0.00	0.83	0.08
Hf	0.72		-0.11	-0.02	-0.36	-0.14
Hg						
Ho	0.18		0.90	0.91	-0.25	0.00
I	0.12	-0.39	0.12	0.13	0.17	0.00
K	-0.20	0.00	0.15	0.00	0.49	0.00
La	-0.20		-0.19	-0.70	-0.04	0.00
Li	-0.44	0.00	-0.94	0.00	-0.01	0.00
Lu	0.15		0.56	-0.90	-0.35	0.93
Mg	-0.17	0.00	0.01	0.00	0.31	0.46
Mn	-0.99		-0.22	-0.01	0.05	-0.01
Mo	-0.07		0.03	-0.20	-0.21	0.00
N_bio	0.16	0.05	0.49	0.01	0.03	
Na	-0.05	0.00	0.51	0.00	0.02	0.00
Nd	-0.62		-0.30	-0.64	-0.06	0.00
NH4N_bio	0.71	0.11	0.23	0.16	0.00	
Ni	-0.30		-0.86	0.24	-0.05	-0.40
NO23N_bio	-0.01	0.22	-0.07	-0.98	-0.43	
NO2N_bio	-0.04	0.25	-0.05	-0.17	-0.02	
NO3N_bio	-0.98	0.27	-0.92	-0.44	-0.18	
O2_field	-0.53	-0.06	-0.60	0.02	-0.39	
P						-0.01
P_bio	0.17	-0.95	-0.39	-0.67	0.00	
Pb	0.00		-0.02	0.33	-0.01	0.00
pH	-0.14	0.00	-0.47	-0.33	-0.11	0.42
pH_field	-0.07	0.49	-0.01	-0.05	-0.11	
PO4P_bio	0.00	-0.86	-0.37	0.80	0.00	
PO4P_hlysis						
PO4P_hlysis_bio	0.49	-0.27	0.35	-0.99	0.01	
Pr	-0.47		-0.28	-0.76	-0.04	0.00
Rb	-0.10		-0.46	0.10	0.99	0.00
S_2-	0.00		-0.65	0.04	0.93	
salinity	-0.70	0.00	0.00	-0.01	0.10	
Sb	0.00		-0.23	0.56	-0.27	0.58
Sc	0.12		0.21	0.72	-0.62	0.00
Si	0.02	0.53	0.43	-0.07	0.02	-0.90
SiO2_bio	0.00	0.10	-0.75	-0.29	0.00	
Sm	0.74		-0.68	0.87	-0.18	0.00
SO4	-0.03	0.00	0.76	-0.01	-0.44	-0.22
SO4S	-0.09	0.00	0.74	-0.01	-0.62	-0.21
Sr	-0.30	0.00	0.03	0.00	0.17	0.00
Tb	0.61		-0.66	-0.61	-0.12	0.00
Th	0.03		0.56	0.08	-0.68	0.00
Tm	0.29		0.99	-0.71	-0.11	-0.20
TOC_bio	0.00	0.00	0.04	0.00	0.00	
U	-0.11		0.41	-0.74	-0.18	0.00
V	0.00		-0.89	-0.51	-0.42	-0.35
Y	0.41		-0.43	-0.70	-0.10	0.00
Yb	0.09		0.59	0.92	-0.28	-0.91
Zn	-0.47		-0.64	0.02	-0.34	-0.03
Zr	0.00		0.95	-0.10	-0.16	0.04

*corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Included in the current monitoring programme (Y=yes, N=no).

Table A3-11. The total number of samples per parameter and object sampled and analysed for groundwater in the bedrock (percussion drilled and cored boreholes) during the period 2002 to 2014. The colour coding ranges from few (red) to many (green) observations.

Percussion drilled boreholes

IDCODE	HFM01	HFM02	HFM04	HFM13	HFM15	HFM16	HFM19	HFM21	HFM27	HFM32
CorrSECUP*	34	38	58	159	85	54	168	22	46	26
CorrSECLOW*	46	48	66	176	100	67	185	32	58	31
CorrSec**	2	2	2	1	1	2	1	3	2	3
MonitProg***	y	y	y	y	y	y	y	y	y	y
10B	3	4	3	5	4	3	5	3	2	3
13C	3	4	4	4	4	3	4	3	3	3
14C	3	4	4	4	4	3	4	3	3	3
18O	12	16	16	16	16	14	16	12	14	16
222Rn	2	4	4	4	4	3	4	2	3	3
226Ra	2	4	4	4	4	3	4	2	3	3
228Ra										
228Th										
230Th	2	4	4	4	4	3	4	2	3	3
232Th	2	3	3	3	3	3	3	2	3	3
234U	2	4	4	4	4	3	4	2	3	3
235U	2	3	3	3	3	3	3	2	3	3
235U/238U		1	1	1	1	1	2		1	1
238U	2	4	4	4	4	3	4	2	3	3
2H	12	16	16	16	16	14	16	12	14	16
34S_SO4	3	4	4	4	4	3	4	3	3	3
36Cl			1							
37Cl	3	4	4	4	4	3	4	3	3	3
3H	12	15	15	15	15	14	15	12	13	15
87Sr	3	4	4	4	4	3	4	3	3	3
Al	3	4	4	4	4	3	4	3	3	3
As	3	4	4	4	4	3	4	3	3	3
B	3	4	4	4	4	3	4	3	3	3
Ba	3	4	4	4	4	3	4	3	3	3
Br	24	28	28	28	28	26	28	24	26	30
Ca	22	28	28	28	27	26	28	24	26	30
Cd	3	4	4	4	4	3	4	3	3	3
Ce	3	4	4	4	4	3	4	3	3	3
Cl	24	28	28	28	28	26	28	24	26	30
Co	3	4	4	4	4	3	4	3	3	3
COND	24	28	28	28	28	26	28	24	26	30
Cr	3	4	4	4	4	3	4	3	3	3
Cs	3	4	4	4	4	3	4	3	3	3
Cu	3	4	4	4	4	3	4	3	3	3
DOC	18	19	19	19	19	18	19	18	18	21
Dy	3	4	4	4	4	3	4	3	3	3
EC_field	23	26	28	25	25	24	25	21	25	28
Er	3	4	4	4	4	3	4	3	3	3
Eu	3	4	4	4	4	3	4	3	3	3
F	24	28	28	28	28	26	28	24	26	30
Fe	19	23	23	23	22	21	23	21	21	24
Fe_2+	6	7	7	7	7	6	7	6	6	6
Fe_tot	6	7	7	7	7	6	7	6	6	6
Gd	3	4	4	4	4	3	4	3	3	3
HCO3	24	28	28	28	28	26	28	23	26	30
Hf	3	4	4	4	4	3	4	3	3	3
Hg	3	4	4	4	4	3	4	3	3	3
Ho	3	4	4	4	4	3	4	3	3	3
I	3	4	5	5	4	3	5	3	3	4
In	2	4	4	4	4	2	4	2	3	3
K	22	28	28	28	27	26	28	24	26	30
La	3	4	4	4	4	3	4	3	3	3
Li	22	28	28	28	27	26	28	24	26	30
Lu	3	4	4	4	4	3	4	3	3	3
Mg	22	28	28	28	27	26	28	24	26	30
Mn	19	23	23	23	22	21	23	21	21	24
Mo	3	4	4	4	4	3	4	3	3	3
Na	22	28	28	28	27	26	28	24	26	30
Nb										
Nd	3	4	4	4	4	3	4	3	3	3
NH4N	8	9	9	9	9	8	9	8	8	9
Ni	3	4	4	4	4	3	4	3	3	3
NO23N	7	8	8	8	8	7	8	7	7	7
NO2N	3	4	4	4	4	3	4	3	3	3
NO3N	3	4	4	4	4	3	4	3	3	3
P	3	4	4	4	4	3	4	3	3	3
Pb	3	4	4	4	4	3	4	3	3	3
pH	24	28	28	28	28	26	28	24	26	30
pH_field	24	27	27	27	27	25	27	23	26	29
PO4P	8	9	9	9	9	8	9	8	8	9
PO4P_hlysis	6	6	6	6	6	5	6	6	6	7
Pr	3	4	4	4	4	3	4	3	3	3
Rb	3	4	4	4	4	3	4	3	3	3
S_2-	18	17	19	18	19	18	19	18	18	21
Sb	3	4	4	4	4	3	4	3	3	3
Sc	3	4	4	4	4	3	4	3	3	3
Se										
Si	22	28	28	28	27	26	28	24	26	30
Sm	3	4	4	4	4	3	4	3	3	3
SO4	24	28	28	28	28	26	27	24	26	27
SO4S	22	28	28	28	27	26	27	24	26	30
Sr	22	28	28	28	27	26	28	24	26	30
Tb	3	4	4	4	4	3	4	3	3	3
Th	3	4	5	4	4	3	4	4	4	3
Tl	3	4	4	4	4	3	4	3	3	3
Tm	3	4	4	4	4	3	4	3	3	3
TOC	18	19	19	19	19	18	18	18	18	21
U	3	4	5	4	4	3	4	4	4	3
V	3	4	4	4	4	3	4	3	3	3
Y	3	4	4	4	4	3	4	3	3	3
Yb	3	4	4	4	4	3	4	3	3	3
Zn	3	4	4	4	4	3	4	3	3	3
Zr	3	4	4	4	4	3	4	3	3	3

Cored boreholes (SFK)

IDCODE	KFM01A	KFM01D	KFM01D	KFM02A	KFM02A	KFM02B	KFM02B	KFM03A	KFM03A	KFM03A	KFM04A	KFM06A	KFM06A	KFM06C	KFM06C	KFM07A	KFM08A	KFM08A	KFM08D	KFM08D	KFM10A	KFM11A	KFM11A	KFM12A
CorrSECUP*	109	311	429	411	490	410	491	634	651	969	230	341	738	531	647	963	265	684	660	825	430	446	690	270
CorrSECLOW*	130	321	438	442	518	431	506	650	820	995	245	362	748	540	666	972	280	694	680	835	440	456	710	280
CorrSec**	5	4	2	5	3	4	2	5	4	2	4	5	3	5	3	2	6	2	4	2	2	4	2	3
MonitProg***	y	y	y	y	y	y	y	y	n	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
10B	9	7	7	8	10	2	2	10		9	3	1	4	1			2	7	5	2	8	3	3	1
13C	6	3	3	6	10	2	2	3		2	3	1	1	1			2	4	2	1	5	2	3	1
14C	6	3	3	6	10	2	2	3		2	3	1	1	1			2	3	2	1	4	2	2	1
18O	25	21	21	25	26	11	11	25	1	26	12	13	18	7	6	8	15	21	16	7	22	18	14	10
222Rn	3	2	2	6	8	2	2	8		6	2	1	1	1				4		1	3	2	3	1
226Ra	3	2	2	6	8	2	2	8		6	2	1	1	1				4		1	3	2	3	1
228Ra																								
228Th																								
230Th	3	3	3	8	17	2	2	16	1	5	2							6	1	1	3	3	3	1
232Th	2	3	3	7	15	2	2	14	1	4	2							6	1	1	3	3	3	1
234U	3	3	3	8	17	2	2	16	1	5	2							6	1	1	3	3	3	1
235U	2	3	3	7	15	2	2	14	1	4	2							6	1	1	3	3	3	1
235U/238U	1				3			1		1		1	1	1										
238U	3	3	3	8	17	2	2	16	1	5	2							6	1	1	3	3	3	1
2H	25	21	21	25	26	11	11	25	1	26	12	13	18	7	6	8	15	21	16	7	22	18	14	10
34S_SO4	4	5	5	7	10	2	2	10		6	3	1	2	1			2	6	3	2	5	5	3	1
36Cl										1														
37Cl	4	4	4	5	7	2	2	7		5	3	1	1	1			2	4	2	2	5	5	3	1
3H	25	21	21	25	27	11	11	24	1	25	12	12	18	7	2	8	15	20	16	7	22	18	14	10
87Sr	4	4	4	5	7	2	2	7		6	3	1	1	1			2	4	2	2	5	5	3	1
Al	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
As	8	8	8	9	11	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
B	8	8	8	9	11	3	3	9		9	3	1	4	1			2	7	5	2	8	5	3	1
Ba	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Br	40	33	34	39	47	23	26	37	3	40	24	25	32	23	22	16	29	37	26	7	36	30	26	22
Ca	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Cd	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Ce	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Cl	40	33	36	39	46	23	26	37	3	40	24	25	33	23	22	16	29	37	27	7	36	33	26	22
Co	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
COND	40	33	36	39	47	23	26	37	3	40	24	25	33	23	22	16	29	37	27	7	36	33	26	22
Cr	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Cs	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Cu	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
DOC	29	26	26	30	35	18	18	28	3	30	18	17	22	16	14	10	21	28	22	5	29	24	18	16
Dy	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
EC_field	33	27	27	33	41	22	25	31	3	34	24	24	27	22	19	16	25	29	19	5	30	21	21	20
Er	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Eu	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
F	40	33	36	39	47	23	26	37	3	40	24	25	33	23	22	16	29	37	26	7	36	30	26	22
Fe	37	32	35	36	47	22	25	33	3	36	20	20	29	20	17	15	27	35	25	5	34	27	21	19
Fe_2+	12	10	10	12	15	6	7	13		12	6	5	7	5		1	6	9	8	3	11	12	6	4
Fe_tot	12	10	10	12	15	6	7	13		12	6	5	7	5		1	6	9	8	3	11	12	6	4
Gd	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
HCO3	40	33	36	39	47	23	26	37	3	40	24	25	33	23	22	16	29	37	27	7	36	33	26	22
Hf	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Hg	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Ho	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
I	10	8	8	9	11	3	3	10		10	3	1	4	1			2	7	5	2	8	5	3	1
In	8	8	8	9	11	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
K	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
La	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Li	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Lu	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Mg	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Mn	37	32	35	36	47	22	25	33	3	36	20	20	29	20	17	15	27	35	25	5	34	27	21	19
Mo	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Na	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Nb																								
Nd	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
NH4N	18	16	16	18	25	8	8	18	1	18	8	7	10	7	5	4	11	16	13	5	17	14	8	6
Ni	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
NO23N	18	16	16	17	25	7	7	17	1	17	7	6	10	6	4	4	10	16	13	5	17	9	7	5
NO2N	13	12	12	13	18	3	3	14		13	3	2	5	2		1	6	11	10	5	12	5	3	1
NO3N	13	12	12	13	18	3	3	13		13	3	2	5	2		1	6	11	10	5	12	5	3	1
P	8	7	7	8	16	2	2	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Pb	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
pH	40	33	36	39	47	23	26	37	3	40	24	25	33	23	22	16	29	37	27	7	36	31	26	22
pH_field	34	28	28	33	41	23	26	32	3	34	24	25	27	23	19	16	26	30	20	6	31	23	23	22
PO4P	18	16	16	18	25	8	8	18	1	18	8	7	10	7	5	4	11	16	13	5	17	10	8	6
PO4P_hlysis	16	15	15	16	21	7	7	14	1	15	6	6	9	6	5	4	11	15	13	5	15	6	6	6
Pr	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Rb	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
S_2-	32	27	34	31	41	19	22	28	3	30	18	17	25	17	14	10	24	29	22	5	29	24	18	16
Sb	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Sc	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Se		1																						
Si	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Sm	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
SO4	39	33	33	39	47	23	26	37	3	40	24	25	32	23	21	16	29	37	25	7	36	29	26	22
SO4S	40	33	35	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Sr	40	33	36	39	48	23	26	37	3	40	23	25	33	23	22	16	29	37	27	7	36	30	26	22
Tb	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Th	11	11	11	14	21	3	3	18	1	12	3	2	6	1		1	3	11	8	2	11	6	3	2
Tl	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Tm	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
TOC	29	26	26	30	35	18	18	28	3	30	18	17	22	16	14	10	21	28	22	5	29	18	18	16
U	14	14	14	17	24	3	3	21	1	15	3	2	6	1		1	6	14	11	4	14	6	3	2
V	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Y	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Yb	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Zn	8	8	8	9	18	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1
Zr	8	8	8	9	12	3	3	10		9	3	1	4	1			2	7	5	2	8	5	3	1

