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Site descriptive modelling
SDM-Site Forsmark

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December 2008

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Summary

In this report meteorological, hydrological and hydrogeological time series data from SKB's site investigation at Forsmark available up to March 31, 2007 (data freeze 2.3) are presented. These data constitute an important input to the conceptual and numerical modelling of the surface hydrology and near-surface hydrogeology at Forsmark (modelling results are presented in other reports from the site descriptive modelling).

Two meteorological stations were established in the site investigation area in May 2003. The measurements at the two stations showed good agreement with less than 5% difference in precipitation over the period of available measurements. The corrected mean annual precipitation of these two stations for the full four-year period of June 2003–May 2007 was 563 mm. The lowest and highest recorded annual precipitation for the available three full calendar-years 2004–2006 were 504 and 578 mm, respectively (average: 537 mm/year). Based on data from nearby stations in their network, SMHI (the Swedish Meteorological and Hydrological Institute) has calculated a 30-year average annual corrected precipitation of 559 mm at Forsmark. There is a strong precipitation gradient from east to west, with an annual corrected precipitation at Örskär (c. 15 km north-east of the study area) that is approximately 200 mm lower than at Lövsta (c. 15 km west of Forsmark). For the full four-year period of June 2003–May 2007, the calculated mean annual potential evapotranspiration at Forsmark was 526 mm.

Surface water levels were recorded in six lakes and at two locations in the Baltic Sea. The highest recorded half-hour value of the sea level, 1.40 m RHB70, was during the "Per" storm (January 2007), which can be compared with 0.94 m during the "Gudrun" storm (January 2005) (the corresponding maximum daily averages were 0.99 and 0.75 m, respectively). For comparison the mean sea water level during the whole monitoring period was –0.04 m RHB70 and the minimum recorded half-hour value –0.68 m (minimum daily average –0.55 m). At high sea water levels, sea water intruded Lake Norra Bassängen, Lake Bolundsfjärden and Lake Lillfjärden, and during the extreme events in January 2005 and January 2007 also Lake Fiskarfjärden. The level of Lake Lillfjärden seemed to be determined mainly by the sea level, while the levels of Lake Norra Bassängen and Lake Bolundsfjärden, were determined by the lake thresholds and the inflow from inland, except for during periods with very high sea levels. Salinity profiles from Lake Bolundsfjärden after the sea water intrusions indicated a strong stratification when the lake had an ice cover, while a complete mixing appeared when the there was no ice cover.

Groundwater levels were automatically recorded in 51 wells in Quaternary deposits. 42 of these wells were located on land, while nine were placed in till below the bottom of lakes and the Baltic Sea. Groundwater levels in Quaternary deposits were in general very shallow. 80% of all recorded groundwater levels in the 42 wells on land were between 0.0 and 2.2 m below ground surface. Groundwater levels in Quaternary deposits were strongly coupled to the ground level. However, as anticipated, a convex local topography resulted in somewhat deeper average groundwater levels than in areas with a concave topography. A classification of the well locations from a recharge-discharge area perspective showed in general very shallow average groundwater levels in discharge areas, while the average depths to groundwater varied substantially in recharge areas. In individual wells, the temporal variation in groundwater level was less than 1.0 m in approximately 40% of the wells and less than 1.5 m in approximately 60% of the wells.

In most percussion-drilled boreholes in bedrock there is a variation in groundwater salinity, and thereby in density, with depth. The groundwater levels recorded are therefore regarded as point water heads. Point water heads (groundwater levels) from 36 percussion-drilled boreholes in the site investigation area were analysed. In the report, no general transformation was made of the actually measured point water heads to fresh water heads or environmental water heads to include the influence of water density effects on horizontal and vertical flow gradients, respectively. However, results from such transformations indicated that in nine sections in the percussion-drilled boreholes there were differences of more than 0.1 m between measured point water heads and environmental water heads. When differences between point water head and environmental water heads are important for the interpretation of the direction of the vertical gradient, comments are given in the text.

Contrary to the wells in Quaternary deposits, there was no evident correlation of the point water head to the elevation of the local ground surface. 23 of the 36 bedrock wells had natural point water heads above the local bedrock surface. All but two well sections in the percussion-drilled boreholes exhibited average point water heads above 0.0 m RHB70. The two outliers were sections in boreholes close to the existing underground SFR-repository where pumping by c. 6 L/s takes place for drainage. All but two of the monitored bedrock well sections within the tectonic lens, constituting the candidate area, had mean natural point water heads below 1.5 m RHB 70. The two outliers had very low transmissivities. The small natural gradients within the tectonic lens indicated high transmissivities in the horizontal and sub-horizontal fracture zones known to exist in the uppermost c. 150 m of the lens. The analysis of responses in other bedrock wells on single distinct disturbances of groundwater levels in three bedrock wells indicated good hydraulic contacts over large distances within the tectonic lens. These responses confirmed the high transmissivities in the uppermost c. 150 m indicated by the small natural gradients.

Surface discharge was measured at four automatic gauging stations. The upstream catchment areas varied in size from 2.3 to 5.6 km^2. The station for the largest catchment area has been in operation since April 2004 and the other three since December the same year. The discharge from the largest catchment area varied between 0 and 212 L/s (0.0–38.0 L/s/km^2) during the period of available measurements (April 2004–March 2007). The average specific discharge for this period was 4.87 L/s/km^2 (154 mm/year). During the two full calendar-years with available measurements at all four stations, 2005 and 2006, the variation in specific discharge at these stations was 126–142 and 167–193 mm/years, respectively. The largest catchment had the highest specific discharge both years.

A model of snow accumulation and snowmelt was calibrated against measured snow water content and used to derive a rainfall+snowmelt (R+S) time series. Daily values from this time series minus daily potential evapotranspiration (R+S-PET) were used for interpretation of hydrological relationships.

In an ordinary correlation study, R^2-values for monthly average groundwater levels in Quaternary deposits to average R+S-PET of prior two months were typically 0.6–0.8. R^2-values in the same range were obtained when the monthly change in groundwater level was correlated to R+S-PET for the same month. In contrast, the correlations between R+S-PET and point water heads in bedrock, according to the ordinary correlations analysis, were weak and inconsistent. Different time periods for averaging and displacement in time were tested. However, a principal component analysis of the bedrock point water heads indicated that approximately 80% of the total variance was coupled to the seasonal variation of R+S-PET. The conclusion was that the annual variation in groundwater levels, both in Quaternary deposits and bedrock is dominated by R+S-PET variations.

Diurnal variations of groundwater levels in Quaternary deposits, often 2–3 cm, were observed in several wells in areas with shallow groundwater during dry summer conditions. These variations were an indication of direct and/or indirect root water uptake from the groundwater zone and illustrated the strong connection between transpiration, and water in the unsaturated zone and the groundwater zone.

The correlations between groundwater levels in Quaternary deposits and the sea level were typically very low with exception of the two wells located in a glaciofluvial deposit close to the sea. Different time periods for averaging and displacement in time were tested. Concerning the correlation between the point water heads in bedrock and the sea level, the ordinary correlation study indicated a typically weak and inconsistent correlation. However, a PLS-model (Partial Least Squares) was applied to further explore the correlations between point water heads, sea level, air pressure, and a simulated groundwater level based on R+S-PET and a tank storage. In the PLS-analysis, at least one section in each of the bedrock boreholes HFM33-35 was classified as probably influenced by sea level changes, and HFM02-04, HFM14-15, HFM18, HFM20, HFM22, HFM30, HFM32, and HFM38 as possibly influenced.

A comparison of lake water levels and groundwater levels in Quaternary deposits in the vicinity or below the lakes showed that groundwater levels for most of the time were higher than the lake water levels. This means that the lakes and their riparian zones act as discharge areas for shallow groundwater, the actual discharge determined by the hydraulic contact between groundwater and surface water. However, during dry summer conditions the groundwater levels in the riparian zones and for some lakes also below the lake, decreased well below the lake water levels, implying that the lakes constituted potential groundwater recharge sources during these periods. This phenomenon confirmed the important influence of root water uptake on shallow groundwater indicated by the diurnal fluctuations discussed above, and was also an indication of a limited hydraulic contact between the lakes and the groundwater.

Where groundwater levels in Quaternary deposits and point water heads in bedrock were observed in wells in close proximity (mostly at core drill sites), the groundwater levels in Quaternary deposits were 1–2 m higher, with Drill site 4 (situated outside the tectonic lens) as an exception. Transformation of point water heads to environmental heads indicated that the difference in groundwater levels in Quaternary deposits and point water heads could not be explained by water density differences but indicated a downward flow gradient from the Quaternary deposits to the bedrock. However, the lack in response in groundwater levels in Quaternary deposits to pumpings in nearby bedrock wells in most cases indicated a limited contact between groundwater in Quaternary deposits and bedrock, at least in the vicinity of the pumping wells. At some of the sites within the tectonic lens with wells in Quaternary deposits and bedrock in close proximity, the groundwater levels in Quaternary deposit decreased below the groundwater levels in the bedrock during dry summer conditions, creating possibilities for an upward groundwater flow from the bedrock to the Quaternary deposits.

The drainage of the SFR-repository (c. 6 L/s) is, together with a high horizontal transmissivity of the upper bedrock, a possible explanation for the generally low groundwater levels recorded in the upper bedrock within the tectonic lens. In particular, such conditions are observed in the northern part of the lens.

Based on a water balance calculation for the full three-year period of April 15, 2004–April 14, 2007 (including measurements of precipitation and discharge, and estimates of storage changes from measured lakes and groundwater levels), and comparison of the precipitation for this period and the long-term average precipitation, the long-term overall water balance of the area was roughly estimated to: P (precipitation) = 560 mm/year, ET (evapotranspiration) = 400–410 mm/year, and Q (runoff) = 150–160 mm/year.

The installation of the monitoring equipment for the site investigation has been an on-going process from the first installations in late 2002. The performed measurements are considered to give a good basis for the description of the site conditions during the period of measurements and to constitute a firm basis for the development of a conceptual model of the hydrological and near-surface hydrogeological conditions. The conclusions regarding the representativity of the present period for long-term average conditions and variations can be summarised as follows:

- Almost four years of meteorological data were available for the analysis. These time series can be used to establish relationships with nearby SMHI stations with much longer time series as a basis for long-term hydrological and hydrogeological modelling. The uncertainties in the correlations will decrease with the continued monitoring at Forsmark.
- The sea and lake level time series are considered to give a good indication of the average conditions and the variations to be expected.
- The groundwater level time series from Quaternary deposits and the upper bedrock are considered to give a good indication of existing average conditions and of the variations to be expected. The possible influence of the SFR drainage on the groundwater levels in bedrock, especially within the tectonic lens, needs to be further investigated.
- The available time series of surface discharge give a good estimate of the average specific discharge in the area, but they are too short to enable firm conclusions on spatial and temporal variations of the discharge to be drawn.
- Existing time series are considered to form a good basis for estimation of the average long-term water balance. However, longer time series of precipitation and surface discharge are needed for better estimates of the spatial and temporal variation of the water balance.