Cored boreholes (SFR)

IDCODE	KFR01	KFR01	KFR02	KFR02	KFR02	KFR02	KFR03	KFR03	KFR03	KFR04	KFR04	KFR04	KFR05	KFR08	KFR08	KFR08	KFR101	KFR102A	KFR102A	KFR104	KFR105	KFR106	KFR106	KFR13	KFR13	KFR13	KFR19	KFR19	KFR55	KFR55	KFR55	KFR56	KFR7A	KFR7A	KFR7A
CorrSECUP*	11	45	43	81	119	137	5	45	57	5	28	44	80	6	36	63	280	214	423	333	265	143	260	4	34	54	3	77	8	22	40	9	2	20	48
CorrSECLOW*	44	62	80	118	136	170	44	56	80	27	43	83	96	35	62	104	342	219	443	455	307	259	300	33	53	77	50	95	21	39	48	82	19	47	75
CorrSec**	2	1	4	3	2	1	4	3	2	4	3	2	2	3	2	1	1	5	2	1	1	2	1	3	2	1	4	2	4	3	2	1	3	2	1
MonitProg***	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n
10B		2	1	1	1	1										2	3	2	2		3														2
13C		4	1	1	1	1										2	3	2	2		1								1	1	1				4
14C		3	1	1	1	1										2	3	2	2		1								1	1	1				3
18O	5	39	5	5	5	5	5	5	4	1	5	5	3	5	5	33	13	12	12	6	9	5	5	2	5	5	1	5	5	5	4	5	5	2	41
222Rn		4	1	1	1											1	2	1	1		1														4
226Ra		4	1	1	1											1	2	1	1		1														4
228Ra		1																																	1
228Th		1																																	1
230Th		3	1	1	1	1										2	1	1	1		1	4	3												3
232Th		3	1	1	1	1										2	1	1	1		1	4	4												3
234U		4	1	1	1	1										2	1	1	1		1	4	4												4
235U		3	1	1	1	1										2	1	1	1		1	4	4												3
235U/238U																																			
238U		4	1	1	1	1										2	1	1	1		1	4	4												4
2H	5	37	5	5	5	5	5	5	4	1	5	5	3	5	5	33	13	12	12	6	9	5	5	2	5	5	1	5	5	5	4	5	5	2	39
34S_SO4		2	1	1	1	1										2	4	3	3		3														2
36Cl																1	1				1														1
37Cl		3	1	1	1	1										2	3	2	2		1														2
3H	4	25	4	4	4	3	4	4	2	1	3	4	2	4	4	23	13	11	11	7	9	5	5		4	4		4	4	4	3	4	4	1	27
87Sr		2	1	1	1	1										2	3	2	2		3														2
Al		2	1	1	1	1										2	4	2	2		3														2
As		2	1	1	1	1										2	3	2	2		3														2
B		2	1	1	1	1										2	4	2	2		3														2
Ba		4	1	1	1	1										2	3	2	2		3														3
Br	6	26	7	4	5	8	3	3	4		5	3	1	3	4	16	27	24	24	15	22	15	15	1	3	3		3	3	3	3	4	3		23
Ca	9	65	11	12	6	9	5	5	6		7	4	2	4	5	37	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	57
Cd		2	1	1	1	1										2	4	2	2		3														2
Ce		4	1	1	1	1										2	4	2	2		3														3
Cl	10	65	12	13	7	10	6	6	7	1	8	5	3	5	6	37	27	24	24	15	22	15	15	2	5	5	1	5	5	5	4	6	5	2	57
Co		2	1	1	1	1										2	4	2	2		3														2
COND	7	25	8	2	3	5	3	3	2		3	2		2	3	20	26	24	24	15	22	15	15	1	2	2		2	2	2	2	3	2		41
Cr		2	1	1	1	1										2	4	2	2		3														2
Cs		4	1	1	1	1										2	4	2	2		3														3
Cu		2	1	1	1	1										2	4	2	2		3														2
DOC	1	10	2	2	2	2	1	1	1		1	1	1	1	1	5	14	15	15	9	17	9	9		1	1		1			1	1	1		10
Dy		2	1	1	1	1										2	4	2	2		3														2
EC_field	4	5	4	1	1	4	1	1	1		1	1		1	1	4	23	24	24	12	13	13	13	1	1	1		1	1	1	1	1	1		4
Er		4	1	1	1	1										2	4	2	2		3														3
Eu		4	1	1	1	1										2	4	2	2		3														3
F	8	48	9	9	5	6	4	4	5		6	3	1	3	4	20	27	24	24	15	22	15	15	1	3	3		3	3	3	3	4	3		42
Fe	6	39	7	7	2	5	3	3	3		3	2	1	2	2	25	24	24	24	12	22	15	15	1	2	2		2	2	2	2	2	2		40
Fe_2+	1	17	3	4	3	3	1	1	3		3	1	1	1	1	3	5	6	6		6				1	1		1	1	1	1	1	1		11
Fe_tot	2	17	3	4	3	3	1	1	3		3	1	1	1	1	3	5	6	6		6				1	1		1	1	1	1	1	1		11
Gd		2	1	1	1	1										2	4	2	2		3														2
HCO3	8	64	12	13	7	10	6	6	7	1	8	5	3	4	5	36	27	24	24	15	22	15	15	2	4	4	1	5	4	4	4	5	4	1	57
Hf		2	1	1	1	1										2	4	2	2		3														2
Hg		2	1	1	1	1										2	4	2	2		3														2
Ho		4	1	1	1	1										2	4	2	2		3														3
I		6	1	1	1	1										2	6	6	6	3	5	3	3												5
In		4	1	1	1	1										2	3	2	2		3														3
K	9	61	11	12	6	8	5	5	6		7	4	2	4	5	35	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	54
La		4	1	1	1	1										2	4	2	2		3														3
Li	7	37	7	4	5	7	4	4	3		4	4	2	4	5	33	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	38
Lu		3	1	1	1	1										2	4	2	2		3														3
Mg	9	65	11	12	6	9	5	5	6		7	4	2	4	5	37	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	57
Mn	6	49	8	9	3	7	3	3	5		5	2	1	2	2	25	24	24	24	12	22	15	15	1	2	2		2	2	2	2	2	2		44
Mo		4	1	1	1	1										2	4	2	2		3														2
Na	9	65	11	12	6	9	5	5	6		7	4	2	4	5	37	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	57
Nb																																			
Nd		4	1	1	1	1										2	4	2	2		3														3
NH4N	1	33	6	10	3	4	1	2	4		4	1	1	1	1	3	8	8	8	3	8	3	3		1	1		1			1	1	1		22
Ni		2	1	1	1	1										2	4	2	2		3														2
NO23N		2	2	1	1	1										2	6	7	7	2	7	3	3		1	1									2
NO2N		32	6	9	2	3	1	1	3		3					2	3	2	2		3				1	1									21
NO3N		25	4	7	1	1	1	1	1		1					2	3	2	2		3														19
P		1	1	1	1	1										1	4	2	2		3														1
Pb		2	1	1	1	1										2	4	2	2		3														2
pH	8	36	12	6	7	10	6	6	7	1	7	5	3	4	5	33	27	24	24	15	22	15	15	1	4	4		4	4	4	3	5	4	1	52
pH_field	4	5	4	1	1	4	1	1	1		1	1		1	1	4	23	24	24	12	13	13	13	1	1	1		1	1	1	1	1	1		4
PO4P		32	6	9	2	3	1	1	3		3					2	7	8	8	3	8	3	3		1	1									21
PO4P_hlysis		1	1	1	1	1										1	6	8	8	2	7	3	3												1
Pr		4	1	1	1	1										2	4	2	2		3														3
Rb		4	1	1	1	1										2	4	2	2		3														3
S_2-	5	36	8	9	2	6	2	2	4		4	2	1	2	2	8	6	15	15		18			1	1	1		2	1	1	2	2	2		28
Sb		2	1	1	1	1										2	4	2	2		3														2
Sc		4	1	1	1	1										2	4	2	2		3														3
Se																																			
Si	7	44	8	6	6	9	4	4	5		6	4	2	4	5	34	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	40
Sm		4	1	1	1	1										2	4	2	2		3														3
SO4	8	47	10	11	5	8	4	4	5		6	3	1	3	4	20	27	24	24	15	22	15	15	1	3	3		3	3	3	3	4	3		41
SO4S	7	35	7	4	5	7	4	4	3		4	4	2	4	5	36	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	37
Sr	7	37	7	4	5	7	4	4	3		4	4	2	4	5	34	27	24	24	15	22	15	15	2	4	4	1	4	4	4	4	5	4	1	38
Tb		2	1	1	1	1										2	4	2	2		3														2
Th		5	1	1	1	1										4	4	2	2		6	7	7												6
Tl		4	1	1	1	1										2	4	2	2		3														3
Tm		2	1	1	1	1										2	4	2	2		3														2
TOC		2	1	1	1	1										4	14	15	15	9	17	9	9												4
U		5	1	1	1	1										4	4	2	2		6	7	7												6
V		2	1	1	1	1										2	4	2	2		3														2
Y		4	1	1	1	1										2	4	2	2		3														3
Yb		3	1	1	1	1										2	4	2	2		3														3
Zn		2	1	1	1	1										2	4	2	2		3														2
Zr		2	1	1	1	1										2	4	2	2		3														2

* corrSECUP=upper section limit, corrSECLOW=lower section limit.
** Section number (from bottom).
*** Included in the current monitoring programme (Y=yes, N=no).

Table A3-12. The percentage of the total number of observations that falls below the reporting limit for all objects and parameters for lake groundwater in the bedrock (percussion drilled and cored boreholes) during the period 2002–2014. The colour coding ranges from few (green) to many (red) observations below reporting limits.

Percussion drilled boreholes

IDCODE	HFM01	HFM02	HFM04	HFM13	HFM15	HFM16	HFM19	HFM27
CorrSECUP*	34	38	58	159	85	54	168	46
CorrSECLOW*	46	48	66	176	100	67	185	58
CorrSec**	2	2	2	1	1	2	1	2
MonitProg***	y	y	y	y	y	y	y	y
10B	0	0	0	0	0	0	0	0
13C	0	0	0	0	0	0	0	0
14C	0	0	0	0	0	0	0	0
18O	0	0	0	0	0	0	0	0
222Rn	0	0	0	0	0	0	0	0
226Ra	0	0	0	0	0	33	0	0
228Ra								
228Th								
230Th	0	0	0	0	0	0	25	0
232Th	0	0	0	33	0	0	0	0
234U	0	0	0	0	0	0	0	0
235U	0	0	0	0	0	0	0	0
235U/238U		0	0	0	0	0	0	0
238U	0	0	0	0	0	0	0	0
2H	0	0	0	0	0	0	0	0
34S_SO4	0	0	0	0	0	0	0	0
36Cl			0					
37Cl	0	0	0	0	0	0	0	0
3H	0	0	0	33	0	0	13	0
87Sr	0	0	0	0	0	0	0	0
Al	0	0	0	0	0	0	0	33
As	0	25	0	100	75	0	100	33
B	0	0	0	0	0	0	0	0
Ba	0	0	0	0	0	0	0	0
Br	0	0	29	0	29	0	0	0
Ca	0	0	0	0	0	0	0	0
Cd	100	75	75	100	100	100	75	100
Ce	0	0	0	0	0	0	0	0
Cl	0	0	0	0	0	0	0	0
Co	0	25	0	100	25	0	100	33
COND	0	0	0	0	0	0	0	0
Cr	0	0	0	25	0	0	0	0
Cs	0	0	0	0	0	0	0	0
Cu	33	100	50	100	50	33	100	100
DOC	0	0	0	0	0	0	0	0
Dy	0	0	0	0	0	0	0	0
EC_field	0	0	0	0	0	0	0	0
Er	0	0	0	0	0	0	0	0
Eu	33	75	50	75	50	67	50	100
F	0	0	0	0	0	0	0	0
Fe	0	0	0	0	0	0	0	0
Fe_2+	0	0	0	0	0	0	0	0
Fe_tot	0	0	0	0	0	0	0	0
Gd	0	0	0	0	0	0	0	0
HCO3	0	0	0	0	0	0	0	0
Hf	0	25	0	100	25	0	75	100
Hg	100	100	100	75	100	67	75	100
Ho	0	0	0	0	0	0	50	0
I	0	0	0	0	0	0	20	0
In	100	100	100	100	100	100	100	100
K	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0
Li	0	0	0	0	4	0	0	0
Lu	0	25	0	0	25	0	50	33
Mg	0	0	0	0	0	0	0	0
Mn	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0
Nb								
Nd	0	0	0	0	0	0	0	0
NH4N	0	0	0	0	0	0	0	0
Ni	0	0	0	25	25	0	25	0
NO23N	14	50	38	13	25	43	38	14
NO2N	0	50	75	50	75	67	50	33
NO3N	67	100	100	25	75	33	50	67
P	0	0	0	100	0	0	25	0
P_bio								
Pb	0	50	0	75	0	0	50	67
pH	0	0	0	0	0	0	0	0
pH_field	0	0	0	0	0	0	0	0
PO4P	0	0	0	67	11	0	67	50
PO4P_hlysis	0	0	0	17	0	0	0	0
Pr	0	25	0	0	25	0	50	67
Rb	0	0	0	0	0	0	0	0
S_2-	6	0	0	0	0	17	0	0
Sb	0	25	25	100	50	0	100	100
Sc	67	100	50	100	50	67	100	100
Se								
Si	0	0	0	0	0	0	0	0
Sm	0	0	0	0	0	0	50	0
SO4	0	0	0	0	0	0	0	0
SO4S	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0	0
Tb	0	50	25	0	50	0	50	100
Th	0	100	20	100	50	33	100	100
Tl	100	100	100	100	100	100	100	100
Tm	0	25	0	0	50	0	50	100
TOC	0	0	0	0	0	0	0	0
U	0	0	0	0	0	0	0	0
V	0	0	0	25	0	0	25	0
Y	0	0	0	0	0	0	0	0
Yb	0	0	0	0	0	0	0	0
Zn	0	100	0	75	50	0	100	67
Zr	0	25	0	75	25	33	50	0

Cored boreholes (SFK)

IDCODE	KFM01A	KFM01D	KFM01D	KFM02A	KFM02B	KFM02B	KFM03A	KFM03A	KFM03A	KFM04A	KFM06A	KFM06C	KFM07A	KFM08A	KFM08A	KFM08D	KFM08D	KFM10A	KFM11A	KFM11A
CorrSECUP*	109	311	429	411	410	491	634	651	969	230	341	531	963	265	684	660	825	430	446	690
CorrSECLOW*	130	321	438	442	431	506	650	820	995	245	362	540	972	280	694	680	835	440	456	710
CorrSec**	5	4	2	5	4	2	5	4	2	4	5	5	2	6	2	4	2	2	4	2
MonitProg***	y	y	y	y	y	y	y	n	y	y	y	y	y	y	y	y	y	y	y	y
10B	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
13C	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
14C	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
18O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
222Rn	0	0	0	0	0	0	0		0	0	0	0			0		0	0	0	0
226Ra	0	0	0	0	0	0	0		0	0	0	0			25		0	0	0	0
228Ra																				
228Th																				
230Th	0	0	0	0	0	0	6	0	0	0					0	0	0	0	0	0
232Th	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0	0
234U	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0	0
235U	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0	0
235U/238U	0						0		0		0	0								
238U	0	0	0	0	0	0	0	0	0	0					0	0	0	0	0	0
2H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34S_SO4	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
36Cl									0											
37Cl	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
3H	8	10	5	0	27	36	33	100	72	42	0	0	100	0	35	0	14	27	0	0
87Sr	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Al	0	0	0	0	0	33	0		0	33	0	0		0	0	20	50	25	0	0
As	100	63	75	67	100	100	50		56	100	100	100		100	0	80	100	63	20	67
B	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Ba	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Br	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd	88	88	88	78	100	100	90		89	67	100	100		100	100	100	100	100	100	100
Ce	0	0	0	0	0	0	0		0	0	0	0		0	100	100	100	0	40	33
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Co	25	13	13	0	0	0	80		78	0	0	0		0	43	80	0	88	0	33
COND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cr	13	0	0	44	0	0	0		22	0	0	0		0	29	20	100	0	0	33
Cs	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Cu	88	75	75	33	67	100	90		89	33	0	0		100	86	100	100	100	60	100
DOC	0	0	0	0	0	0	4	0	13	0	0	0	0	0	4	0	0	0	0	6
Dy	0	0	0	0	0	0	100		89	67	0	0		0	100	100	100	0	100	100
EC_field	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Er	0	0	0	0	0	0	100		100	100	0	0		0	100	100	100	0	100	100
Eu	13	88	50	100	100	100	100		89	100	100	100		100	100	100	100	25	100	100
F	0	0	0	3	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fe	0	0	51	0	0	0	0	0	58	0	0	0	93	0	43	16	40	0	26	10
Fe_2+	0	0	0	0	0	0	0		0	0	0	0	100	0	0	0	0	0	17	0
Fe_tot	0	0	0	0	0	0	0		0	0	0	0	100	0	0	0	0	0	0	0
Gd	0	0	0	0	0	0	100		78	67	0	0		0	100	100	100	0	100	67
HCO3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	88	75	75	100	100	67	100		100	100	100	100		100	100	100	100	88	100	100
Hg	100	100	100	89	67	67	100		78	100	100	100		100	100	100	100	100	100	67
Ho	0	25	0	0	0	67	100		100	100	100	100		100	100	100	100	0	100	100
I	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
In	100	100	100	100	100	100	100		100	100	100	100		100	100	100	100	100	100	100
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0		0	0	0	0		0	71	100	100	0	60	33
Li	0	12	19	0	0	0	8	0	8	0	0	0	0	3	41	26	0	0	0	0
Lu	0	75	13	100	33	100	100		100	100	100	100		100	100	100	100	13	80	100
Mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mn	0	0	0	0	0	0	0	0	0	0	0	0	20	0	9	0	0	0	0	0
Mo	0	0	25	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nb																				
Nd	0	0	0	0	0	0	0		0	0	0	0		0	100	100	100	0	60	67
NH4N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ni	13	0	13	22	0	0	50		44	0	0	0		0	43	40	0	38	0	0
NO23N	22	13	13	24	43	0	29	0	12	14	0	17	0	0	19	8	0	18	22	43
NO2N	23	42	25	77	0	0	86		54	33	50	50	100	33	91	60	60	67	100	67
NO3N	15	8	8	38	33	33	31		8	67	0	50	0	0	27	10	0	17	40	67
P	88	0	0	100	100	100	80		100	100	100	100		50	100	100	100	88	100	100
P_bio																				
Pb	88	75	75	89	100	100	80		89	100	0	0		100	86	100	100	88	40	100
pH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pH_field	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PO4P	89	69	31	94	100	100	89	100	83	88	86	86	50	82	81	92	40	88	60	63
PO4P_hlysis	19	0	0	63	29	29	14	100	20	67	17	67	25	9	20	54	0	0	83	33
Pr	0	0	0	0	0	0	80		56	67	0	100		100	100	100	100	0	100	100
Rb	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
S_2-	0	0	0	0	0	0	0	0	0	6	0	0	30	0	3	0	0	0	13	0
Sb	88	63	63	56	100	100	60		0	0	0	0		0	0	0	0	75	0	0
Sc	88	88	88	100	100	100	100		33	100	100	100		100	100	100	100	100	100	67
Se		0																		
Si	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sm	0	0	0	0	0	0	100		78	100	0	100		100	100	100	100	0	80	100
SO4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SO4S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tb	0	75	0	78	0	100	100		100	100	100	100		100	100	100	100	0	100	100
Th	91	82	91	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Tl	100	100	100	100	100	100	100		100	100	100	100		100	100	100	100	100	100	100
Tm	0	75	0	89	0	100	100		100	100	100	100		100	100	100	100	0	100	100
TOC	0	0	0	0	0	0	7	0	13	0	0	0	0	0	4	0	0	0	0	6
U	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
V	0	0	0	22	0	0	40		44	0	0	0		0	43	0	0	0	0	0
Y	0	0	0	0	0	0	0		0	0	0	0		0	0	0	0	0	0	0
Yb	0	0	0	0	0	0	100		100	100	0	0		0	100	100	100	0	100	100
Zn	63	63	38	56	67	67	100		67	0	0	0		0	29	80	0	75	0	67
Zr	50	0	0	56	67	67	100		100	100	0	100		100	100	100	100	25	80	100

Cored boreholes (SFR)

IDCODE	KFR01	KFR01	KFR02	KFR02	KFR02	KFR03	KFR03	KFR04	KFR04	KFR05	KFR08	KFR08	KFR101	KFR102A	KFR102A	KFR104	KFR105	KFR106	KFR106	KFR13	KFR13	KFR19	KFR19	KFR55	KFR55	KFR56	KFR7A	KFR7A
CorrSECUP*	11	45	43	119	137	5	57	5	44	80	36	63	280	214	423	333	265	143	260	34	54	3	77	8	40	9	20	48
CorrSECLOW*	44	62	80	136	170	44	80	27	83	96	62	104	342	219	443	455	307	259	300	53	77	50	95	21	48	82	47	75
CorrSec**	2	1	4	2	1	4	2	4	2	2	2	1	1	5	2	1	1	2	1	2	1	4	2	4	2	1	2	1
MonitProg***	n	n	n	n	n	n	n	n	n	n	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n
10B		0	0	0	0							0	0	0	0		0											0
13C		0	0	0	0							0	0	0	0		0							0	0			0
14C		0	0	0	0							0	0	0	0		0							0	0			0
18O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
222Rn		0	0	0								0	0	0	0		0											0
226Ra		0	0	0								0	0	0	0		0											0
228Ra		0																										0
228Th		0																										0
230Th		33	0	0	0							0	0	0	0		0	0	0									33
232Th		33	0	0	0							0	0	0	0		0	0	0									33
234U		0	0	0	0							0	0	0	0		0	0	0									0
235U		0	0	0	0							0	0	0	0		0	0	0									0
235U/238U																												
238U		0	0	0	0							0	0	0	0		0	0	0									0
2H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34S_SO4		0	0	0	0							0	0	0	0		0											0
36Cl												0	0				0											0
37Cl		0	0	0	0							0	0	0	0		0											0
3H	25	4	0	0	0	0	50	0	0	0	0	0	62	0	45	43	22	0	0	0	0		0	0	0	0	0	7
87Sr		0	0	0	0							0	0	0	0		0											0
Al		0	0	0	0							0	0	0	0		0											0
As		100	100	100	100							100	0	100	50		100											100
B		0	0	0	0							0	0	0	0		0											0
Ba		0	0	0	0							0	0	0	0		0											0
Br	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
Ca	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cd		100	100	100	100							100	75	100	50		100											100
Ce		25	0	0	0							0	0	0	0		0											0
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Co		100	100	100	0							100	0	0	0		33											50
COND	0	0	0	0	0	0	0		0		0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
Cr		0	0	0	0							50	25	0	0		33											0
Cs		0	0	0	0							0	0	0	0		0											0
Cu		100	100	100	100							100	75	50	0		67											100
DOC	0	10	0	0	0	0	0		0	0	0	0	0	0	0	0	24	0	0	0	0		0		0	0		10
Dy		0	0	0	0							0	0	0	0		0											0
EC_field	0	0	0	0	0	0	0		0		0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
Er		50	0	0	0							0	0	0	0		0											0
Eu		100	100	0	100							100	50	0	100		100											100
F	13	2	11	0	0	0	0		33	0	25	0	0	0	0	0	0	0	0	0	0		0	0	0	25		2
Fe	0	0	0	0	0	0	0		0	0	0	0	0	0	0	17	0	0	0	0	0		0	0	0	0		0
Fe_2+	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0			0	0		0	0	0	0		0
Fe_tot	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0			0	0		0	0	0	0		0
Gd		0	0	0	0							0	25	0	0		0											0
HCO3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf		100	100	100	100							100	100	100	100		100											100
Hg		100	100	100	100							100	100	100	100		100											100
Ho		50	0	0	0							0	75	0	100		0											0
I		0	0	0	0							0	0	0	0	0	0	0	0									0
In		100	100	100	100							100	100	100	100		100											100
K	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
La		50	0	0	0							0	25	0	0		0											0
Li	0	0	0	0	0	0	0		0	0	0	0	0	4	0	7	0	0	0	0	0	0	0	0	0	0	0	3
Lu		33	0	0	0							0	100	50	100		33											0
Mg	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mn	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
Mo		0	0	0	0							0	0	0	0		0											0
Na	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nb																												
Nd		50	0	0	0							0	25	0	0		0											0
NH4N	0	3	17	0	0	0	0		0	0	0	0	0	0	0	0	13	0	0	100	0		0		0	0		0
Ni		0	0	0	0							0	0	0	0		0											0
NO23N		50	50	100	0							0	33	29	14	0	0	0	0	100	100							0
NO2N		38	33	100	100	0	67					50	0	100	100		33			100	100							10
NO3N		24	0	100	0	0	0					50	0	0	0		0											63
P		100	100	100	100							100	25	100	100		100											100
P_bio																												
Pb		0	0	0	0							50	75	50	50		67											0
pH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
pH_field	0	0	0	0	0	0	0		0		0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
PO4P		9	33	50	33	0	0					100	43	100	100	100	100	100	67	100	100							10
PO4P_hlysis		100	0	0	100							0	0	75	100	50	86	67	33									0
Pr		100	0	0	100							0	100	0	0		33											33
Rb		0	0	0	0							0	0	0	0		0											0
S_2-	40	44	13	50	67	100	25		50	100	0	50	0	20	47		67			0	100		0	100	100	0		79
Sb		100	0	100	100							100	25	50	50		100											100
Sc		50	100	100	100							100	100	100	100		100											100
Se																												
Si	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sm		50	0	0	0							0	75	0	0		0											0
SO4	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0		0
SO4S	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tb		50	0	0	0							0	100	50	100		33											0
Th		80	100	100	100							100	100	100	100		83	100	100									83
Tl		50	100	100	100							100	100	100	100		100											67
Tm		0	0	0	0							0	100	50	100		33											0
TOC		0	0	0	0							0	0	0	0	0	24	0	0									0
U		0	0	0	0							0	0	0	0		0	0	0									0
V		0	0	0	0							0	0	0	0		67											0
Y		0	0	0	0							0	0	0	0		0											0
Yb		33	0	0	0							0	0	0	0		0											0
Zn		0	100	100	0							100	25	0	0		0											100
Zr		0	0	0	100							0	100	100	100		100											0

* corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Section number (from bottom).