Sammanfattning

I föreliggande rapport presenteras meteorologiska, hydrologiska och hydrogeologiska tidsserier av data från SKB:s platsundersökning i Forsmark t o m 2007-03-31 (SKB:s datafrys 2.3). Dessa data är en viktig del av underlaget för den konceptuella och numeriska modelleringen av ythydrologi och ytnära hydrogeologi i Forsmark (redovisas i andra rapporter från den platsbeskrivande modelleringen).

Två meteorologiska mätstationer etablerades i platsundersökningsområdet i maj 2003. Mätningarna vid de båda stationerna visade på god överensstämmelse; skillnaden i nederbörd för hela mätperioden var mindre än 5%. Den genomsnittliga korrigerade årliga medelnederbörden för fyraårsperioden juni 2003–maj 2007 var 563 mm. Den lägsta och högsta årliga nederbörden för de tre tillgängliga hela kalenderåren 2004–2006 var 504 respektive 578 mm (medelvärde för de tre åren 537 mm). Baserat på data från närliggande SMHI-stationer har SMHI beräknat normalnederbörden för en 30-årsperiod till 559 mm. I området finns en tydlig öst-västlig gradient i nederbörden, där nederbörden på Örskär (ca 15 nordost om det studerade området) är ca 200 mm lägre än i Lövsta (ca 15 km väster om Forsmark). För fyraårsperioden juni 2003–maj 2007 beräknades den genomsnittliga årliga potentiella evapotranspirationen i Forsmark till 526 mm.

Ytvattennivåer mättes i sex sjöar i platsundersökningsområdet och på två platser i havet. För havsnivån var det högsta noterade halvtimmesvärdet 1,40 m RHB70 under stormen ”Per” i januari 2007. Detta värde kan jämföras med 0,94 m RHB70, som var det högsta uppmätta värdet under stormen ”Gudrun” i januari 2005. De högsta dygnsmedelvärden som uppmättes vid dessa tillfällen var 0,99 respektive 0,75 m RHB70. Medelvattennivån i havet var under mätperioden –0,04 m RHB70 och miniminivån var –0,68 (dygnsminimivärdet var –0,55 m). Vid höga havsnivåer tränger havsvatten in i Norra Bassängen, Bolundsfjärden och Lillfjärden och vid extremt höga nivåer, som i januari 2005 och januari 2007, också i Fiskarfjärden. Nivån i Lillfjärden bestäms huvudsakligen av havsnivån, medan nivåerna i Norra Bassängen och Bolundsfjärden bestäms av sjötrösklarna och inflödet från landsidan, utom vid mycket höga havsvattenstånd. Salthaltsprofiler från Bolundsfjärden efter de kraftiga havsvatteninflödena indikerade en stark skiktning när sjön var istäckt medan vattnet var väl omblandat när istäcke saknades.

Grundvattennivåer registrerades i 51 grundvattenrör i jordlagren. Av dessa var 42 belägna på land och nio satta i morän under sjöar och hav. Ca 80% av alla registrerade mätvärden i rör belägna på land låg mellan 0 och 2,2 m under markytan. Grundvattennivåerna i jord var starkt kopplade till markytans nivå. Som väntat var dock grundvattennivån något djupare under markytan i områden med en konvex lokal topografi. En klassificering av grundvattenrörens lägen i inströmnings- och utströmingsområden visade på en generellt mycket marknära grundvattennivå i utströmningsområden medan djupet till grundvattenytan varierade relativt kraftigt i inströmningsområdena. Den tidsmässiga variationen under mätperioden var mindre än 1,0 m i ca 40% av grundvattenrören och mindre än 1,5 m i ca 60% av rören.

I de flesta av hammarborrhålen i berg varierar salthalten, och därmed grundvattnets densitet, med djupet. De mätta grundvattennivåerna tolkas därför som s k point water heads. Grundvattennivåer från 36 hammarborrhål analyserades. I den aktuella rapporten har ingen generell transformation gjorts av mätta point water heads till “fresh water heads” eller “environmental water heads” for att inkludera densitetsskillnadernas effekt på horisontella respektive vertikala flödesgradienter. Resultaten från sådana transformeringar indikerade att det var en större skillnad än 0,1 m mellan point water head och environmental water head i nio av hammarborrhålens sektioner. I de fall skillnader mellan point water head och environmental water head varit viktiga för riktningen av den vertikala flödesgradienten har detta kommenterats i texten.

I motsats till vad som gällde för grundvattennivåerna i jord, fanns det ingen tydlig korrelation mellan grundvattennivån i berg och markytans nivå. I 23 av de 36 hammarborrhålen låg den genomsnittliga grundvattennivån högre än bergytan och i alla mätsektioner utom två låg grundvattennivån högre än 0,0 m RHB70. De två sektionerna med lägre nivåer fanns i borrhål i direkt närhet till det befintliga SFR-förvaret där en dräneringspumpning sker med ca 6 L/s. I borrhålen i den tektoniska linsen

låg den genomsnittliga grundvattennivån lägre än 1,5 m RHB70 utom i två mätsektioner. De två avvikande sektionerna hade mycket låg transmissivitet. De små naturliga gradienterna i den tektoniska linsen indikerar en hög transmissivitet i de horisontella och sub-horisontella sprickzoner som påvisats i de övre ca 150 m av berget inom linsen. Analyser av responser i andra hammarborrhål vid pumpning i tre borrhål indikerade god hydraulisk kontakt över långa avstånd inom den tektoniska linsen. Dessa responser bekräftar de höga transmissiviteter i de övre ca 150 m av berget som de små naturliga gradienterna indikerar.

Avrinningen mättes i fyra stationer med automatisk registrering. Avrinningsområdenas storlek för dessa stationer varierade mellan 2,3 och 5,6 km^2. Mätningarna i det största avrinningsområdet påbörjades i april 2004 och i de övriga tre i december samma år. Avrinningen från det största området varierade mellan 0,0 och 212 L/s (0,0–38,0 L/s/km^2) under mätperioden (april 2004–mars 2007). Den årliga specifika avrinningen var under denna period 4,87 L/s/ km^2 (154 mm). Under de två hela kalenderår, då mätningar fanns tillgängliga för alla fyra mätstationerna, 2005–2006, var den specifika avrinningen 126–142 respektive 167–193 mm/år. Det största avrinningsområdet hade den högsta specifika avrinningen båda åren.

En modell för snöackumulation och snösmältning kalibrerades mot mätt vatteninnehåll i snötäcket och användes för att ta fram en tidsserie för regn plus snösmältning. Dagliga värden från denna tidsserie minus dagliga värden för den potentiella evapotranspirationen (R+S-PET) användes för att studera samband mellan meteorologiska data och hydrologiska och hydrogeologiska tidsserier.

Vid studier av korrelationen mellan grundvattennivåerna i jord och R+S-PET erhölls R^2-värden mellan 0,6 och 0,8 mellan månadsmedelvärdet för grundvattennivån och R+S-PET för de närmast föregående två månaderna för de flesta grundvattenrör. Samma R^2-intervall erhölls för korrelationen mellan skillnaden i grundvattennivå under en månad och R+S-PET under samma månad. Däremot erhölls ingen tydlig korrelationen mellan R+S-PET och grundvattennivån i berg. Olika tidsperioder för medelvärdesbildning och tidsförskjutning testades. En principalkomponentanalys indikerade emellertid att ca 80% av variationerna i grundvattennivå i berg kunde förklaras med R+S-PET. Slutsatsen är därför att den årliga variationen i grundvattennivå, såväl i jord som i berg, i huvudsak styrs av nederbörd och avdunstning.

Dygnsvariationer i grundvattennivån i jord, ofta 2–3 cm, observerades i många av observationsrören under torra somrar. Dessa variationer indikerar ett indirekt eller direkt växtupptag av vatten från grundvattenzonen och illustrerar ett starkt samband mellan växternas transpiration och vattnet i den omättade zonen och grundvattenzonen.

Korrelationen mellan grundvattenivån i jord och havsnivån var mycket låg utom för två observationsrör i isälvsmaterial mycket nära havet. Olika tidsperioder för medelvärdesbildning och tidsförskjutning testades. Ingen tydlig linjär korrelation fanns heller mellan grundvattennivån i berg och havsnivån. En PLS-modell (Partial Least Squares) användes för att ytterligare studera sambandet mellan grundvattennivån i berg och havsnivån. Modellen indikerade at minst en sektion i hammarborrhålen HFM33-35 troligen påverkades av havsnivån och att minst en sektion i HFM02-04, HFM14-15, HFM18, HFM20, HFM22, HFM30, HFM32 och HFM38 möjligen också var påverkade.

En jämförelse mellan sjönivåer och grundvattennivåerna i jord runt och under sjöarna visade att grundvattennivåerna under större delen av året var högre än sjönivåerna. Detta betyder att sjöarna och strandkanterna utgör utströmningsområden för jordgrundvattnet och att utströmningens storlek bestäms av hur bra den hydrauliska kontakten är mellan yt- och grundvatten. Under torra sommarförhållanden låg emellertid grundvattennivåerna i strandkanten, och i vissa fall även under sjöarna, betydligt lägre än sjönivåerna. Detta betyder att sjöarna under dessa perioder utgör potentiella inströmningsområden. Förhållandena visar på den inverkan på grundvattennivåerna som växternas vattenupptag har, men indikerar också att den hydrauliska kontakten mellan yt- och grundvatten är begränsad.

Där grundvattennivåobservationer fanns i både jord och berg på samma plats inom den tektoniska linsen, låg grundvattennivån i jord en till två meter högre än i berg. Beräkningar av environmental heads visade att skillnaden i nivå inte kunde tillskrivas skillnader i salthalt utan indikerade en nedåtriktad grundvattenströmning från jord till berg. Bristen på respons i grundvattennivån i jord vid pumpningar i närbelägna bergborrhål i det flesta fall indikerar dock en begränsad hydraulisk kontakt mellan grundvatten i jord och berg, i varje fall i närheten av pumpbrunnarna. På vissa platser med närbelägna observationspunkter i jord och berg inom den tektoniska linsen, sjönk grundvattennivån i jord emellertid under grundvattennivån i berg under torra sommarförhållanden. Därmed skapades möjlighet för ett uppåtriktat grundvattenflöde från berg till jord under dessa perioder.

Pumpningen för dränering av SFR (ca 6 L/s) utgör, tillsammans med en hög horisontell transmissivitet i den övre delen av berget, en möjlig förklaring till de generellt låga grundvattennivåerna i den övre delen av berget i den tektoniska linsen, särskilt i den norra delen av linsen.

Baserat på en beräkning av vattenbalansen för treårsperioden 15 april 2004–14 april 2007 (inkluderande mätt nederbörd och avrinning och uppskattningar av magasinsförändringar från yt- och grundvattennivåmätningar) och jämförelse av nederbörden under den aktuella perioden och långtidsmedelvärdet för nederbörden, har den långsiktiga vattenbalansen för området uppskattats till: P (nederbörd) = 560 mm/år, ET (evapotranspiration) = 400–410 mm/år och Q (avrinning) = 150–160 mm/år.