*** Included in the current monitoring programme (Y=yes, N=no).

Table A3-13. The coefficient of variation (CV) expressed in percent for all objects and parameters with at least 5 observations representing a time period longer than one year for groundwater in the bedrock (percussion drilled and cored boreholes). The CV is defined as the ration between the arithmetic standard deviation and the arithmetic mean. The colour coding ranges from low (green) to high (red) variability.

	Percussion drilled boreholes										Cored boreholes (SFK)																							Cored boreholes (SFR)																				
IDCODE	HFM01	HFM02	HFM04	HFM13	HFM15	HFM16	HFM19	HFM21	HFM27	HFM32	KFM01A	KFM01D	KFM01D	KFM02A	KFM02A	KFM02B	KFM02B	KFM03A	KFM03A	KFM04A	KFM06A	KFM06A	KFM06C	KFM06C	KFM07A	KFM08A	KFM08A	KFM08D	KFM08D	KFM10A	KFM11A	KFM11A	KFM12A	KFR01	KFR01	KFR02	KFR02	KFR02	KFR02	KFR03	KFR03	KFR03	KFR04	KFR08	KFR08	KFR101	KFR102A	KFR102A	KFR104	KFR105	KFR106	KFR106	KFR56	KFR7A
CorrSECUP*	34	38	58	159	85	54	168	22	46	26	109	311	429	411	490	410	491	634	969	230	341	738	531	647	963	265	684	660	825	430	446	690	270	11	45	43	81	119	137	5	45	57	28	36	63	280	214	423	333	265	143	260	9	48
CorrSECLOW*	46	48	66	176	100	67	185	32	58	31	130	321	438	442	518	431	506	650	995	245	362	748	540	666	972	280	694	680	835	440	456	710	280	44	62	80	118	136	170	44	56	80	43	62	104	342	219	443	455	307	259	300	82	75
CorrSec**	2	2	2	1	1	2	1	3	2	3	5	4	2	5	3	4	2	5	2	4	5	3	5	3	2	6	2	4	2	2	4	2	3	2	1	4	3	2	1	4	3	2	3	2	1	1	5	2	1	1	2	1	1	1
MonitProg***	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	y	y	y	y	y	y	y	n	n
10B											0	0	0	2	0			0	0								1			0																								
13C											14			11	31																																							
14C											36			29	5																																							
18O	5	6	4	5	10	5	6	5	5	4	6	4	3	4	5	3	3	4	3	7	5	2	6	7	1	5	4	3	6	6	5	8	5		8										5	4	7	7	5	3				4
222Rn														13	32			40	62																																			
226Ra														67	56			77	27																																			
230Th														46	54			105									38																											
232Th														50	73			107									57																											
234U														15	19			26									119																											
235U														24	26			32									115																											
238U														23	19			27									117																											
2H	3	24	2	4	6	2	4	3	4	5	44	4	4	4	4	4	5	3	3	5	4	5	3	3	1	5	4	4	4	5	6	6	3		6										6	3	5	5	5	2				4
34S_SO4														9	6			7	4								5																											
37Cl															160			77																																				
3H	15	21	17	32	26	12	47	18	16	26	19	23	25	38	23	18	20	23	28	41	21	41	19			25	32	20	32	40	40	60	16		73										72		14	33		21				53
87Sr															0			0	0																																			
Al											116	35	42	133	157			80	20								107			48																								
As																											14																											
B											4	7	7	4	5			2	5								2			7																								
Ba											57	13	19	18	10			5	7								6			16																								
Br	54	92	21	8	127	23	15	30	17	11	9	15	12	10	11	11	19	8	7	10	8	17	19	19	7	44	14	7	10	12	22	16	8	5	13	4			11						13	8	18	15	12	16	9	20		11
Ca	46	78	5	4	65	12	11	25	12	8	6	13	14	4	4	3	4	4	5	4	3	5	5	12	6	28	3	8	10	5	6	16	4	39	27	14	10	4	4			14	81		26	9	5	20	10	5	13	28		22
Cd															34																																							
Ce											13	54	26	15	34			14	55											29																								
Cl	41	89	15	3	172	8	8	28	9	4	4	5	6	1	2	1	1	1	2	1	1	2	1	7	2	20	1	5	7	2	5	11	2	16	10	5	6	4	6	8	15	13	5	13	4	6	4	7	4	2	5	14	6	13
Co											59	76	56	19	70																																							
COND	24	56	4	3	94	4	8	12	7	4	4	5	5	1	1	1	1	1	3	1	1	4	6	7	1	17	1	4	6	2	4	9	1	14	10	6									5	4	3	6	5	2	6	12		13
Cr											93	66	101		77			83	130											41																								
Cs											32	15	16	60	7			41	13								11			9																								
Cu														61																																								
DOC	11	10	6	15	20	8	191	28	4	52	166	59	98	43	127	29	12	108	204	12	25	45	20	74	88	32	119	48		22	39	154	24		34											34	16	50	15	80	29	96		33
Dy											8	96	36	24	26															61																								
EC_field	26	56	21	3	102	5	7	15	18	4	6	4	5	5	4	2	2	2	3	20	4	3	2	4	4	15	2	6		3	3	3	2													4	3	6	6	2	4	13		
Er											9	109	46	24	20															58																								
Eu											45																			38																								
F	8	9	7	7	46	5	6	16	10	11	17	14	9	9	10	12	7	14	9	7	6	8	7	10	6	7	5	11	10	11	11	30	24	20	17	14	13		10				13		20	12	6	13	17	6	18	17		18
Fe	47	76	10	17	29	13	11	27	10	8	25	47	107	35	18	8	9	20	86	17	46	42	40	84		22	54	65		29	71	152	17	22	17	14	28								39	11	102	8	32	9	33	34		31
Fe_2+	45	78	5	4	42	23	13	29	16	13	18	44	120	46	12	12	6	24	102	9		55				10	63	68		17	56	105			11												10	5		17				24
Fe_tot	44	77	4	5	42	22	13	28	15	13	17	44	119	44	11	12	7	24	101	9		56				6	61	67		17	73	104			8												10	6		14				24
Gd											11	72	22	18	27															59																								
HCO3	6	10	2	16	12	2	21	5	11	11	26	136	98	7	3	4	6	23	46	6	21	40	12	104	55	18	51	48	86	10	75	95	14	28	21	20	26	12	14	8	6	9	11		3	5	4	45	14	4	19	36		76
Hf																																																						
Hg																																																						
Ho											9	93	32	23																176																								
I											19	41	34	15	16			27	29								15			33					41											16	3	35						
K	21	34	6	6	49	6	9	9	5	6	9	26	29	6	6	8	6	10	14	5	21	12	10	35	10	10	8	14	16	6	10	30	6	14	18	15	15	15	13			27	35		33	21	5	19	11	5	11	28		29
La											16	41	16	19	29			13	38											22																								
Li	20	34	14	9	62	9	11	11	8	9	13	19	12	63	11	13	15	14	12	9	8	10	9	14	11	512	16	12	9	8	11	9	12	9	12	8			11						252	8	8	8	11	8	8	22		10
Lu											12		56																	41																								
Mg	43	75	4	9	91	11	10	24	10	7	9	35	52	4	3	3	2	10	10	5	18	15	6	54	21	12	20	23	37	5	9	76	8	31	31	10	12	9	15			13	10		6	7	4	13	13	5	12	10		20
Mn	49	84	6	7	41	10	8	27	10	6	10	33	55	4	7	3	4	10	40	7	28	28	12	61	50	27	39	23		5	19	88	12	10	14	24	45		29						32	8	140	13	11	5	15	19		28
Mo											34	20	43	15	26			9	11								11			5																								
N_bio																																																						
Na	22	50	5	5	105	4	7	8	6	5	5	5	4	5	4	6	5	4	4	4	5	5	4	6	5	12	6	6	6	5	7	6	5	6	12	8	23	6	9			29	10		5	6	5	4	7	5	7	8		16
Nd											12	62	20	15	33			18	57											47																								
NH4N	37	50	7	5	64	25	37	13	22	8	13	37	128	3	5	4	3	23	121	2	50	20	12			27	12	23		2	49	79	17		78		88									39	9	55		23				37
Ni											56	66	90	46	59																																							
NO23N	103			126	192			74	157		133	172	224	195	313		159	116	149	148	120	62				135	227	155		211	143																	73		128				
NO2N											94	66	46		45				52																78		31																	90
NO3N											130	193	204	212	250			102	153							85	172	167		175					430																			86
P												38	43																																									
Pb																																																						
pH	2	2	1	1	3	2	2	2	1	1	2	3	3	1	2	1	1	2	7	2	2	6	3	6	8	1	7	4	11	2	4	6	3	2	2	5	2	2	2	3	1	5	2		3	1	1	1	2	1	2	1		4
pH_field	3	3	1	3	2	3	3	2	2	2	3	3	4	3	3	3	2	2	7	3	11	6	10	7	7	2	6	4	8	2	5	6	5													4	1	3	4	1	3	2		
PO4P	69	62	13		77	21		65					50																						210		63																	57
PO4P_hlysis	36	15	3		23		14	28	12	42	57	61	52	15	85			44	67			32				28	33	50		15																68								
Pr											13	63	22	19	30															40																								
Rb											4	5	6	57	6			9	5								3			15																								
S_2-	38	33	29	40	31	63	163	127	48	51	104	229	67	71	247	23	281	153	173	118	86	126	171	89	88	240	199	142		46	101	47	109		215	165										45	75	53		72				212
Sb																			120								23																											
Sc																			12																																			
Si	6	6	7	5	11	4	5	7	5	7	6	6	6	6	7	8	7	5	11	5	8	10	6	30	18	14	23	7	37	7	11	11	9	8	12	9	11	13	9				13		13	5	9	9	6	8	6	7		14
Sm											12	66	23	17	25															54																								
SO4	12	49	6	4	115	14	8	11	6	6	15	29	18	4	4	4	5	9	14	5	17	13	6	20	9	26	6	16	10	4	24	37	15	41	24	55	43		35				24		3	13	5	16	14	5	6	27		12
SO4S	14	53	8	4	110	15	7	14	8	8	16	30	20	5	6	6	4	9	13	5	17	6	6	22	8	27	9	16	11	6	6	38	19	4	13	8			17						6	10	7	11	15	5	6	28		6
Sr	48	79	9	6	88	7	12	23	11	9	6	17	18	6	5	6	5	6	4	5	7	6	5	18	6	36	5	10	8	6	7	18	3	13	104	7			5						163	10	17	19	9	3	12	31		92
Tb											10		27																	61																								
Th																																																						
Tl																																																						
Tm											10		51																	51																								
TOC	6	10	6	18	20	4	203	29	7	28	151	50	71	52	14	10	15	29	171	19	25	48	22	84	31	33	119	42		21	32	129	19													38	18	52	25	84	31	98		
U											30	123	78	31	17			32	60			27				38	164	42		25	64																			10	24	42		45
V											25	115	71	41	26			28												55																								
Y											6	89	26	25	16			23	41								21			44																								
Yb											14	112	58	25	23															44																								
Zn															86																																							
Zr												191	178																	173																								

* corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Section number (from bottom).

*** Included in the current monitoring programme (Y=yes, N=no).

Table A3-14. Normalised means for all surface water objects and parameters for groundwater in the bedrock (percussion drilled and cored boreholes). The normalisation is made per parameter based on all chemical data from the surface water in the Forsmark area, including lake water, stream water, precipitation and sea water. The scaling is made per parameter by subtracting the overall mean for all objects, from the individual means for each object, followed by a division by the standard deviation for all objects. This scales the values per parameter to overall zero mean and a unit variance of 1 (the colour coding in the compilation range between –2 and 2, from red to yellow to green, i.e. from low to high values).