Installationen av mätutrustning för platsundersökningen har skett successivt med start i slutet av 2002. De utförda mätningarna bedöms ge ett gott underlag för beskrivning av förhållanden på platsen och utgöra en god grund för framtagandet av en konceptuell modell gällande de hydrologiska och ytnära hydrogeologiska förhållandena på platsen. Beträffande mätningarnas representativitet för längre tidsperioder kan följande konstateras:

- Nästan fyra års meteorologiska mätningar fanns tillgängliga för analysen. Dessa tidsserier kan användas för att etablera samband med omkringliggande SMHI-stationer med mycket längre tidsserier som grund för långtidssimuleringar av hydrologiska och hydrogeologiska förhållanden.
- Tidsserierna för havs- och sjönivåer bedöms ge en bra indikation gällande rådande förhållanden och variationerna i dessa.
- Grundvattennivåmätningarna i jord och berg bedöms ge en god bild av rådande förhållanden och de variationer som kan förväntas i dessa. Den möjliga inverkan av pumpningen för dränering av SFR på grundvattennivåerna i berg, framförallt inom den tektoniska linsen, behöver undersökas ytterligare.
- De tillgängliga tidsserierna gällande avrinningen bedöms ge en bra grund för uppskattning av den genomsnittliga specifika avrinningen, men de är för korta för att dra några definitiva slutsatser gällande den rumsliga och tidsmässiga variationen.
- De tillgängliga tidsserierna bedöms ge en bra grund för en uppskattning av den genomsnittliga vattenbalansen. Längre tidsserier behövs emellertid för att bättre uppskatta de rumsliga och tidsmässiga variationerna i vattenbalansen.

Contents

1 Introduction

1.1 Background

The Swedish Nuclear Fuel and Waste Management Company (SKB) has conducted site investigations at two different locations, the Forsmark and Laxemar-Simpevarp areas, with the objective of siting a geological repository for spent nuclear fuel. The investigations were divided into two phases referred to as *Initial site investigation phase* and *Complete site investigation phase*, respectively /SKB 2001/. The results from the investigations at the sites are used as input to the site descriptive modelling. A *Site Descriptive Model (SDM)* is an integrated description of the site and its regional setting, covering the current state of the geosphere and the biosphere as well as ongoing natural processes of importance for long-term safety. The SDM shall summarise the current state of knowledge of the site, and provide parameters and models to be used in further analyses within Safety Assessment, Repository Design and Environmental Impact Assessment.

The first steps of the site descriptive modelling of the Forsmark area were taken with versions 0, 1.1 and 1.2 of the Forsmark site descriptive model reported in /SKB 2002, SKB 2004/ and /SKB 2005/, respectively. The final SDM, which is version 2.3 in the series of SDM's produced, is based on data available up to March 31, 2007. This SDM is designated "SDM-Site Forsmark" to mark that it provides the Forsmark site data to be used within the SR-Site safety assessment. The present report on meteorological, hydrological and near-surface hydrogeological time series data is a background report to SDM-Site Forsmark.

Forsmark is located in the municipality of Östhammar in eastern central Sweden, c. 120 km north of Stockholm. The location of the Forsmark site investigation area and the surface areas covered by the site descriptive models are shown in Figure 1-1. Specifically, models are developed on a regional scale (hundreds of square kilometres) and on a local scale (tens of square kilometres). These model areas include the candidate area, within which most of the deep rock boreholes are located.

1.2 Scope and objective

The present report is produced as a background report for the version 2.3/SDM-Site model of the Forsmark area, constituting the final modelling step in the site investigation phase, and includes a presentation and an integrated analysis of meteorological, hydrological and near-surface hydrogeological data. The data presented herein constitute a basic input to the conceptual and numerical modelling of the hydrology and hydrogeology at Forsmark. The associated SDM-Site conceptual modelling and the descriptive model is presented in /Johansson 2008/ and the numerical modelling in /Bosson et al. 2008/.

Compared with the report on meteorological, hydrogeological and hydrogeological monitoring data produced for the 2.1 modelling /Juston et al. 2007/ the present report includes presentation and analyses of the extended time series now available. Hydro(geo)chemical data are not included in the report.

The objectives of this document are to:

- present and analyse the data on meteorology, surface hydrology and near-surface hydrogeology that are available in the Forsmark 2.3 datasets,
- perform integrated analysis and present relationships between the different datasets,
- discuss implications of the results of the data analysis for the conceptual hydrogeological model of the Forsmark area.

All data used in the report were extracted from the SKB Sicada database. Most of the data analysed herein have been described in the SKB P-report series. These reports contain comprehensive data presentations and references are made to them in connection to the analysis of the different datasets.

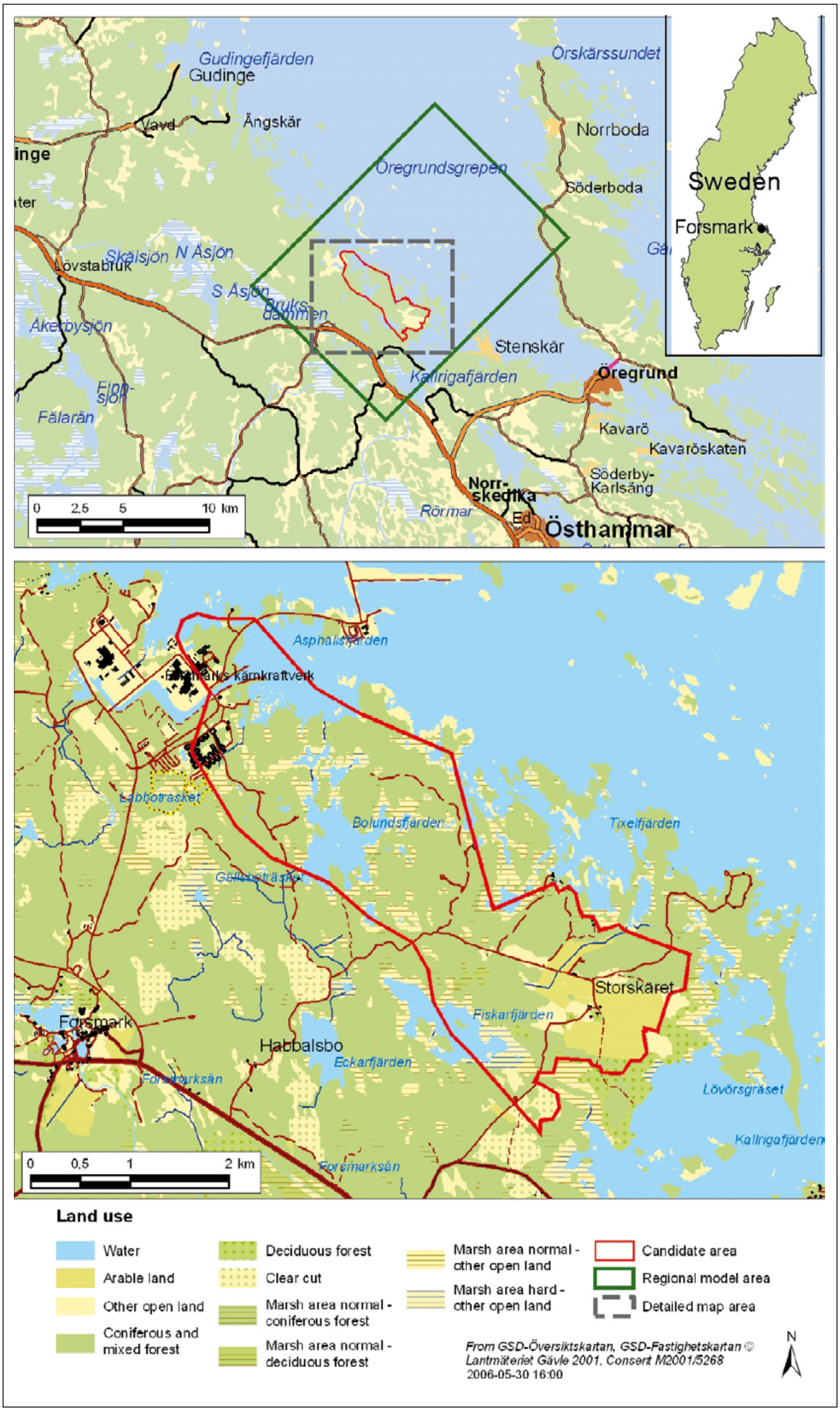

***Figure 1-1.** Overview of the Forsmark area and identification of the regional model area and the candidate area.*

1.3 Physiographic setting

The Forsmark area is situated on the eastern coast of Sweden. The regional model area shown in Figure 1-1 includes a part of Öregrundsgrepen, which is a part of the Baltic Sea. The land area within the site investigation area is characterized by a low relief with a small-scale topography. The study area is almost entirely below 20 m RHB70, see Figure 1-2.

There is a relatively strong west-east gradient in precipitation in the region. The highest precipitation occurs some distance inland from the coast. For example, the mean annual precipitation at Lövsta, c. 15 km inland (to the west), is 690 mm, which can be compared with the corresponding value of 492 mm measured on the island of Örskär, c. 15 km north-east of the study area. These values are mean values for the period 1994–2006 obtained from the Swedish Meteorological and Hydrological Institute (SMHI) and stored in the SKB Sicada database. The precipitation data are corrected for wind losses etc by 9% and 16% for Lövsta and Örskär, respectively, according to /Wern and Jones 2006/. Some 25–30% of the annual precipitation falls in the form of snow. The locations of the meteorological stations are shown in Figure 2-2 below.

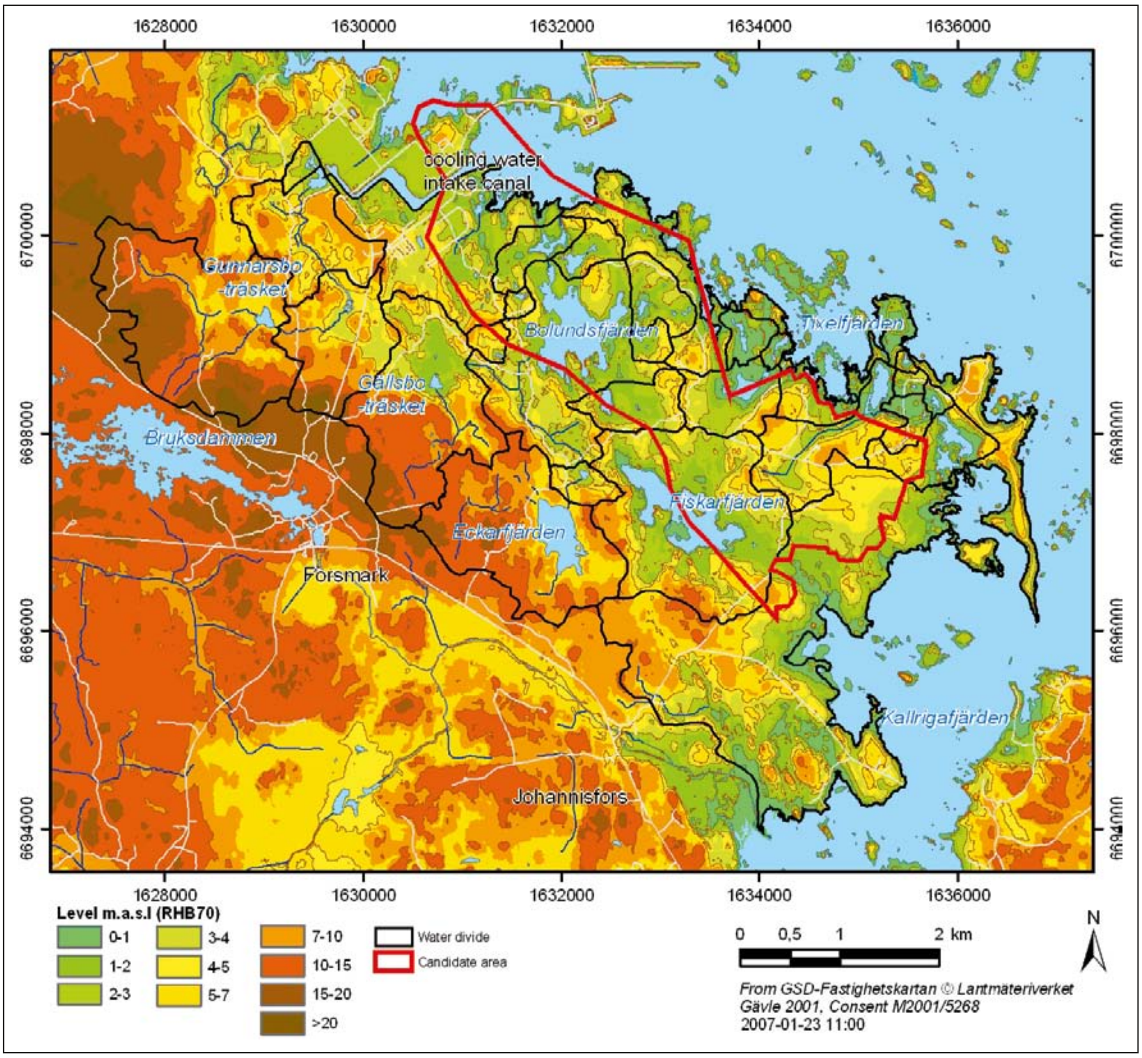

Figure 1-2. *Topographical map of the candidate area and its surroundings with surface water divides indicated.*

From regional data the mean annual precipitation in the Forsmark site investigation area has been estimated to 559 mm for the period 1961–1990 by SMHI /Johansson 2008, Appendix 1/. The average corrected precipitation for 2004–2006 at the two stations within the site investigation area was 537 mm/year. During the same period the potential evapotranspiration was calculated to 509 mm/year based on data from the two same stations. The winters are slightly milder at the coast than inland. The mean annual temperatures at Örskär and Films kyrkby were 5.5 and 5.0°C, respectively, for the period 1961–1990. During 2004–2006 the mean annual temperatures were higher, 7.1, 6.9 and 6.1°C at Örskär, Forsmark and Films kyrkby, respectively. The vegetative period, defined as the period with daily mean temperatures exceeding 5°C, was approximately 180 days for 1961–1990 compared with approximately 210 during 2004–2006. Based on the synoptic observations at Örskär, the mean annual global radiation was calculated to 930 kWh/m^2 for the period 1961–1990. At Forsmark, the mean annual global radiation was 949 kWh/m^2 during 2004–2006.

As described by /Brunberg et al. 2004/, 25 "lake-centred" catchments and sub-catchments have been delineated, ranging in size from 0.03 km^2 to 8.67 km^2. Forest is dominating and covers approximately 70% of the total catchment areas. Only in the southeast, at Storskäret, agriculture is an important land use, see Figure 1-1. The main lakes are Lake Fiskarfjärden (0.752 km^2), Lake Bolundsfjärden (0.609 km^2), Lake Eckarfjärden (0.282 km^2) and Lake Gällsboträsket (0.185 km^2). The lakes are shallow with mean depths and maximum depths ranging from approximately 0.1 to 0.9 m and 0.4 to 2.2 m, respectively /Brunberg et al. 2004/. Sea water flows into the most low-lying lakes during events of high sea water levels.

No major water courses flow through the catchment areas delineated in Figure 1-2. The brooks downstream Lake Gunnarsboträsket, Lake Eckarfjärden and Lake Gällsboträsket carry water most of the year, but can still be dry for long time periods during dry summers and early autumns such as in 2003 and 2006. Many brooks in the area have been deepened for considerable distances for draining purposes. However, the riparian zones are still wide at many locations and relatively large areas are inundated during periods of high water flows. Surface discharge is measured at four stations within the site investigation area. If the full three-year period of April 15, 2004 until April 14, 2007, for which discharge measurements are available from the station with the largest catchment, is considered, the corrected mean precipitation was 546 mm/year while the mean specific discharge of the largest catchment of 5.6 km^2 was 154 mm/year.

From a comparison of groundwater and surface water levels at the start and end of the period it can be concluded that the these storages were a little smaller at the end of the period but only corresponding to a difference of c. 5 mm/year. The mean precipitation was 13 mm/year lower than the 30-year normal precipitation estimated by SMHI /Johansson 2008, Appendix 1/. Since approximately 2/3 of the precipitation goes to evapotranspiration, the precipitation deficit should correspond to a discharge deficit of approximately 5 mm/year. These estimates of storage changes and precipitation deficit indicate that the measured three-year mean discharge should be close the long-term normal discharge. A rough estimate of the long-term overall water balance of the area is then as follows: P (precipitation) = 560 mm/year, ET (actual evapotranspiration) = 400–410 mm/year, and Q (runoff) = 150–160 mm/year.

Wetlands are frequent and cover more than 25% of some sub-catchments /Johansson et al. 2005/. Bogs are found in the most elevated parts of the area only. These bogs are small and the peat cover is not very thick (< 3 m) /Fredriksson 2004/. Fens and marshes are frequent in the more low-lying parts of the area. The peat in the wetlands can rest directly on till, or be underlain by gyttja and/or sand and clay above the till. This means that the hydraulic contact with the surrounding groundwater system varies among the wetlands in the area.

A map of the Quaternary deposits (QD) in the central terrestrial part of the site investigation area is shown in Figure 1-3. From this map, it is obvious that till is the dominating Quaternary deposit, covering approximately 75% of the terrestrial area. Bedrock outcrops are frequent, but constitute only approximately 5% of the area. Wave-washed sand and gravel, clay, gyttja clay and peat cover 3–4% each. The only glaciofluvial deposit, the Börstilåsen esker, runs in a north-south direction along the coast (cf. the "green belt" on the map, Figure 1-3). The Quaternary deposits are shallow, usually less than 5 m deep /Hedenström et al. 2008/. The greatest depth to bedrock recorded in a drilling southeast of Lake Fiskarfjärden was 16 m.

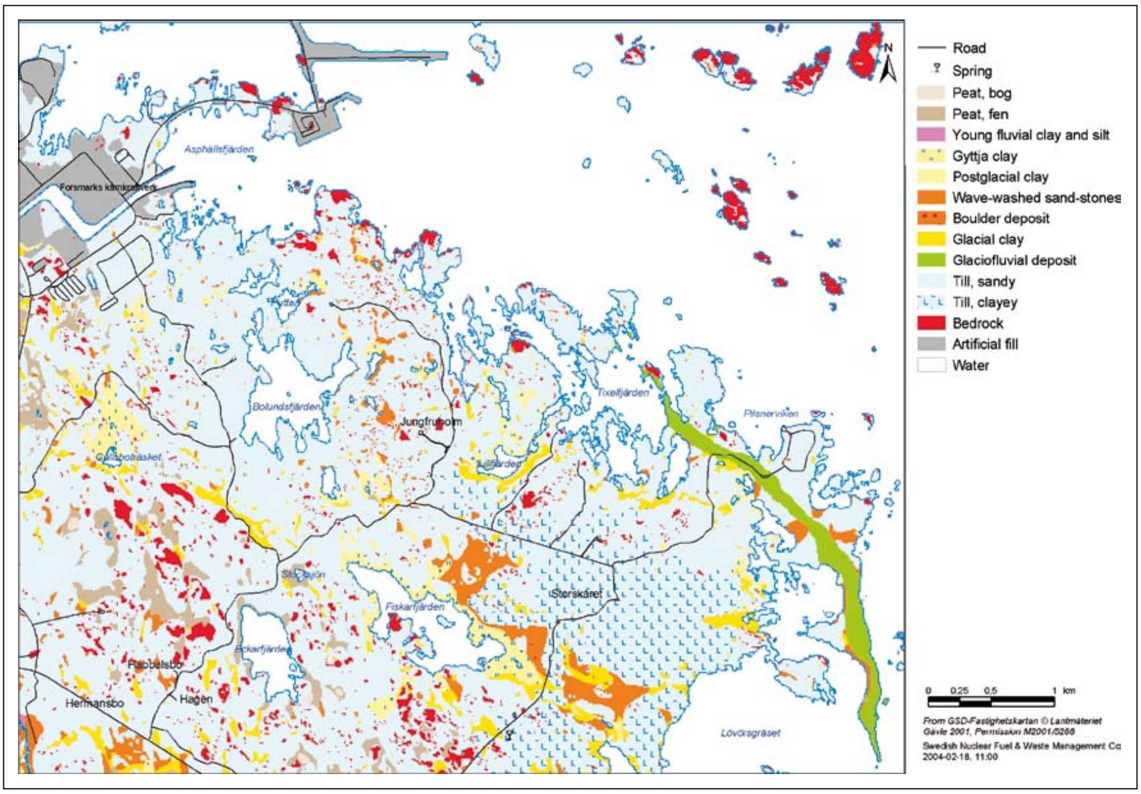

Figure 1-3. *Detailed map of Quaternary deposits /Sohlenius et al. 2004/.*

The hydraulic properties of the till are mainly determined by the grain size distribution, the compactness, and structures such as lenses of sorted material. From generic and site-specific data it is known that in the uppermost part of the till, the hydraulic conductivity and specific yield are much higher than further down the profile, see e.g. /Lind and Lundin 1990, Lundin et al. 2005/. This is mainly due to soil forming processes, probably with ground frost as the single most important process, resulting in higher porosity and formation of macro-pores. However, wave washing also implies that the till at exposed locations is coarser at the ground surface, and at some locations coarse out-washed material has been deposited.

Based on generic and site specific data, the saturated hydraulic conductivity in the uppermost part of the till can be estimated to 10^{-5}–10^{-4} m/s and the specific yield to between 10% and 20%, with the higher values close to the surface. The total porosity can typically be estimated to 30–40% mainly depending on depth. Below the depth interval strongly influenced by the soil forming processes, the hydraulic conductivity and the porosity of the till are considerably lower. The results from the slug tests indicate a higher hydraulic conductivity at the Quaternary deposit/bedrock interface than in the till itself, with geometric mean values of $1.2 \cdot 10^{-5}$ m/s and $1.3 \cdot 10^{-6}$ m/s, respectively /Johansson 2008/. From site specific and generic data, the total porosity and specific yield of the till below the upper c. 0.5 metre can be estimated to 20–30% and 2–5%, respectively /Johansson 2008/. The hydraulic conductivity values given for till below the uppermost c. 0.5–1 m are horizontal conductivities. The site-specific measurements indicate a K_h/K_v-ratio (K_h is the horizontal and K_v the vertical hydraulic conductivity) of approximately 30 below this depth /Johansson 2008/.