	Percussion drilled boreholes										Cored boreholes (SFK)																								Cored boreholes (SFR)																																		
IDCODE	HFM01	HFM02	HFM04	HFM13	HFM15	HFM16	HFM19	HFM21	HFM27	HFM32	KFM01A	KFM01D	KFM01D	KFM02A	KFM02A	KFM02B	KFM02B	KFM03A	KFM03A	KFM03A	KFM04A	KFM06A	KFM06A	KFM06C	KFM06C	KFM07A	KFM08A	KFM08A	KFM08D	KFM08D	KFM10A	KFM11A	KFM11A	KFM12A	KFR01	KFR01	KFR02	KFR02	KFR02	KFR02	KFR03	KFR03	KFR03	KFR04	KFR04	KFR04	KFR05	KFR08	KFR08	KFR08	KFR101	KFR102A	KFR102A	KFR104	KFR105	KFR106	KFR106	KFR13	KFR13	KFR13	KFR19	KFR19	KFR55	KFR55	KFR55	KFR56	KFR7A	KFR7A	KFR7A
CorrSECUP*	34	38	58	159	85	54	168	22	46	26	109	311	429	411	490	410	491	634	651	969	230	341	738	531	647	963	265	684	660	825	430	446	690	270	11	45	43	81	119	137	5	45	57	5	28	44	80	6	36	63	280	214	423	333	265	143	260	4	34	54	3	77	8	22	40	9	2	20	48
CorrSECLOW*	46	48	66	176	100	67	185	32	58	31	130	321	438	442	518	431	506	650	820	995	245	362	748	540	666	972	280	694	680	835	440	456	710	280	44	62	80	118	136	170	44	56	80	27	43	83	96	35	62	104	342	219	443	455	307	259	300	33	53	77	50	95	21	39	48	82	19	47	75
CorrSec**	2	2	2	1	1	2	1	3	2	3	5	4	2	5	3	4	2	5	4	2	4	5	3	5	3	2	6	2	4	2	2	4	2	3	2	1	4	3	2	1	4	3	2	4	3	2	2	3	2	1	1	5	2	1	1	2	1	3	2	1	4	2	4	3	2	1	3	2	1
MonitProg***	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n
10B	-0.3	0.2	0.4	-0.3	-0.2	-0.3	-0.5	0.1	-0.3	-0.7	-0.3	-0.3	-0.2	0.2	-0.2	0.1	-0.7	-0.6		-0.2	-0.1	-0.3	-1.0	-1.3			-0.2	-0.6	-0.1	-0.1	-0.2	-0.4	-0.6	-0.1		-0.4	-0.6	-0.4	-0.2	0.1										0.1	-0.3	-0.5	-0.3		-0.6														-0.2
13C	0.0	-0.4	-0.9	1.0	-0.3	-0.4	0.6	-0.9	0.4	0.6	-0.2	-1.7	-2.2	1.0	1.1	1.0	1.1	-1.0		-1.2	1.3	-0.3	-1.6	-0.3			-1.7	-0.8	-1.2	-2.4	0.7	-1.0	-1.0	-1.5		0.6	-0.9	0.0	-0.7	0.2										1.1	-1.2	0.4	0.3		-0.3								0.1	0.1	0.5				0.7
14C	0.0	0.1	0.2	-0.2	0.0	0.0	0.0	0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.2	-0.2	-0.2	-0.2	0.0		0.1	-0.2	-0.1	0.1	-0.1			0.0	0.0	-0.1	0.1	-0.2	0.1	0.1	-0.1		-0.2	-0.3	-0.3	-0.3	-0.3										0.0	-0.2	-0.2	-0.1		-0.3								-0.2	-0.2	-0.2				-0.1
18O	0.1	-0.1	-0.3	0.5	-0.1	-0.1	0.7	-0.1	0.3	0.7	-0.1	0.1	0.1	0.2	0.7	0.4	0.7	-0.3	-0.4	-1.0	0.5	-0.4	-0.3	-0.1	-0.6	-0.8	-1.0	-0.8	-0.2	-0.4	0.7	-0.4	-0.3	-1.5	0.6	0.2	-1.1	-0.5	0.0	-0.2	-1.1	-1.1	-0.9	0.1	-0.7	0.4	0.7	0.9	0.7	0.9	-1.5	0.1	-0.4	-1.2	-1.1	-0.1	-1.4	-1.2	-0.6	0.3	0.9	0.8	0.1	0.4	0.4	0.9	0.8	0.7	0.6
222Rn	-0.6	-0.6	-0.5	-0.1	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.4	-0.4	-0.1	-0.1	1.1	0.7	-0.3	2.8		-0.7	-0.3	-0.6	-0.6	-0.4				-0.3		-0.5	-0.5	-0.3	-0.3	-0.6		-0.4	1.3	0.4	1.0											-0.4	-0.6	0.2	-0.5		2.4														0.0
226Ra	-0.7	-0.6	-0.7	-0.5	-0.7	-0.7	-0.6	-0.7	-0.5	-0.6	0.0	-0.4	0.1	-0.3	-0.2	-0.1	-0.4	1.9		1.3	-0.5	-0.3	0.1	-0.2				0.2		1.2	-0.4	-0.4	0.4	-0.2		-0.6	0.5	0.3	0.3											-0.5	-0.2	-0.3	-0.5		0.5														-0.6
228Ra																																				-0.1																																	-0.9
228Th																																				-0.5																																	1.2
230Th	-0.1	-0.2	-0.1	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2							-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.1		-0.2	-0.2	-0.2	-0.2	-0.2										-0.1	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2												-0.2
232Th	0.1	-0.6	0.5	-0.4	0.2	-0.2	0.0	-0.6	-0.2	-0.6	0.3	0.0	-0.3	0.5	-0.1	-0.2	-0.5	0.6	-1.1	-0.6	-0.1							-0.1	-0.2	0.4	0.2	0.3	-0.2	0.1		1.3	-0.9	-0.4	-1.0	-0.5										1.0	-0.7	0.1	-0.8		0.4	-0.5	0.6												0.1
234U	-0.4	-0.4	-0.7	-0.1	-0.4	-0.6	-0.6	-0.5	-0.2	0.0	-0.7	-0.7	-0.7	0.6	2.5	0.5	-0.5	-0.2	-0.3	-0.8	-0.1							-0.7	-0.7	-0.8	-0.6	-0.8	-0.7	0.7		-0.5	0.2	-0.1	-0.2	-0.2										-0.5	1.6	-0.5	-0.2		1.2	0.3	-0.3												-0.3
235U	-0.2	-0.3	-0.7	-0.3	-0.3	-0.6	-0.6	-0.6	-0.2	-0.1	-0.7	-0.7	-0.8	0.2	2.4	-0.2	-0.5	0.2	0.0	-0.8	-0.1							-0.7	-0.7	-0.8	-0.6	-0.8	-0.7	0.3		-0.6	-0.3	-0.3	-0.4	-0.3										-0.7	1.3	-0.6	-0.1		0.4	0.1	-0.1												-0.5
235U/238U		0.2	1.0	0.0	-0.5	1.5	-0.2		-0.2	0.3	-0.9				-0.1			0.0		1.4		-0.4	-2.4	-0.9																																													
238U	-0.3	-0.3	-0.6	-0.3	-0.3	-0.5	-0.5	-0.5	-0.2	-0.1	-0.6	-0.7	-0.7	0.2	2.7	-0.2	-0.4	0.2	0.0	-0.7	-0.2							-0.6	-0.6	-0.7	-0.6	-0.7	-0.6	0.4		-0.6	-0.3	-0.3	-0.4	-0.3										-0.5	0.9	-0.5	-0.1		0.2	0.1	-0.1												-0.5
2H	0.2	0.2	-0.3	0.6	-0.3	-0.1	0.9	-0.2	0.5	0.9	0.2	0.3	0.5	0.3	1.0	0.7	1.2	-0.3	-0.4	-1.3	0.7	-0.6	-0.2	-0.2	-0.9	-0.6	-1.3	-0.8	0.0	-0.1	1.0	-0.6	-0.3	-2.3	0.5	0.1	-2.1	-1.1	-0.6	-1.0	-2.1	-2.1	-1.8	-0.2	-1.6	0.1	0.6	0.9	0.7	1.0	-2.2	0.1	-0.7	-1.7	-1.8	-0.2	-2.0	-2.2	-1.6	-0.2	1.0	0.7	-0.3	0.1	0.1	1.0	0.6	0.6	0.6
34S_SO4	-1.4	-0.6	-1.4	-0.1	-0.2	-2.1	0.0	-2.7	-0.1	0.5	-0.2	0.7	2.8	-0.2	0.0	0.0	0.0	0.3		1.1	-0.1	0.5	0.8	0.2			1.9	1.0	0.8	0.7	0.0	0.2	2.6	0.7		-0.2	0.3	0.3	0.2	0.1										-0.5	0.3	-1.4	-1.2		-0.1														-0.3
36Cl			-0.7																	-0.7																																0.6	1.8				1.6														0.4
37Cl	0.5	0.3	1.0	0.2	-0.3	1.0	0.4	0.7	0.4	0.9	-0.3	-0.6	-0.4	-0.6	-0.6	-0.1	0.0	0.4		0.5	0.0	-0.2	0.1	0.1			-1.2	-0.7	-2.4	0.5	-1.4	0.3	0.1	0.2		0.2	0.1	0.2	0.0	-0.1										-0.6	0.4	-0.6	0.6		0.3														0.5
3H	0.0	0.1	0.1	-0.2	0.1	0.0	-0.2	0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0.3	0.3	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.2	1.2	0.0	0.1	0.5	0.7	0.6	0.6	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	-0.2		-0.1	-0.1		0.7	0.1	0.1	0.0	0.7	0.2	0.2	0.1
87Sr	3.0	2.3	0.2	-0.5	1.4	0.1	1.2	3.0	2.0	3.0	0.5	0.8	0.7	-1.1	-0.3	-0.6	-0.2	-0.6		-0.4	-0.6	-0.7	-0.6	-0.6			-0.3	-0.4	-0.2	-0.5	0.0	-1.1	-0.7	-0.9		-1.0	-1.1	-1.0	-1.0	-1.0										-0.9	-1.0	-1.0	-0.9		-1.0														-1.0
Al	-0.3	-0.3	-0.2	-0.1	-0.3	-0.3	-0.3	-0.2	0.1	-0.1	-0.2	-0.3	-0.2	0.0	0.0	-0.2	-0.3	-0.2		-0.1	-0.2	-0.2	-0.3	-0.3			-0.3	-0.2	-0.2	-0.3	-0.2	-0.1	0.3	-0.2		-0.2	-0.3	-0.2	-0.1	0.2										-0.1	-0.1	-0.1	0.1		0.3														-0.2
As	-0.5	-0.6	-0.5		-0.6	0.3		-0.5	-0.3	0.3		-0.4	-0.5	-0.1				1.6		0.1			0.0					0.4	-0.2		-0.1	-0.3	-0.2	0.7																	0.2		-0.4																	
B	-1.5	-2.0	-2.7	-0.7	-2.1	-2.0	-1.1	-2.6	-1.6	-0.2	0.4	0.1	0.1	-0.3	-0.4	-0.2	-0.3	1.8		1.1	-0.7	1.3	0.6	1.8			0.8	0.1	-0.2	0.2	0.2	1.8	0.8	0.8		0.2	1.4	0.6	0.4	0.1										-0.7	0.8	1.3	0.8		1.5														-0.6
Ba	-0.6	-0.5	-0.7	-0.6	-0.6	-0.7	-0.6	-0.7	-0.6	-0.6	-0.3	0.4	0.8	-0.5	-0.5	-0.5	-0.5	-0.3		2.0	-0.5	-0.2	0.1	-0.5			1.1	0.2	0.2	0.2	-0.5	-0.5	-0.2	0.4		-0.6	-0.4	-0.4	-0.3	-0.4										-0.7	0.7	-0.4	-0.5		-0.3														-0.7
Br	-0.9	-0.9	-1.0	-0.1	-0.9	-0.9	-0.3	-0.9	-0.7	-0.5	-0.4	0.0	0.1	-0.1	-0.2	-0.2	-0.3	0.3	0.2	2.7	0.0	0.1	0.7	-0.1	0.3	4.1	0.0	0.8	0.5	1.0	-0.2	-0.1	0.9	-0.1	-0.6	-0.5	-0.4	-0.4	-0.3	-0.4	-0.5	-0.4	-0.4		-0.4	-0.4	-0.5	-0.6	-0.6	-0.6	-0.6	-0.4	-0.3	-0.5	-0.5	-0.4	-0.5	-0.4	-0.4	-0.3		-0.6	-0.4	-0.4	-0.4	-0.6	-0.5		-0.4
Ca	-1.0	-1.0	-1.0	0.1	-1.0	-1.0	-0.2	-1.0	-0.7	-0.6	-0.4	-0.1	0.1	0.1	-0.2	0.0	-0.2	0.4	0.4	2.6	0.3	0.1	0.9	0.1	0.4	4.1	0.0	0.9	0.5	1.0	0.0	0.3	0.9	0.0	-0.6	-0.3	-0.2	-0.1	0.0	0.0	-0.3	-0.1	-0.2		0.2	-0.4	-0.6	-0.8	-0.7	-0.7	-0.7	-0.4	-0.1	-0.6	-0.4	-0.4	-0.6	-0.2	-0.1	-0.3	-0.8	-0.8	-0.3	-0.4	-0.4	-0.8	-0.7	-0.4	-0.2
Cd		-0.9	-0.9				-0.5	-0.9		-0.5	-0.6	-0.5	-0.6	0.3	0.2			1.4		0.3	4.8																														-0.4		-0.7															
Ce	-0.6	-0.7	-0.5	0.8	-0.6	-0.7	-0.6	-0.5	-0.6	-0.7	1.1	1.2	2.7	0.2	1.0	1.0	0.1	-0.3		0.0	-0.5	-0.4	-0.3	-0.7			-0.6				-0.2	-0.7	-0.6	-0.6		-0.7	-0.2	-0.3	-0.1	-0.6										-0.6	-0.7	-0.3	-0.6		-0.5														-0.6