For the only glaciofluvial deposit in the area, the Börstilåsen esker, the obtained hydraulic conductivity of $2 \cdot 10^{-4}$ m/s is relatively low, and the storativity of $2 \cdot 10^{-3}$ indicates mainly confined conditions /Werner et al. 2004/. Site-specific hydraulic data for clay, gyttja and peat are relatively sparse /Johansson 2004, Werner and Lundholm 2004a, Alm et al. 2006/. However, the available data indicate a horizontal hydraulic conductivity of c. $3 \cdot 10^{-7}$ m/s below the uppermost 0.5–1 m of the soil profile for all three deposits. Also for these deposits a K_h/K_v-ratio of approximately 30 was obtained /Johansson 2008/.

The stratigraphy of bottom sediments in lakes has been investigated, and typical profiles have been identified for some of the lakes /Hedenström 2003, Hedenström 2004, Vikström 2005/. Typically, the sediment stratigraphy from down and up is glacial and/or postglacial clay, sand and gravel, and nested layers of gyttja in different fractions. The clay layer is missing in parts of the area below Lake Bolundsfjärden. However, pumping tests in the vicinity of this lake still indicate a very limited hydraulic contact between the lake and the groundwater in till below the lake /Werner and Lundholm 2004a, Gokall-Norman and Ludvigson 2007ab/.

The bedrock hydrogeology reveals a significant hydraulic anisotropy within the tectonic lens, which covers the body of the candidate area. The upper c. 150 m of bedrock contains high-transmissive horizontal fractures/sheet joints. These fractures/sheet joints occur at different elevations in the percussion drilled boreholes, but are found to interconnect hydraulically across large distances (2 km). The bedrock in between the horizontal fractures/sheet joints, however, is considerably less conductive (hydraulic conductivity c. $1\cdot10^{-11}$ –$1\cdot10^{-8}$ m/s) except where it is intersected by transmissive steeply-dipping or gently-dipping deformation zones.

Below the uppermost c. 150 m of bedrock there are no high-transmissive horizontal fractures/sheet joints and the conductive fracture frequency becomes very low and the fractures fairly low-transmissive. In some of the 1,000 m deep cored boreholes there are almost no flowing fractures observed below c. 150 m depth. A section illustrating the conceptual hydrogeological model of the Quaternary deposits and the upper bedrock at the Forsmark site is shown in Figure 1-4.

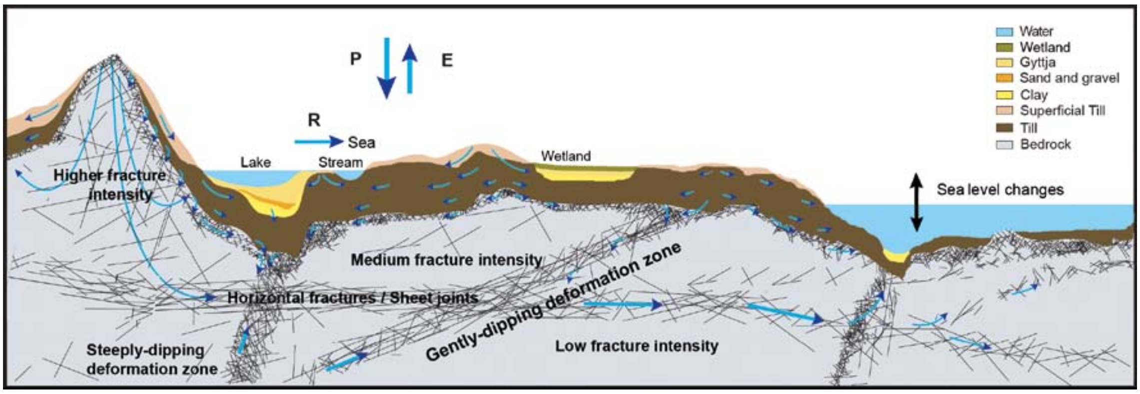

Figure 1-4. *Section illustrating the conceptual hydrogeological model of the Quaternary deposits and the upper bedrock at the Forsmark site /Follin et al. 2007a/.*

2 Presentation of data

2.1 Time series data

2.1.1 Introduction to the time series data

There are five principal time series datasets reviewed in this document. Those are time series of meteorological data, surface water levels, surface water discharge, and groundwater levels in the Quaternary deposits and in the bedrock. The installation of monitoring equipment to measure these time series has been an ongoing process in the Forsmark site investigation area. Figure 2-1 gives an historical overview of the number of available data records for each dataset from January 2003 through the March 2007 data freeze 2.3. The short-term variations in the number of available data are due to malfunctions of equipments and specific tests in some wells.

All data used in the present report are derived from SKB's Sicada and GIS databases. In Table 2-1 references are given to SKB P-reports up to data freeze 2.3 in which data have been continuously presented during the site investigation. All elevation data are given in the RHB70 national height system.

The meteorological data of most concern in this study were precipitation (P) and potential evapotranspiration (PET) time series. P was measured and PET was calculated at two stations in the study area from May 2003, but with some intervals of missing data. This study also utilized longer P and PET time series data from close-by SMHI stations for comparison.

Surface water levels were measured in the sea at two locations and in six of the larger lakes in the study area (Bolundsfjärden, Eckarfjärden, Fiskarfjärden, Norra Bassängen, Gällsboträsket, and Lillfjärden). Surface water discharges in streams were measured at four flume gauging stations /Johansson 2005a/. The first station became operational in April 2004 and the other three followed eight months later in December 2004.

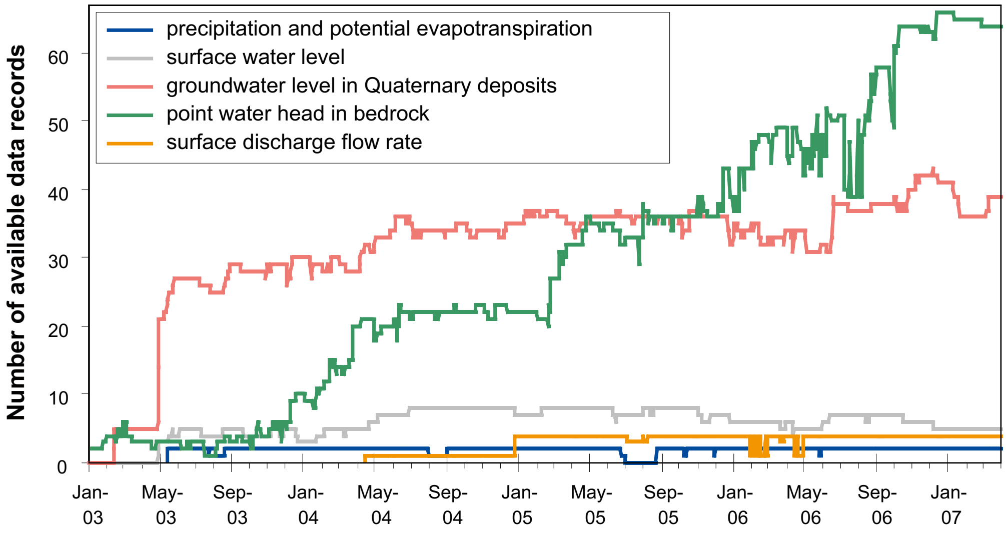

Figure 2-1. Overview of the availability of data from time series of meteorological data, surface water levels, surface discharge, and groundwater levels in the Quaternary deposits and in the percussion-drilled boreholes in bedrock.

Table 2-1. Available meteorological, hydrological and near-surface hydrogeological data with references to the corresponding reports in the SKB P-report series.

Available site data Data specification	Reference
Meteorological data	
Regional data	
Precipitation, temperature, wind, humidity and global radiation up to March 2007	Lindell et al. 2000, Larsson-McCann et al. 2002, Wern and Jones 2006, Wern and Jones 2007a, Wern and Jones 2007b, Sicada
Site Investigation data	
Precipitation, temperature, wind, humidity, global radiation and potential evapotranspiration June 2003–March 2007 from the meteorological stations at Högmasten and Storskäret	Juston och Johansson 2005, Wern and Jones 2006, Wern and Jones 2007a, Wern and Jones 2007b, Sicada
Snow depth, ground frost and ice cover	Aquilonius and Karlsson 2003, Heneryd 2004, Heneryd 2005, Heneryd 2006, Heneryd 2007, Sicada
Hydrological data	
Regional data	
Regional discharge data	Lindell et al. 2000, Larsson-McCann et al. 2002, Sicada
Site Investigation data	
Geometric data on catchment areas, lakes and water courses	Brunberg et al. 2004, Brydsten och Strömgren 2005, SKB GIS
Installation of automatic discharge gauging stations	Johansson 2005a
Automatic discharge measurements	Johansson and Juston 2007, Sicada
Manual discharge measurements	Nilsson et al. 2003, Nilsson and Borgiel 2004, Johansson 2005b, Nilsson and Borgiel 2005, Nilsson and Borgiel 2007, Sicada
Installation of surface water level gauges	Johansson 2003, Werner and Lundholm 2004b
Level measurements in lakes and the sea	Nyberg et al. 2004, Nyberg and Wass 2005, Nyberg and Wass 2006, Nyberg and Wass 2007, Sicada
Hydrogeological data	
Inventory of private wells	Ludvigson 2002
Installation of groundwater monitoring wells, abstraction wells and BAT filter tips	Johansson 2003, Johansson 2004, Werner et al. 2004, Werner and Lundholm 2004b, Werner et al. 2006
Groundwater levels in QD and bedrock	Nyberg et al. 2004, Nyberg and Wass 2005, Nyberg and Wass 2006, Nyberg and Wass 2007, Sicada

In total, groundwater levels were automatically registered in 51 groundwater monitoring wells in Quaternary deposits. These include eight boreholes that were installed in till under surface waters. Measurements in many of these wells started in May 2003 and this month is therefore generally taken as the first month of time series analysis in this report. Most groundwater time series from these wells were interrupted for one or more intervals of various lengths after they came online; hence the number of available data records is not constant through the study period (Figure 2-1). The maximum number of wells monitored simultaneously was 43.

The number of percussion-drilled boreholes in the bedrock producing point water head data increased steadily during the study period. As of March 2007, there were 38 percussion-drilled wells. Most of these wells were sectioned with between 1–3 packers. The maximum number of borehole sections measured simultaneously was 66.

It should be noted that, due to considerable differences in groundwater salinity and thereby in density with depth, groundwater levels measured in percussion-drilled boreholes in the bedrock should be regarded as point water heads. For some of the wells, these heads need to be transformed to so-called environmental water heads in order to interpret vertical groundwater flow components (for a discussion of groundwater levels, point water heads and environmental water heads, see /Juston et al. 2007, Johansson 2008/).

2.1.2 Meteorological data

Figure 2-2 and Figure 2-3 show locations for Högmasten and Storskäret meteorological stations in the Forsmark site investigation area, as well as for several nearby SMHI stations.

The following parameters are measured at Högmasten and Storskäret:

- Precipitation.
- Air temperature.
- Barometric pressure (only at Högmasten).
- Wind speed and direction.
- Air humidity.
- Global radiation (only at Högmasten).

© Lantmäteriverket Gävle 2007.
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Figure 2-2. *SKB's two meteorological stations within the Forsmark site investigation area, Högmasten and Storskäret, and nearby SMHI stations.*

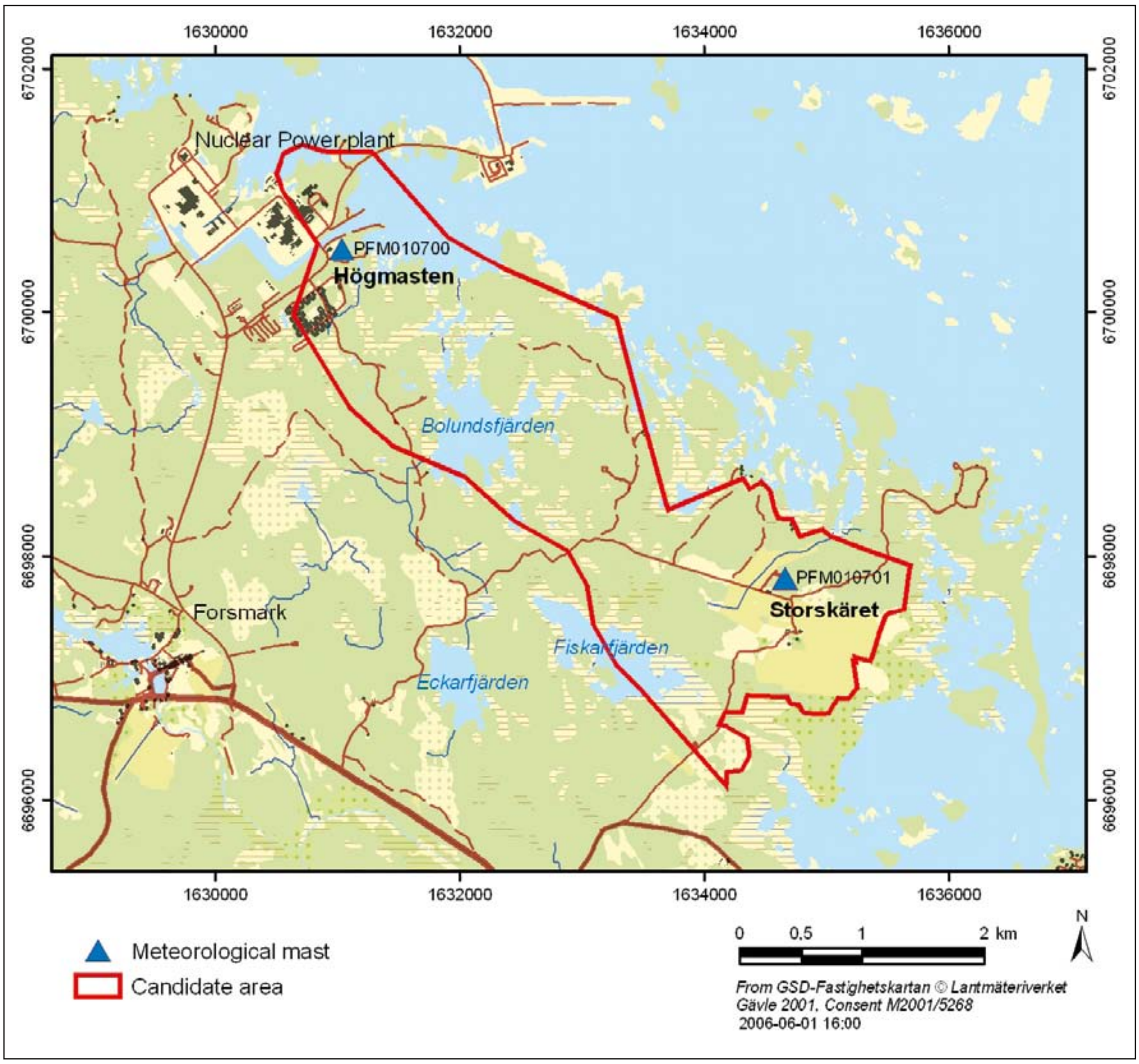

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Figure 2-3. *Detailed map of the locations of the meteorological stations, Högmasten and Storskäret, within the Forsmark site investigation area.*

The wind is measured at 10 m above ground level and the other parameters at 2 m. Data are collected every half-hour. The data values of the different parameters are valid for the following time periods:

- *Precipitation:* Accumulated sum of precipitation every 30 minutes. The 30-minutes precipitation value is the difference between two adjacent accumulated precipitation sums.
- *Air temperature:* 30-minutes mean of one-second values.
- *Barometric pressure:* 30-minutes mean of one-second values.
- *Wind speed and wind direction:* The last 10-minutes mean value for the preceding 30 minutes. Hence, for the 10:00 data the measurement is from 09:51 to 10:00.
- *Relative humidity:* 30-minutes mean of one-second values.
- *Global radiation:* 30-minutes mean of one-second values.

All precipitation data presented in this report are corrected for losses (i.e. precipitation is increased) according to /Alexandersson 2003/ (general methodology) and /Wern and Jones 2007a/ (SKB stations). The corrections largely compensate for wind losses. The monthly and annual corrections for the different stations are shown in Tables 2-3 and 2-4.

Table 2-3. Corrections of measured precipitation (increases, in percent) at SMHI's stations according to /Alexandersson 2003/.

	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
Film Kyrkby A	13	16	19	15	13	14	11	13	13	13	14	16	14
Söderby-Karlsäng D	10	11	10	10	12	12	9	9	8	8	8	9	10

Table 2-4. Corrections of measured precipitation (increases, in percent) at SKB's stations according to /Wern and Jones 2007a/.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Högmasten	13	14	13	11	10	10	10	10	10	10	11	12	11
Storskäret	13	14	13	11	10	10	10	10	10	10	11	12	11

The potential evapotranspiration, $E_{p,}$ is calculated from the Penman equation:

$$E_P = (\frac{\Delta \cdot (R_n - G)}{(\Delta + \gamma) \cdot L} + \frac{\gamma \cdot f(u) \cdot (e_s - e)}{(\Delta + \gamma)}) \cdot tstep$$

where

Δ	proportionality constant
R_n	net radiation flux density
G	heat flux density into ground
γ	psychrometric constant
$f(u)$	function of wind speed
e_s	saturated water vapor pressure
e	water vapor pressure
L	latent heat of vaporisation
$tstep$	time step

The method is described in detail in /Eriksson 1981/. Measured data every 30-minutes of temperature, relative humidity, wind speed and global radiation are required as input data to the equation to calculate the potential evapotranspiration. The wind speed is measured at 10 m above the ground but for the estimation of potential evapotranspiration the wind speed is re-calculated to a value representing 2 m above the ground. This is done by multiplying the measured value by a factor of 0.8. The net radiation is calculated from the measured global radiation and the albedo is set to 0.12 when the ground is not covered with snow and to 0.5 when there is a snow cover. The applied method included heat storage in the ground.

In general the meteorological measurements at Högmasten and Storskär have worked well. The only longer period of data loss was when the precipitation gauges were out of function from end of June until mid-August 2005.

In addition to the monitoring at the two meteorological stations, a set of meteorological winter parameters, i.e. snow depth, ground frost penetration depth and ice cover, have been measured and observed. In addition to these parameters, the water content of the snow was calculated from the weight of snow samples at every measurement. The snow depth and ice cover measurements started in the winter 2002/2003, while the ground frost and snow water content measurements started in the winter 2003/2004. The ground frost measurements were stopped after the 2005/2006 season. The measurements and observations were carried out weekly during the season. The locations of the monitoring points are shown in Figure 2-4.

In north-eastern Uppland, where the site investigation area is located, there is a relatively strong west-east gradient in precipitation. Figure 2-5 shows the 13 years of data available in the SKB Sicada database of annual total precipitation from three nearby precipitation stations maintained by SMHI at Lövsta, Östhammar, and Örskär. The figure also includes data from the station Söderby-Karlsäng established in 2004 (see Figure 2-2 for the location of the stations). The average precipitation at Lövsta, approximately 15 km west of Forsmark, was 690 mm, as compared with 492 mm at Örskär, a small island approximately 15 km north-east of Forsmark. In Figure 2-6 the annual precipitation at the same SMHI-stations is shown for the years 2004–2006 together with the average of the 13 years of data available in the SKB Sicada database.

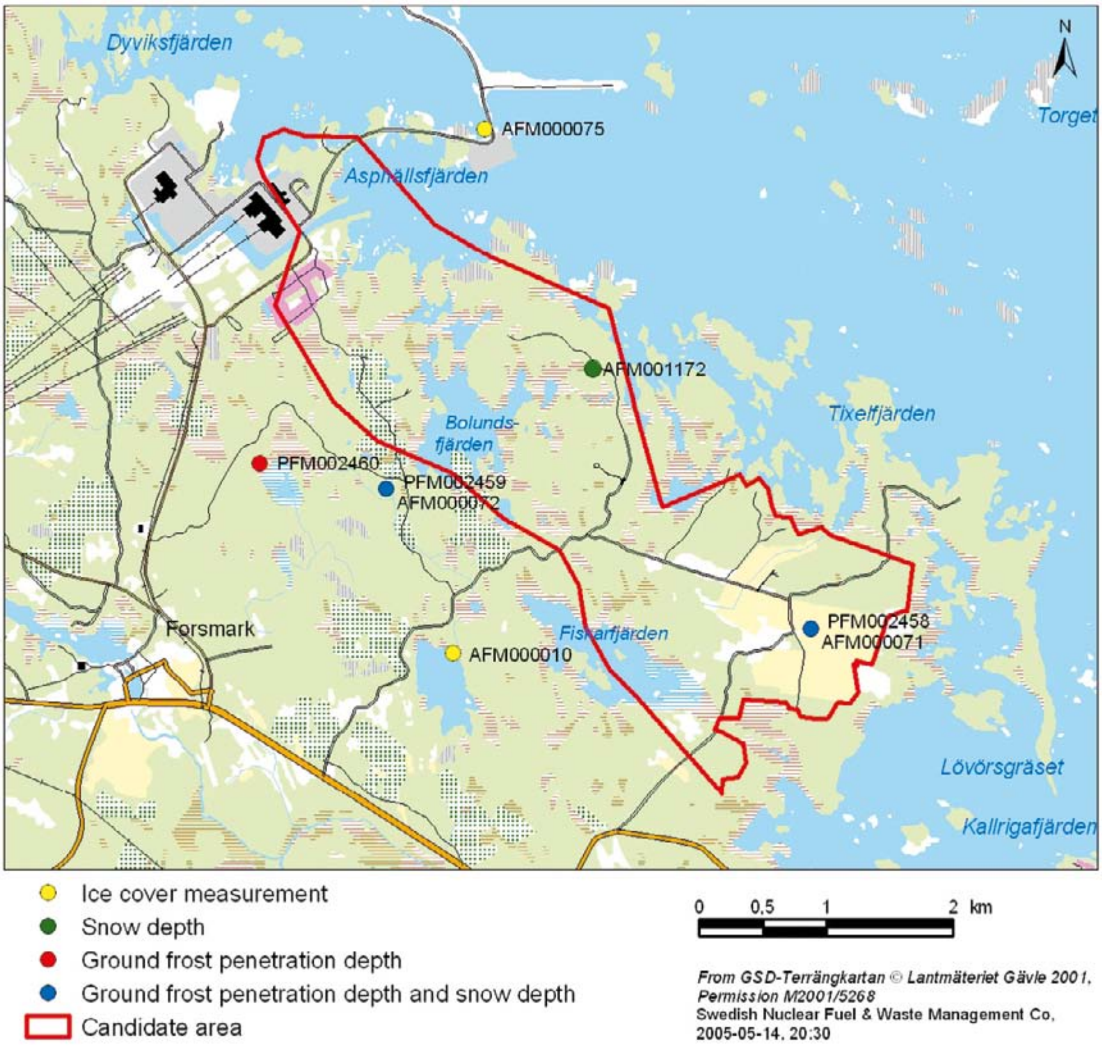


Figure 2-4. *Locations of monitoring points for meteorological winter parameters.*