Cl	-1.5	-1.5	-1.7	0.3	-1.6	-1.6	0.2	-1.6	-0.8	-0.2	-0.2	0.0	0.1	0.4	0.4	0.4	0.4	0.5	0.5	2.3	0.6	0.1	0.8	0.2	0.3	3.7	-0.1	0.7	0.4	0.8	0.4	0.1	0.9	-0.3	-0.5	-0.2	-0.3	-0.1	0.1	-0.1	-0.4	-0.3	-0.3	-0.4	-0.3	-0.1	-0.2	-0.6	-0.6	-0.5	-0.9	-0.2	-0.1	-0.8	-0.4	-0.1	-0.7	-0.2	-0.2	-0.1	-0.6	-0.7	-0.2	-0.1	-0.2	-0.6	-0.3	0.0	0.1
Co	-0.3	-0.4	-0.4		-0.4	-0.4		-0.4	-0.4	-0.3	-0.4	-0.4	-0.3	0.0	0.1	-0.1	0.3	-0.4		0.1	5.3	1.1		-0.1			-0.4	-0.3	-0.4	-0.3	-0.4	-0.3	-0.3	0.2						-0.4											-0.1	-0.3	0.1		-0.4														-0.4
COND	-1.5	-1.6	-1.7	0.3	-1.6	-1.7	0.3	-1.7	-0.8	-0.2	-0.2	-0.1	0.1	0.4	0.4	0.4	0.4	0.4	0.5	2.0	0.6	0.0	0.7	0.2	0.2	3.3	-0.2	0.6	0.4	0.8	0.4	0.0	0.8	-0.4	-0.5	-0.3	-0.4	-0.1	0.0	0.0	-0.5	-0.3	-0.3		-0.2	-0.1		-0.6	-0.6	-0.5	-1.0	-0.1	-0.2	-0.9	-0.4	-0.1	-0.7	-0.2	-0.2	-0.1		-0.6	-0.2	-0.1	-0.2	-0.6	-0.4		0.0
COND_sel																																-1.0																																					
Cr	0.2	-0.2	-0.1	-0.2	0.1	-0.2	-0.1	-0.2	-0.1	-0.1	-0.1	0.0	0.3	-0.1	-0.1	-0.1	-0.1	-0.1		0.0	0.4	-0.2	-0.2	-0.2			-0.1	-0.1	-0.2		-0.2	-0.2	0.4	-0.2		-0.2	0.0	-0.3	-0.2	-0.2										-0.3	-0.2	-0.1	0.2		-0.3														-0.2
Cs	-0.2	-0.2	-0.2	-0.2	3.6	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	3.1	-0.2	-0.1	-0.2	-0.1		-0.2	-0.2	-0.2	-0.2	-0.2			-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2	-0.2	-0.2										-0.2	-0.2	-0.2	-0.2		-0.2														-0.2
Cu	-0.4		-0.8		-0.7	-0.7					-0.2	-0.7	-0.7	0.1	-0.5	-0.5		-0.5		0.0	0.1	-0.1	0.0	-0.2				-0.5				-0.4		-0.7				-0.7													-0.5	0.5	-0.4		0.7															
DOC	1.8	1.8	1.5	-0.4	2.6	2.6	0.2	1.2	0.5	0.3	0.1	-0.1	0.2	-0.4	-0.2	-0.4	-0.4	-0.4	-0.6	-0.5	-0.5	-0.4	-0.3	-0.4	-0.4	-0.6	-0.3	-0.5	-0.3	-0.3	-0.3	-0.5	-0.6	-0.6	-0.4	-0.4	-0.3	-0.3	-0.4	-0.4	-0.6	-0.5	-0.3		0.5	-0.2	0.2	-0.2	-0.3	-0.4	-0.5	-0.5	-0.6	-0.6	-0.6	-0.4	0.4		-0.4	-0.5		-0.2			0.0	-0.3	-0.1		-0.4
Dy	0.4	-0.4	-0.3	0.5	-0.3	-0.4	2.4	-0.2	-0.4	-0.4	0.3	-0.4	-0.1	-0.2	-0.3	0.1	-0.3			-0.4	-0.4	-0.4		-0.4			-0.4				2.0			-0.4		-0.3	-0.1	0.1	0.2	-0.3										-0.1	-0.4	-0.3	-0.4		-0.3														-0.1
EC_field	-1.5	-1.6	-1.8	0.4	-1.7	-1.7	0.3	-1.7	-0.7	-0.2	-0.1	0.0	0.1	0.4	0.5	0.4	0.5	0.5	0.4	2.1	0.5	0.1	0.7	0.2	0.3	3.4	-0.2	0.7	0.4	0.7	0.5	0.1	0.9	-0.4	-0.6	-0.4	-0.3	0.1	0.1	0.1	-0.5	-0.3	-0.1		-0.3	0.0		-0.6	-0.6	-0.5	-1.0	-0.1	-0.1	-0.8	-0.4	-0.1	-0.7	-0.1	-0.1	0.0		-0.6	-0.2	-0.1	-0.1	-0.5	-0.4		-0.3
Er	0.6	-0.5	-0.4	1.6	-0.4	-0.6	0.0	-0.1	-0.5	-0.7	1.0	-0.6	0.0	-0.2	-0.5	0.4	-0.5					-0.7		-0.7			-0.7				2.8			-0.6		-0.2	0.0	0.7	0.8	-0.1										0.2	-0.7	-0.4	-0.6		-0.4														0.3
Eu	5.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2			-0.2	-0.2	-0.2							-0.1											-0.1							-0.2	-0.2												-0.2	-0.2																		
F	2.9	1.4	1.5	-0.3	-1.0	2.9	-0.4	0.5	0.2	-0.2	0.6	1.0	-0.3	0.0	0.5	0.6	0.6	0.6	0.5	0.1	-0.7	-0.2	-0.1	-0.9	-0.4	0.0	-0.3	-0.2	-0.4	-0.7	0.2	-0.5	-0.1	-1.2	-0.7	-0.9	-0.8	-0.9	-0.6	-0.5	-0.6	-1.0	-0.9		-0.5	0.0	-0.8	-0.6	-0.3	-0.1	0.5	-0.1	0.1	0.3	-0.3	0.3	0.6	-0.4	-0.5	0.0		0.2	-0.3	-0.5	-0.2	-0.9	0.7		-0.3
Fe	-0.6	-0.5	-0.6	0.9	0.0	-0.6	1.5	-0.4	0.3	1.0	-0.6	-0.2	-0.7	-0.4	0.1	0.2	1.1	-0.5	-0.5	-0.6	0.2	-0.3	-0.6	-0.5	-0.6	-0.7	-0.2	-0.6	-0.6	-0.6	1.8	-0.6	-0.5	-0.6	-0.5	-0.5	-0.6	-0.4	0.0	0.4	-0.1	-0.1	-0.1		-0.4	-0.1	0.1	-0.5	-0.5	-0.1	-0.6	-0.3	-0.3	-0.7	-0.4	-0.2	-0.5	0.4	-0.3	0.0		-0.5	-0.2	-0.2	-0.1	-0.5	0.5		1.5
Fe_2+	-0.5	-0.4	-0.6	1.3	0.1	-0.6	1.9	-0.4	0.6	1.2	-0.6	0.1	-0.8	-0.4	0.3	0.6	1.6	-0.5		-0.6	0.5	-0.1	-0.6	-0.5			-0.1	-0.7	-0.6	-0.7	2.5	-0.7	-0.2	-0.7	-0.6	-0.6	-0.6	-0.4	0.1	-0.3	0.0	0.2	-0.1		-0.4	0.1	0.3	-0.5	-0.5	0.3	-0.7	-0.4	-0.3		-0.5				0.0	0.3		-0.5	0.0	-0.4	0.0	-0.5	1.4		1.9
Fe_tot	-0.5	-0.4	-0.6	1.3	0.1	-0.6	2.0	-0.4	0.6	1.3	-0.6	0.1	-0.8	-0.4	0.3	0.6	1.6	-0.4		-0.6	0.5	-0.1	-0.6	-0.5			-0.1	-0.7	-0.6	-0.7	2.5	-0.7	-0.2	-0.7	-0.6	-0.6	-0.5	-0.4	0.1	-0.3	0.0	0.2	-0.1		-0.4	0.1	0.4	-0.5	-0.5	0.3	-0.7	-0.4	-0.3		-0.4				0.0	0.3		-0.5	0.0	-0.4	0.0	-0.5	1.4		2.0
Gd	0.2	-0.5	-0.4	0.7	-0.4	-0.5	-0.1	-0.3	-0.5	-0.6	0.6	-0.3	0.4	-0.2	-0.3	0.3	-0.4			-0.5	-0.5	-0.6		-0.6			-0.6				3.2		-0.5	-0.5		-0.4	-0.1	0.1	0.2	-0.4										-0.2	-0.6	-0.3	-0.5		-0.4														-0.3
HCO3	2.6	2.2	2.1	-0.1	2.6	2.6	0.1	2.7	1.2	0.6	-0.2	-0.7	-0.6	-0.2	0.0	-0.1	0.0	-0.8	-0.9	-0.9	-0.2	-0.7	-0.9	-0.5	-0.7	-0.8	-0.4	-0.8	-0.7	-0.8	-0.2	-0.9	-0.8	-0.6	-0.1	-0.3	-0.6	-0.5	-0.4	-0.4	-0.5	-0.5	-0.5	-0.2	-0.4	-0.1	-0.1	0.0	0.0	-0.1	-0.5	-0.2	-0.6	-0.8	-0.3	-0.2	-0.2	-0.5	-0.4	-0.3	-0.1	-0.1	-0.2	-0.1	-0.2	0.0	-0.1	-0.1	-0.1
Hf	-0.3	-0.4	-0.3		-0.3	-0.3	-0.4	-0.3			-0.4	1.4	0.2				-0.4														4.4																																						
Hg				-0.5		-0.5	-0.5			-0.1				-0.5	-0.6	-0.6	-0.6			0.9													2.7																																					
Ho	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2	-0.1	-0.1	-0.2		-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.2														1.8			-0.2		-0.1	-0.1	-0.1	-0.1	-0.1										-0.1	-0.2	-0.2			-0.2														-0.1
I	-0.5	-0.5	-0.5	-0.3	-0.4	-0.5	-0.4	-0.5	-0.4	-0.3	-0.3	0.0	0.0	-0.1	-0.1	0.9	10.3	0.0		0.8	-0.2	0.0	0.1	-0.2			0.3	0.5	0.1	0.5	-0.4	-0.2	-0.1	0.0		-0.3	-0.1	0.0	0.1	0.2										-0.4	-0.1	-0.1	-0.2	-0.1	-0.3	-0.3	-0.2												0.1
In																																																																					
K	-0.2	-0.2	-0.9	0.4	-0.5	-0.9	2.5	-0.4	1.4	3.6	0.2	-0.2	-0.4	0.4	1.6	0.7	1.8	0.0	-0.1	-0.7	0.6	-0.4	-0.6	-0.2	-0.7	-0.4	-0.1	-0.5	-0.4	-0.6	1.0	-1.0	-0.5	-0.9	-0.6	-0.8	-1.0	-0.9	-0.9	-0.9	-0.8	-0.8	-0.9		-0.9	-0.6	-0.1	0.2	-0.8	0.0	-1.0	-0.7	-0.7	-1.1	-0.9	-0.1	-0.4	-1.0	-1.0	-0.6	-0.7	-0.5	-0.7	-0.6	-0.6	0.5	0.4	-0.3	-0.1
La	-0.7	-0.8	-0.7	0.5	-0.7	-0.8	-0.7	-0.7	-0.7	-0.7	1.0	1.6	3.0	0.2	0.9	0.9	0.1	-0.1		0.3	-0.4	-0.4	-0.2	-0.7			-0.7	-0.7			-0.3	-0.7	-0.6	-0.6		-0.6	-0.4	-0.5	-0.3	-0.7										-0.7	-0.7	-0.4	-0.7		-0.5														-0.7
Li	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	1.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.6	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0		0.0	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	0.0	-0.1	-0.1	0.0	-0.1	-0.1	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.1	0.0
Lu	-0.4	-0.8	-0.6	2.3	0.1	-1.1	1.2	0.2	-1.0		0.5	-0.8	-0.7		0.6	0.0															0.8	1.6				-0.5	-0.5	0.9	1.0	-0.3										0.0		-1.0			-0.7														0.3
Mg	-1.0	-1.0	-1.2	1.3	-1.0	-1.2	1.6	-1.1	0.0	0.7	0.2	-0.7	-0.8	1.2	1.6	1.4	1.7	-0.5	-0.6	-1.2	1.6	-0.6	-1.0	-0.2	-0.8	-1.0	-0.7	-1.1	-0.9	-1.1	1.3	-0.9	-0.8	-0.8	0.3	0.5	-0.2	0.1	0.5	0.4	0.0	0.0	0.0		0.1	0.5	0.6	0.4	0.1	0.3	-0.9	0.2	-0.2	-1.0	-0.1	0.8	-0.4	-0.2	-0.2	0.4	0.2	0.2	0.3	0.5	0.5	0.4	0.7	1.2	1.5
Mn	-0.9	-0.9	-0.9	1.7	-0.6	-0.9	1.1	-0.8	-0.2	-0.1	-0.3	-0.5	-0.8	1.0	1.4	1.3	1.3	-0.6	-0.6	-1.0	2.5	-0.6	-0.7	-0.2	-0.8	-0.9	-0.4	-0.9	-0.8	-0.9	0.7	-0.9	-0.8	-0.5	0.0	-0.3	-0.5	-0.4	0.3	0.3	0.6	0.9	1.1		1.1	0.3	0.2	-0.2	-0.2	0.0	-0.4	0.1	-0.3	-0.8	0.7	0.3	-0.5	-0.2	-0.4	0.2		0.0	0.1	0.2	0.2	-0.5	0.2		1.4
Mo	-0.3	-0.3	-0.4	-0.4	-0.3	-0.1	-0.4	-0.3	-0.3	-0.2	-0.1	-0.4	-0.4	-0.1	0.6	-0.3	-0.3	0.0		-0.3	0.0	2.9	7.1	0.4			-0.3	0.0	0.0	0.0	-0.4	-0.2	0.0	-0.1		-0.4	-0.4	-0.4	-0.4	-0.3										-0.4	-0.2	-0.3	-0.3		-0.4														-0.3
Na	-1.7	-1.9	-2.2	0.5	-2.1	-2.1	0.8	-2.1	-0.7	0.5	0.2	0.0	0.1	0.7	1.1	0.9	1.2	0.6	0.5	1.1	0.7	0.0	0.4	0.3	-0.1	2.3	-0.3	0.2	0.1	0.5	0.9	-0.2	0.6	-0.9	-0.3	0.1	-0.6	0.0	-0.1	-0.2	-0.8	-0.7	-0.8		-0.4	0.4	0.3	-0.2	-0.4	0.0	-1.2	0.3	-0.1	-1.0	-0.4	0.3	-0.8	-0.4	-0.3	0.3	-0.1	-0.1	0.1	0.4	0.2	-0.2	0.3	0.5	0.6
Nb																																																																					