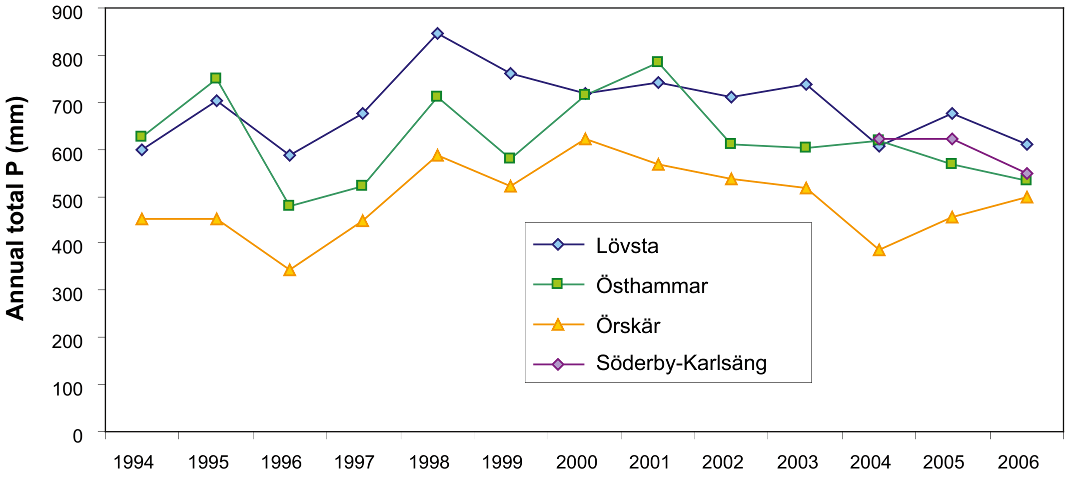


***Figure 2-5.** Annual corrected precipitation (P) at four regional SMHI stations (the station Söderby-Karlsäng was established 2004; data were missing at Örskär for November 1995).*

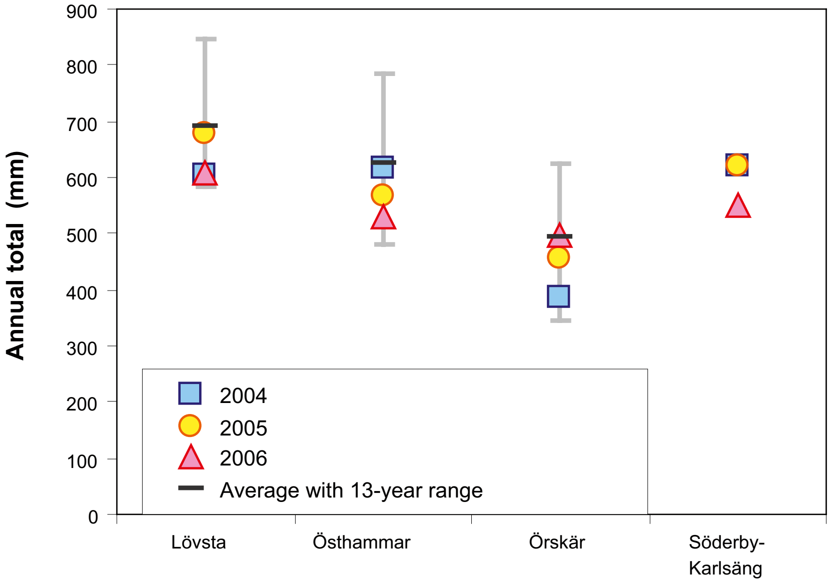


***Figure 2-6.** Precipitation data from SMHI-stations surrounding the site investigation area (the station Söderby-Karlsäng was established in 2004).*

Figure 2-7 shows daily corrected precipitation measured at Högmasten and Storskäret stations within the Forsmark site investigation area from May 14, 2003 through March 31, 2007. Figure 2-8 shows that daily data at these stations were well-correlated, particularly during non-summer months. The difference in correlation between daily precipitation during summer (defined here as June, July and August) and non-summer periods can be explained by localised convective storms that are typical during summer months.

Figure 2-9 presents monthly total precipitation for the two SKB stations and the three SMHI stations Lövsta, Östhammar and Örskär. Similar seasonal patterns are observable at these five stations, with Örskär typically reporting the lowest rainfall on a month-to-month basis.

In Figure 2-10 annual precipitation from SKB's stations in Forsmark, Högmasten and Storskäret, are presented together with data from the SMHI-stations, for the three full years of available data up to data freeze 2.3. Data for both hydrological and calendar years are shown (hydrological years October 2003–September 2006, and calendar years 2004–2006). Missing data at the SKB stations were estimated by regression analysis where the SMHI-stations Lövsta, Östhammar and Örskär were used.

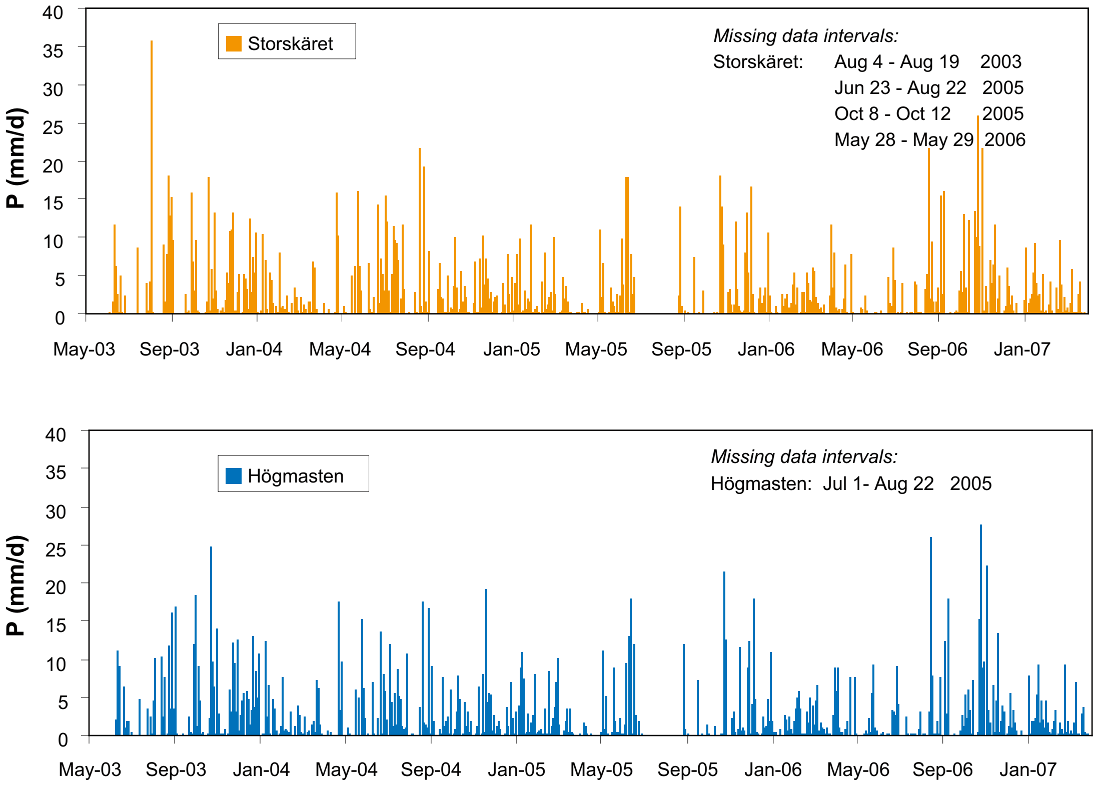


Figure 2-7. *Daily corrected precipitation (P) measured at Högmasten (PFM010700) and Storskäret (PFM010701). Tick marks on the X-axis indictate the first dates of the labelled months.*

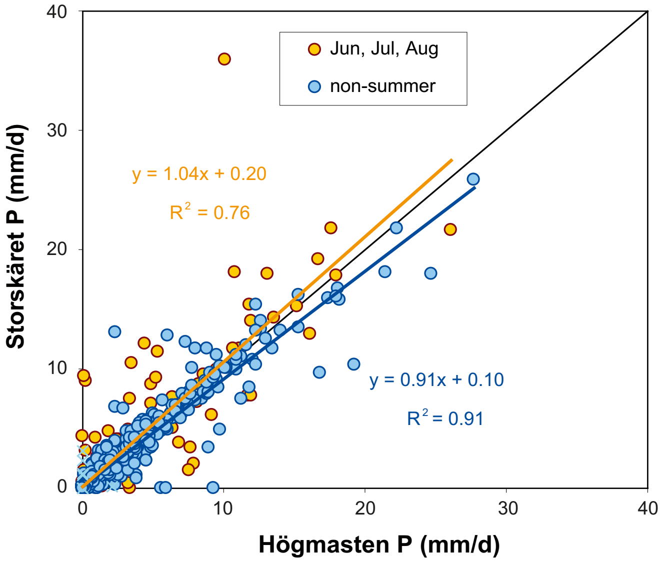


Figure 2-8. *Correlation of daily measured precipitation (P) at Högmasten (PFM010700) and Storskäret (PFM010701), shown separately for summer months and the remainder of the year.*