Nd	-0.5	-0.7	-0.6	1.1	-0.6	-0.8	-0.6	-0.5	-0.7	-0.8	1.4	0.7	2.9	0.0	0.2	0.9	-0.2	-0.5		-0.4	-0.6	-0.6	-0.6	-0.8			-0.7				0.7	-0.8	-0.6	-0.7		-0.1	0.0	0.0	0.1	-0.7										-0.3	-0.8	-0.2	-0.6		-0.5														-0.3
NH4N	0.1	0.0	-0.2	1.0	0.2	0.0	1.7	-0.2	1.1	1.8	0.3	-0.2	-0.3	1.3	2.5	1.8	2.6	-0.5	-0.6	-0.7	1.1	-0.4	-0.5	-0.2	-0.6	-0.8	-0.3	-0.7	-0.5	-0.6	0.9	-0.7	-0.4	-0.7	-0.4	-0.6	-0.7	-0.6	-0.8	-0.8	0.2	-0.2	-0.5		-0.7	-0.6	-0.5	-0.5	-0.6	-0.4	-0.7	-0.7	-0.6	-0.8	-0.8	-0.5	-0.7			-0.6		-0.7			-0.7	-0.5	-0.4		-0.4
Ni	0.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.2		0.2	-0.1	-0.2	-0.2	-0.1			-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2	-0.2	-0.2										-0.2	-0.1	-0.2	-0.1		-0.1														-0.2
NO23N	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	-0.2	0.1	0.0	-0.2	0.0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.2	-0.2	-0.1	-0.1	1.7	1.3	-0.2	-0.1	0.7	-0.2	-0.2	-0.2		-0.2	-0.2			-0.2										-0.2	-0.2	0.3	-0.2	0.3	-0.2	-0.2	-0.1												-0.2
NO2N	0.3	-0.4	-0.4	-0.6	-0.3	-0.4	-0.5	-0.5	-0.4	-0.5	-0.4	-0.5	-0.5	-0.2	-0.5	-0.5	-0.5	0.1		-0.4	-0.1	0.0	-0.6	-0.4			2.1	-0.6	-0.1	-0.6	-0.4		-0.6			0.3	0.3	0.2			0.1	0.1	0.1		0.1					-0.3	-0.6				-0.4														0.9
NO3N	-0.2			-0.2	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2		-0.1	-0.2	-0.2	-0.2	-0.1		-0.2	0.9	0.7	-0.1	-0.1	0.3	-0.2	-0.1	-0.2		0.6	-0.2	-0.2		-0.2	-0.2	-0.2	-0.2		-0.2					-0.2	-0.2	0.3	-0.2		-0.2														-0.2
P	1.7	0.6	0.2		-0.1	2.9	-0.7	0.4	-0.3	-0.7	-1.0	0.0	-0.6					-1.0									-0.8				-0.8																				-0.6																		
Pb	-0.3	-0.2	-0.3	0.2	-0.2	-0.3	-0.1	-0.3	-0.1	-0.2	-0.2	-0.3	-0.3	-0.1	0.4			0.3		0.4		-0.2	-0.1	-0.2				0.2			-0.2	-0.2		-0.2		-0.1	-0.3	-0.3	-0.2	-0.2										-0.1	-0.3	-0.3	-0.2		-0.1														-0.1
pH	0.6	0.3	0.4	-0.5	-0.9	0.7	-0.6	0.1	-0.3	-0.7	0.2	-0.4	0.0	-0.4	-0.5	-0.3	-0.4	-0.3	-0.1	0.0	-0.6	0.1	0.4	0.1	0.8	3.3	0.2	2.6	0.7	2.2	-0.3	0.4	1.0	0.1	-0.3	-0.2	-0.1	-0.3	-0.4	-0.4	-0.5	-0.4	-0.6	-0.5	-0.5	-0.3	-0.3	-0.1	-0.1	-0.2	0.3	0.1	-0.2	0.2	0.0	-0.1	0.3	-0.1	-0.1	-0.3		-0.1	-0.2	-0.3	-0.3	0.0	-0.4	-0.9	-0.7
pH_field	0.4	0.0	0.0	-0.6	-1.0	0.2	-0.7	-0.2	-0.4	-1.0	0.0	-0.1	0.1	-0.6	-0.7	-0.5	-0.6	-0.2	0.2	0.1	-0.9	-0.3	0.6	-0.5	0.8	3.3	0.2	2.4	0.8	2.0	0.0	0.7	1.2	-0.1	-0.5	-0.4	-0.3	-0.1	-0.2	-0.5	-0.1	-0.1	-0.3		-0.4	-0.1		-0.4	-0.4	-0.4	-0.2	-0.1	-0.3	-0.3	-0.2	-0.5	0.0	-0.2	0.2	-0.1		0.2	-0.1	-0.5	0.1	0.0	-0.2		-0.6
PO4P	1.5	0.6	0.2	-0.6	-0.3	2.9	-0.5	0.0	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.6			-0.5		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6			0.2	-0.2	0.1	-0.5	-0.3	-0.1	-0.1	-0.4		0.1						-0.5						-0.6												0.4
PO4P_bio																																																																					
PO4P_hlysis	3.7	2.2	0.9	-0.4	0.3	4.4	-0.1	0.8	0.5	-0.1	-0.4	0.0	-0.3	-0.4	-0.4	-0.4	-0.4	-0.4		-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	-0.4	-0.4	-0.4	-0.3	-0.4	-0.4				-0.4		-0.4										-0.4	-0.3	-0.4		-0.4	-0.4	-0.4	-0.4												-0.4
Pr	-0.7	-0.9	-0.8	0.6	-0.7	-0.9	-0.8	-0.7	-0.8		0.9	0.7	2.3	-0.1	0.1	0.6	-0.4	-0.6		-0.1	-0.4	-0.7									-0.2						-0.4	-0.4	-0.2											-0.8		-0.5	-0.8		-0.7														-0.8
Rb	-0.3	-0.3	-0.3	-0.1	-0.3	-0.3	-0.1	-0.3	-0.2	-0.2	-0.1	-0.1	0.0	4.7	0.0	0.1	0.0	-0.1		-0.2	-0.1	-0.2	-0.2	-0.2			-0.2	-0.2	-0.2	-0.2	0.0	-0.3	-0.2	-0.3		-0.3	-0.3	-0.3	-0.3	-0.3										-0.3	-0.3	-0.2	-0.2		-0.3														-0.2
S_2-	-0.2	-0.3	-0.3	-0.3	-0.1	-0.3	-0.1	-0.2	-0.3	-0.2	0.2	0.2	3.1	0.0	0.0	-0.3	-0.2	0.0	-0.2	0.0	-0.1	-0.1	0.1	0.1	0.2	-0.3	-0.1	-0.3	0.1	0.0	-0.3	-0.1	-0.1	-0.1	-0.3	-0.3	0.2	-0.3	-0.3	-0.3		-0.3	-0.2		-0.3	-0.3		-0.3	-0.3	0.9	-0.3	-0.3	-0.3		-0.3			-0.3	-0.3			-0.2				-0.3			-0.3
Sb	-0.1	-0.1	-0.1		-0.1	-0.1		-0.1			-0.1	-0.1	-0.1	-0.1	-0.1			-0.1		-0.1	-0.1	-0.1	-0.1	-0.1			-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0			-0.1														-0.1	-0.1	-0.1															
Sc	-1.2		-1.2		-1.2	-1.2					-1.1	-1.2	-1.1							0.2													0.0			-1.3																																
Se																																																																					
Si	0.0	0.1	0.2	0.6	1.0	0.0	0.1	0.5	0.1	-0.2	1.2	2.7	3.0	0.7	0.3	1.1	0.9	0.4	-0.1	-0.4	0.1	0.0	0.3	-0.3	-0.5	-1.0	0.4	-0.7	0.0	-0.3	0.5	-0.6	-0.3	-0.8	-0.3	-0.8	-0.4	-0.5	-0.5	-0.6	-0.4	-0.5	-0.7		-0.5	-0.6	-0.8	-0.4	-0.3	-0.6	-0.6	-0.4	-0.4	-0.5	-0.5	-0.4	-0.5	-0.7	-0.6	-0.6	-1.1	-0.4	-0.5	-0.5	-0.5	-0.3	-0.6	-0.9	-0.5
Sm	-0.1	-0.7	-0.6	0.7	-0.6	-0.7	-0.1	-0.4	-0.7		0.8	-0.1	1.2	-0.3	-0.3	0.4	-0.5			-0.5		-0.7									2.7	-0.6		-0.7		-0.7	-0.1	0.0	0.2	-0.6										-0.4	-0.7	-0.4	-0.7		-0.5														-0.6
SO4	-0.5	-1.0	-1.3	1.3	-1.2	-1.0	1.5	-0.9	0.3	0.6	0.2	-0.7	-1.0	1.0	1.5	1.2	1.5	-0.4	-0.4	-1.3	1.4	-0.8	-0.9	0.0	-1.0	-0.9	-0.9	-1.0	-0.7	-0.7	1.8	0.0	-0.8	-1.1	0.3	0.5	-0.7	-0.4	0.5	0.4	-0.7	-0.6	-0.7		-0.5	0.7	0.7	0.6	0.5	0.9	-1.2	0.5	-0.1	-1.0	-0.1	0.5	-0.6	-0.2	0.0	0.4		0.6	0.4	0.6	0.6	0.7	0.8		1.2
SO4S	-0.5	-1.0	-1.3	1.4	-1.2	-1.1	1.6	-0.9	0.4	0.7	0.2	-0.7	-0.9	1.1	1.6	1.2	1.6	-0.3	-0.5	-1.3	1.4	-0.7	-0.9	0.1	-1.0	-1.0	-0.9	-1.1	-0.7	-0.7	1.9	0.0	-0.8	-1.1	0.8	0.8	-0.4	0.4	0.7	0.6	-0.5	-0.3	-0.2		-0.2	0.7	0.9	0.7	0.6	0.9	-1.3	0.5	0.0	-1.0	0.0	0.5	-0.7	-0.4	-0.1	0.5	0.7	0.7	0.4	0.7	0.7	0.8	1.0	0.9	1.0
Sr	-1.0	-0.9	-1.0	0.0	-0.9	-1.0	-0.4	-1.0	-0.8	-0.8	-0.5	-0.1	0.1	-0.1	-0.3	-0.2	-0.4	0.4	0.3	2.5	0.2	0.2	0.8	0.0	0.4	3.8	0.0	0.8	0.4	0.8	-0.2	0.5	1.0	0.3	-0.6	-0.1	0.1	0.2	0.2	0.2	-0.1	0.1	0.1		0.1	-0.2	-0.5	-0.7	-0.6	-0.6	-0.5	-0.1	0.1	-0.3	-0.1	-0.3	-0.4	0.1	0.1	-0.1	-0.7	-0.7	-0.2	-0.2	-0.3	-0.7	-0.6	-0.4	-0.2
Tb	0.2	-0.6	-0.6	0.9	-0.5	-0.7	0.3	-0.5			0.1	-0.4	-0.2	-0.4	-0.6	-0.1															2.1					-0.6	-0.4	-0.2	-0.1	-0.6										-0.4		-0.5			-0.6														-0.4
Th	-0.3		-0.3		-0.3	-0.3					-0.2	-0.2	-0.2																								-0.3																			0.0														-0.3
Tl																																				0.6																																	0.5
Tm	0.1	-0.8	-0.7	1.7	-0.7	-1.1	0.0	-0.2			0.5	-0.7	-0.5	-0.8		0.1															1.6					-0.6	-0.5	0.5	0.6	-0.5										-0.1		-0.8			-0.8														0.1
TOC	1.6	1.6	1.3	-0.5	2.3	2.3	0.2	1.0	0.4	0.1	0.0	-0.2	0.0	-0.5	-0.5	-0.6	-0.5	-0.6	-0.7	-0.6	-0.6	-0.5	-0.5	-0.5	-0.5	-0.7	-0.4	-0.6	-0.4	-0.4	-0.4	-0.7	-0.7	-0.7		-0.6	-0.7	-0.7	-0.6	-0.6										-0.5	-0.6	-0.6	-0.7	-0.8	-0.7	-0.5	0.2												-0.5
U	-0.2	-0.2	-0.5	-0.2	-0.2	-0.4	-0.5	-0.5	-0.1	0.1	-0.5	-0.6	-0.6	0.3	3.2	-0.1	-0.4	0.3	0.1	-0.6	0.0	-0.3	-0.6	0.6			-0.2	-0.6	-0.6	-0.6	-0.5	-0.6	-0.5	0.2		-0.5	-0.1	-0.2	-0.3	-0.2										-0.3	0.9	-0.4	0.0		0.3	0.2	-0.1												-0.4
V	1.7	1.1	1.7	-0.4	1.4	3.8	-0.2	1.6	0.2	-0.2	-0.6	0.2	-0.1	-0.2	-0.3	-0.5	-0.5	-0.4		-0.4	-0.5	-0.3	-0.4	-0.3			0.3	-0.5	-0.3	-0.3	-0.4	-0.5	-0.2	0.5		-0.5	-0.6	-0.6	-0.6	-0.5										-0.3	-0.5	-0.5	-0.5		-0.6														0.2
Y	0.2	-0.3	-0.3	3.7	-0.3	-0.6	0.1	0.1	-0.3	-0.5	2.8	-0.3	1.1	0.5	0.0	1.7	0.0	-0.6		-0.6	-0.4	-0.6	-0.7	-0.5			-0.5	-0.7	-0.7	-0.7	1.6	-0.7	-0.6	-0.4		-0.2	1.1	2.2	2.7	1.2										1.0	-0.5	0.1	-0.3		0.2														1.1
Yb	0.4	-0.4	-0.2	2.9	-0.3	-0.7	0.0	0.5	-0.5	-0.9	1.1	-0.8	-0.1	-0.3	-0.7	0.7	-0.8					-1.0		-1.0			-1.0				1.7			-0.8		0.0	0.1	1.6	1.6	0.1										0.5	-0.9	-0.5	-0.9		-0.3														0.9
Zn	-0.3		-0.3	-0.3	-0.3	-0.3		-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3			-0.2	-0.3	-0.3		-0.3			-0.3	-0.2	-0.1	-0.3	-0.3	-0.2	-0.2	-0.3		-0.3		-0.3		-0.3											-0.3	-0.1	7.3		0.0														
Zr	2.4	1.5	1.6	-0.5	2.5	1.8	-0.2	1.4	0.0	-0.5	-0.5	0.0	-0.4	-0.5	-0.4	-0.6	-0.5					-0.6									-0.1	-0.6				-0.6	-0.6		-0.6										-0.6																			-0.6

* corrSECUP=upper section limit, corrSECLOW=lower section limit.

** Section number (from bottom).

*** Included in the current monitoring programme (Y=yes, N=no).

Table A3-15. Regression analysis of times series consisting of at least 10 sampling occasions ranging over a period of at least 4 years for groundwater in the bedrock (percussion drilled and cored boreholes). The numbers in the table represent the probabilities for the hypothesis that there is no time-trend in data, i.e. p values between –0.05 and 0.05 indicates statistical significant temporal patterns that cannot be explained as a random variation. The sign (and colour) of the probabilities represents the direction of the trends (orange – increasing, blue – decreasing).

	Percussion drilled boreholes										Cored boreholes (SFK)																						Cored boreholes (SFR)												
IDCODE	HFM01	HFM02	HFM04	HFM13	HFM15	HFM16	HFM19	HFM21	HFM27	HFM32	KFM01A	KFM01D	KFM01D	KFM02A	KFM02A	KFM02B	KFM02B	KFM03A	KFM03A	KFM04A	KFM06A	KFM06A	KFM06C	KFM06C	KFM07A	KFM08A	KFM08A	KFM08D	KFM10A	KFM11A	KFM11A	KFM12A	KFR01	KFR01	KFR02	KFR02	KFR02	KFR08	KFR101	KFR102A	KFR102A	KFR105	KFR106	KFR106	KFR7A
CorrSECUP*	34	38	58	159	85	54	168	22	46	26	109	311	429	411	490	410	491	634	969	230	341	738	531	647	963	265	684	660	430	446	690	270	11	45	43	81	137	63	280	214	423	265	143	260	48
CorrSECLOW*	46	48	66	176	100	67	185	32	58	31	130	321	438	442	518	431	506	650	995	245	362	748	540	666	972	280	694	680	440	456	710	280	44	62	80	118	170	104	342	219	443	307	259	300	75
CorrSec**	2	2	2	1	1	2	1	3	2	3	5	4	2	5	3	4	2	5	2	4	5	3	5	3	2	6	2	4	2	4	2	3	2	1	4	3	1	1	1	5	2	1	2	1	1
MonitProg***	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	n	n	n	n	n	y	y	y	y	y	y	n
10B															0.67			0.03																											
13C															-0.06																														
14C															-0.07																														
18O	-0.47	-0.07	-0.56	-0.25	0.00	-0.21	0.00	-0.31	-0.13	-0.25	0.00	0.00	-0.16	-0.36	0.00	-0.39	-0.26	-0.14	-0.24	-0.71	-0.11	-0.07				0.00	-0.08	-0.46	-0.80	0.00	0.00	-0.32		0.00				-0.01	-0.01	0.00	0.00				-0.90
230Th															-0.15			-1.00																											
232Th															-0.05			-0.76																											
234U															-0.31			0.00																											
235U															-0.50			0.00																											
238U															-0.30			0.00																											
2H	-0.23	0.36	0.28	0.74	-0.01	-0.33	-0.23	-0.85	-0.46	0.31	-0.46	-0.31	-0.70	0.14	-0.88	0.82	0.69	-0.29	0.40	-0.82	-0.12	0.76				0.00	-0.26	0.31	0.15	-0.43	0.00	-0.01		0.00				0.00	0.00	-0.01	0.00				-0.01
34S_SO4															0.49			0.02																											
37Cl																																													
3H	-0.38	-0.38	0.00	0.78	0.05	-0.29	-0.30	-0.02	0.28	0.00	0.44	0.52	-0.42	-0.39	-0.69			0.47			0.51	-0.95				-0.07	0.87	0.74	-0.04	0.00	-0.01			0.00				0.00		-0.56					0.00
87Sr																																													
Al															0.08			-0.55																											
As																																													
B															0.22																														
Ba															0.07			0.92																											
Br	0.00	0.00	0.00	0.97	0.00	-0.06	0.74	-0.01	0.00	-0.09	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.01	-0.09	-0.26	-0.09	-0.65	-0.07	0.04	-0.17	0.00	-0.01	-0.92	-0.01	-0.90	0.00	-0.60		0.00				0.47	-0.49	0.00	0.24	0.00	0.17	-0.03	0.00
Ca	0.00	0.00	0.91	0.00	-0.01	0.00	0.02	-0.02	0.00	-0.05	-0.12	0.00	0.00	0.31	-0.69	-0.15	-0.29	0.29	-0.03	-0.52	-0.32	0.00	0.97	0.00	-0.63	0.00	0.44	0.00	0.01	0.00	0.00	-0.14		0.00	0.05	0.15		0.00	0.00	-0.01	0.00	0.03	0.01	-0.22	0.00
Cd																																													
Ce															0.00			-0.86																											
Cl	0.00	0.00	0.00	0.00	0.00	0.18	0.18	-0.01	0.00	0.57	-0.46	0.00	0.00	0.23	-0.54	-0.92	-0.87	-0.41	-0.03	0.02	-0.10	0.00	0.00	0.00	-0.83	0.00	0.00	0.10	0.00	0.00	0.00	-0.25	0.00	0.00	0.12	0.02	0.01	-0.10	0.00	0.00	0.00	0.18	0.00	-0.01	0.00
Co															0.00																														
COND	0.00	0.00	0.00	0.00	0.00	-0.50	0.63	-0.02	0.00	0.55	-0.16	0.00	0.00	0.03	-0.06	0.11	0.11	0.18	0.20	0.27	-0.74	0.06	0.64	0.00	-0.04	0.00	0.01	0.05	0.00	0.00	0.00	-0.25		0.00				0.09	0.00	0.00	0.00	0.01	0.00	-0.05	0.00
Cr															-0.92			0.85																											
Cs															0.77			0.00																											
Cu																																													
DOC	0.10	0.00	0.01	0.00	0.01	-0.27	0.00	0.90	0.00	-0.29	0.00	0.00	0.00	-0.24	-0.63	-0.14	0.00	0.90	0.00	-0.41	0.81	0.74	0.16	0.67	-0.39	0.00	-0.28	-0.19	0.00	0.00	0.00	-0.19							-0.11	0.00	0.00	-0.09			
Dy															0.00																														
EC_field	0.00	0.00	0.33	0.00	0.00	0.99	0.91	-0.04	-0.03	0.89	0.00	0.29	0.00	-0.47	0.80	0.43	0.38	-0.20	-0.27	0.12	0.00	0.06	-0.56	0.00	-0.07	0.00	-0.86	0.12	0.01	0.00	0.00	0.26							0.00	0.00	0.00	-0.02	0.02	0.00	
Er															0.00																														
Eu																																													
F	0.00	0.05	-0.02	0.50	0.00	-0.04	0.45	0.16	0.58	0.94	0.69	-0.73	0.00	-0.66	-0.65	-0.38	-0.61	0.24	0.02	-0.06	-0.44	0.01	0.21	0.74	0.72	-0.70	0.62	0.00	-0.34	0.00	0.53	-0.43		0.16				0.08	-0.42	0.00	0.92	-0.94	0.00	0.00	0.00
Fe	0.00	-0.02	0.00	0.00	0.44	-0.33	0.01	-0.01	0.00	0.00	-0.78	0.00	-0.01	-0.01	0.00	0.00	-0.42	0.00	-0.01	-0.12	0.00	0.00	0.00			0.27	0.00	0.67	0.00	0.00	0.00	0.00		0.95				0.14	0.00	0.96	-0.79	0.09	0.00	-0.13	0.00
Fe_2+											-0.08	0.00	-0.01	-0.02	-0.15			-0.05	0.00										0.00	-0.01				-0.46											0.00
Fe_tot											-0.08	0.00	-0.01	-0.01	-0.16			-0.05	0.00										-0.01	-0.19				-0.13											0.00
Gd															0.00																														
HCO3	0.00	0.00	0.00	-0.27	0.31	0.32	-0.05	0.05	0.52	-0.09	0.00	0.00	0.00	0.00	-0.01	0.00	-0.03	0.00	-0.12	0.00	0.00	-0.02	0.00	0.00	-0.55	-0.52	0.76	0.32	-0.54	0.00	0.00	0.00		0.00	0.52	0.00	0.01	-0.55	0.00	0.00	0.00	-0.44	-0.63	0.10	0.32
Hf																																													
Hg																																													
Ho																																													
I											0.45				-0.56			-0.18	-0.26																										
K	0.00	0.00	0.00	0.58	0.00	-0.94	-0.07	-0.12	0.91	0.70	0.00	0.00	0.00	0.62	0.10	-0.28	0.12	0.00	0.00	0.16	-0.07	0.00	-0.16	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.01		-0.85	-0.59	0.59		-0.05	0.00	-0.01	0.00	0.00	0.00	-0.98	0.00
La															0.00			-0.33																											
Li	0.00	0.00	0.01	0.37	0.00	0.03	-0.60	-0.72	-0.11	-0.79	-0.01	-0.03	0.00	-0.21	-0.89	0.00	0.12	-0.65	0.31	0.11	0.65	-0.05	-0.94	-0.36	-0.61	0.58	-0.10	-0.06	-0.25	0.68	0.00	0.16		0.87				-0.79	0.00	-0.60	0.01	-0.85	0.16	-0.05	-0.03
Lu																																													
Mg	0.00	0.00	0.01	0.00	-0.02	0.00	0.09	-0.04	-0.07	0.58	-0.49	0.00	0.00	0.00	0.46	0.44	0.07	0.00	0.00	0.19	0.00	0.00	-0.01	0.00	0.87	0.00	-0.15	-0.10	0.00	-0.01	0.00	0.00		0.00	0.60	0.02		-0.09	0.48	0.00	0.00	0.00	0.01	-0.03	0.00
Mn	0.00	-0.01	0.03	0.00	0.00	0.00	0.07	-0.03	0.00	0.21	-0.66	0.00	0.00	0.14	-0.01	0.00	-0.03	0.00	0.00	-0.14	0.00	0.00	-0.02	-0.27	0.23	0.06	-0.01	0.38	-0.02	-0.06	0.00	-0.03		0.01				0.00	0.00	0.94	0.00	0.01	0.00	-0.01	0.00
Mo															0.20			0.31																											
Na	0.00	0.00	0.00	0.00	0.00	0.84	0.36	-0.19	-0.38	0.02	0.11	0.00	0.00	0.01	0.09	0.04	0.02	0.09	0.06	0.04	0.15	0.00	0.03	0.12	0.90	0.00	0.03	0.79	0.19	0.00	0.00	0.39		-0.04	0.36	-0.47		0.00	0.00	-0.01	-0.19	0.00	0.00	-0.15	0.00
Nd															0.00			-0.40																											
NH4N											-0.29	0.00	0.09	0.72	0.32			0.00	-0.05			0.00				-0.02	-0.05	0.21	-0.05	0.00				0.91											-0.31
Ni															-0.01																														
NO23N											0.83	0.48	-0.45	-0.55	-0.37			-0.89	0.76							-0.16	-0.57	-0.49	-0.42																
NO2N											0.77																							-0.40											0.00
NO3N											0.27	-0.85	-0.80		-0.54				0.52										0.88					0.02											
P																																													
Pb																																													
pH	0.00	0.00	0.20	-0.58	0.00	0.02	0.00	0.40	0.16	0.17	0.00	0.07	0.07	0.01	0.01	0.03	0.01	0.16	0.00	0.02	0.00	0.00	0.08	0.00	-0.14	-0.10	0.42	-0.01	0.01	0.00	0.00	0.38		0.47	-0.57		0.18	0.35	0.00	0.01	0.00	0.61	0.00	0.10	0.00
pH_field	0.00	0.01	0.73	0.03	-0.13	0.16	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.79	0.78	0.21	0.85	-0.63	0.00	0.00	0.05	0.00	0.02	0.00	-0.16	0.78	0.02	0.00	0.03	0.01	0.00	0.12							-0.02	0.13	-0.11	0.27	0.00	-0.61	
PO4P													0.27																					0.00											-0.15
PO4P_hlysis											-0.26	-0.28	0.84					0.18	-0.01							-0.04	0.00		0.52																
Pr															0.00																														
Rb															0.49			-0.11																											
S_2-	0.00	0.00	-0.53	0.03	0.02	0.00	0.00	0.00	0.01	0.75	-0.47	-0.06	0.69	-0.38	0.82	-0.01	-0.89	-0.76	-0.12	0.01	0.69	1.00	0.66	0.26		-0.39	-0.75	-0.10	0.00	0.15	0.31	0.18		0.19						0.00					
Sb																																													
Sc																																													
Si	-0.05	0.83	-0.03	-0.08	0.00	-0.15	-0.52	-0.10	-0.39	-0.17	0.00	0.00	0.00	-0.02	-0.69	-0.01	-0.25	-0.15	0.00	-0.01	-0.12	0.00	-0.01	0.00	0.67	0.00	0.56	-0.33	0.57	0.00	0.00	0.00		0.00				0.00	-0.22	0.00	0.00	0.00	0.46	-0.95	0.00
Sm															0.00																														
SO4	0.00	0.00	-0.14	0.75	0.00	0.00	-0.39	-0.04	0.00	-0.31	-0.05	0.00	0.00	0.00	-0.20	-0.07	-0.11	0.00	0.04	0.00	0.00	-0.05	0.00	0.00	-0.01	0.00	-0.03	-0.08	0.09	0.38	0.00	0.00		0.00	0.00	0.00		0.19	0.00	0.00	0.00	0.84	0.05	0.75	0.00
SO4S	0.00	0.00	-0.01	0.36	0.00	0.00	-0.38	0.00	0.00	-0.10	-0.02	0.00	0.00	-0.81	-0.04	-0.02	-0.02	0.00	-0.02	0.00	0.00	0.00	-0.01	0.00	-0.20	0.00	0.00	0.00	0.62	-0.29	0.00	0.00		-0.62				0.01	0.09	0.00	0.00	-0.39	0.31	-0.82	0.56
Sr	0.00	0.00	0.00	0.00	-0.02	-0.33	0.00	-0.01	0.00	-0.15	-0.04	0.00	0.00	0.01	0.02	0.00	0.00	0.00	-0.02	0.20	0.00	0.00	0.04	0.00	-0.01	0.00	0.05	0.00	0.01	0.00	0.00	0.00		0.26				0.05	0.00	-0.61	0.00	-0.42	0.01	-0.25	0.49
Tb																																													
Th																																													
Tm																																													
TOC	0.00	0.00	0.01	0.00	0.01	-0.71	0.00	0.78	0.70	-0.01	0.00	0.00	0.00	-0.02	-0.38	0.00	-0.04	-0.09	0.00	-0.82	0.88	0.73	0.31	0.56	-0.16	0.00	-0.24	-0.10	0.00	0.00	0.00	-0.03							-0.06	0.00	0.00	-0.10			
U											-0.16	-0.01	0.00	-0.06	-0.20			0.00	-0.09								-0.01	0.00	0.48																
V															-0.14																														
Y															0.04			-0.04																											
Yb															0.01																														
Zn															-0.78																														

* corrSECUP=upper section limit, corrSECLOW=lower section limit.
** Section number (from bottom).
*** Included in the current monitoring programme (Y=yes, N=no).

Arkitektkopia AB, Bromma, 2017

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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