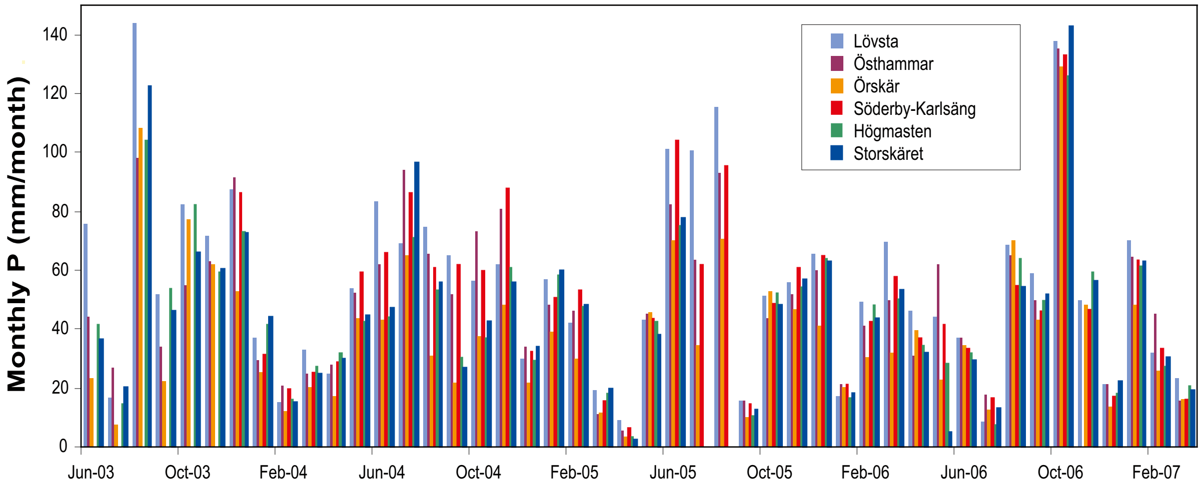
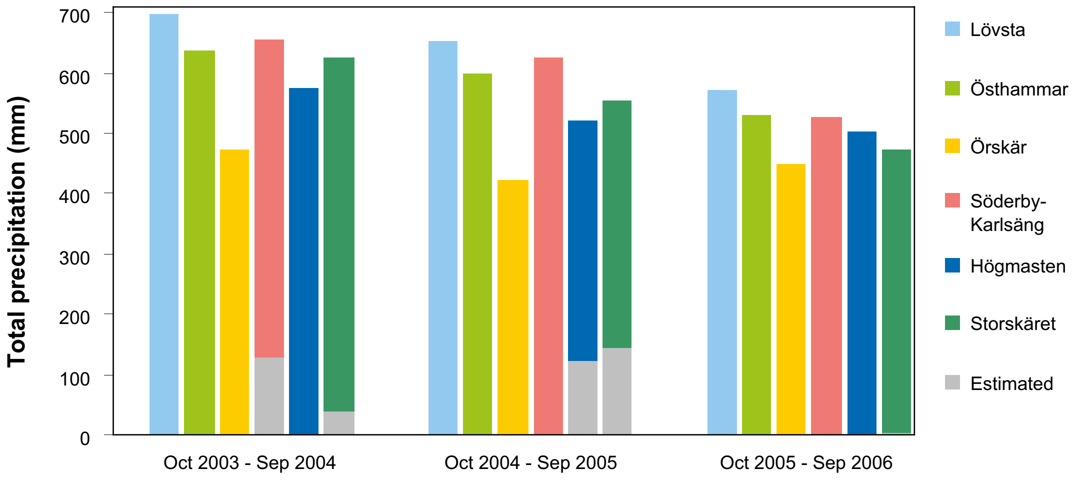


Figure 2-9. *Monthly total precipitation (P) time series measured at the two SKB stations (Högmasten and Storskäret) and four nearby SMHI stations (Lövsta, Östhammar, Örskär, and Söderby-Karlsäng).*



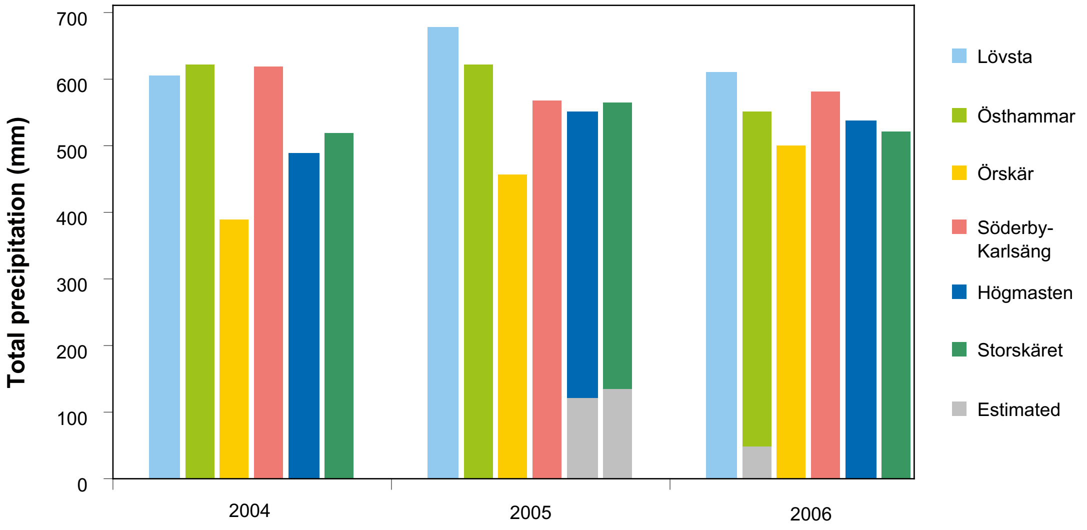


Figure 2-10. *Comparison of annual precipitation at the SKB stations, Högmasten and Storskäret, and at surrounding SMHI stations (upper graph: hydrological years, lower graph: calendar years).*

Table 2-5 presents annual precipitation data from Forsmark (averages of the Högmasten and Storskäret stations) for the same three-year periods as in Figure 2-10. In addition, data for the four-year period of June 2003–May 2007 are presented to make maximum use of site specific data.

Based on regional data the mean annual precipitation in the Forsmark site investigation area has been estimated by SMHI to 559 mm (with a standard deviation of 106 mm) for the period 1961–1990 /Johansson 2008, Appendix 1/. From Table 2-5 it can be concluded that the precipitation during the site investigation has been quite close to the long-term average. In Figure 2-11 monthly corrected precipitation is shown for the full four-year period of June 2003–May 2007 and in Figure 2-12 the average monthly precipitation during this period is compared with the long-term monthly averages calculated by SMHI. The annual averages for the two compared periods were 558 and 568 mm, respectively. In Figure 2-12 it can be seen that the seasonal variations during the period June 2003–May 2007 follow the long-term variations quite well, but with displacements between neighbouring months.

Figure 2-13 shows the water content in snow accumulations measured at three stations within site investigation area (see Figure 2-4 for the locations of the stations). Air temperature and snow water content data were used in this study primarily to calibrate a snowmelt model, which in turn was used to estimate a site average "surface inflow" time series with separately identified snowmelt and rainfall events.

Table 2-5. Annual, corrected, average precipitation at Forsmark (average of the Högmasten and Storskäret stations) for three different time periods.

Time period	Corrected precipitation (mm)
Jan. 2004–Dec. 2006	537
Oct. 2003–Sep. 2006	536
June 2003–May 2007	563

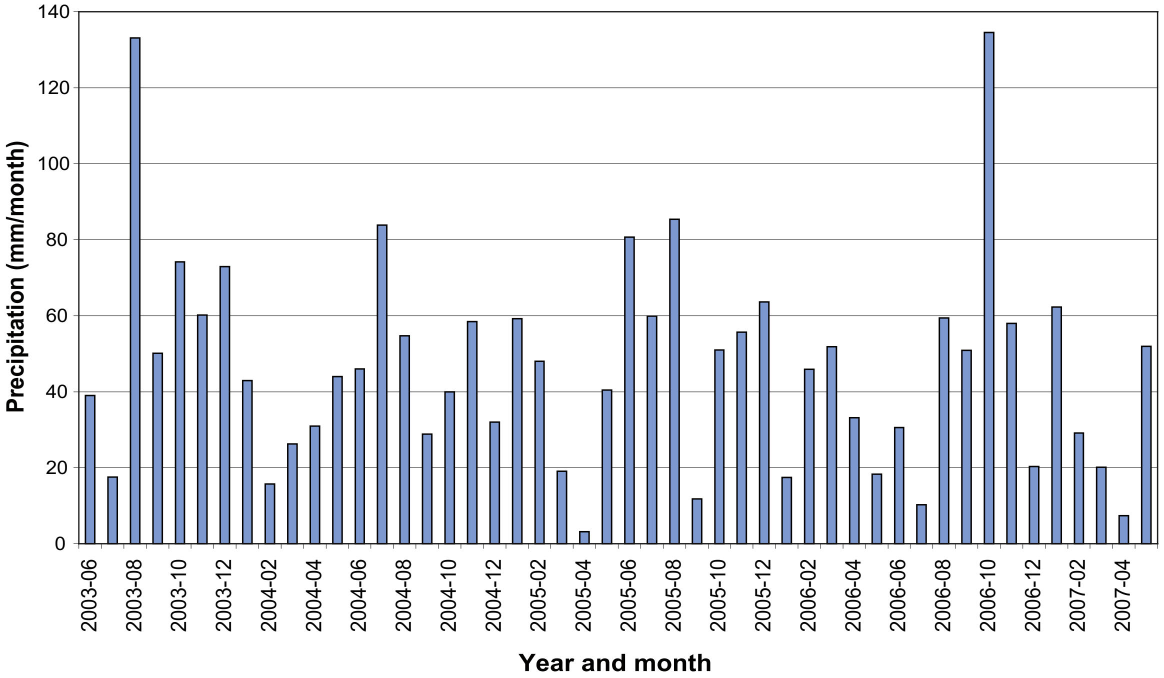


__Figure 2-11.__ Monthly precipitation at Forsmark (average of Högmasten and Storskäret data) for the full period of June 2003–May 2007.

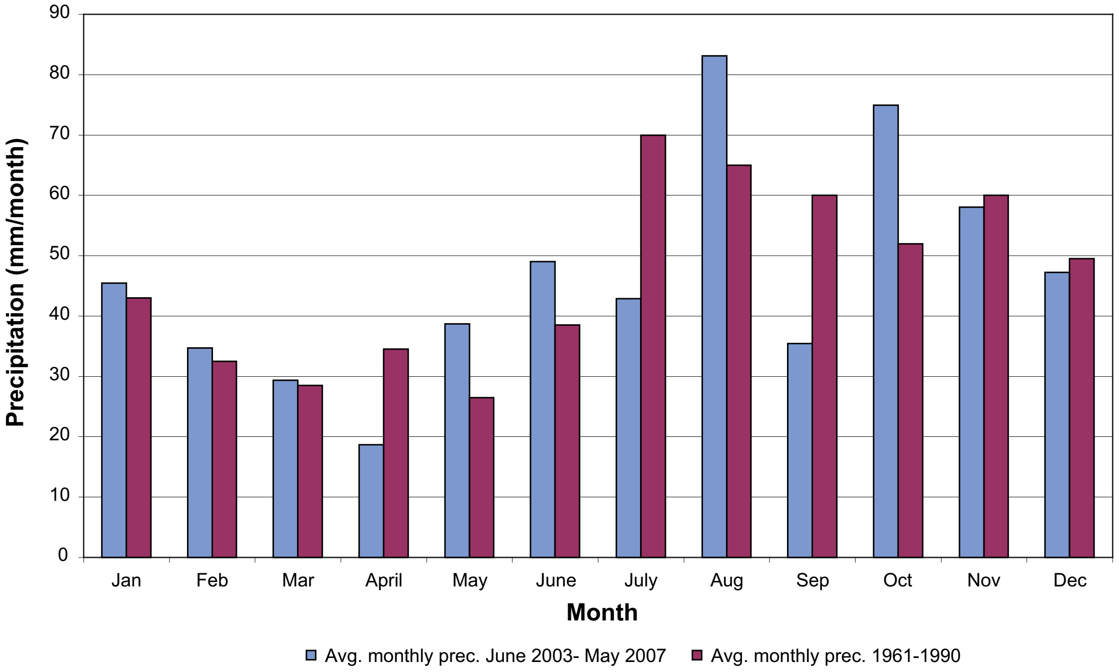


***Figure 2-12.** Average corrected monthly precipitation at Forsmark (average of Högmasten and Storskäret data) for full four-year period June 2003–May 2007 compared with the long-term average for the period 1961–1990 calculated by SMHI for Forsmark.*

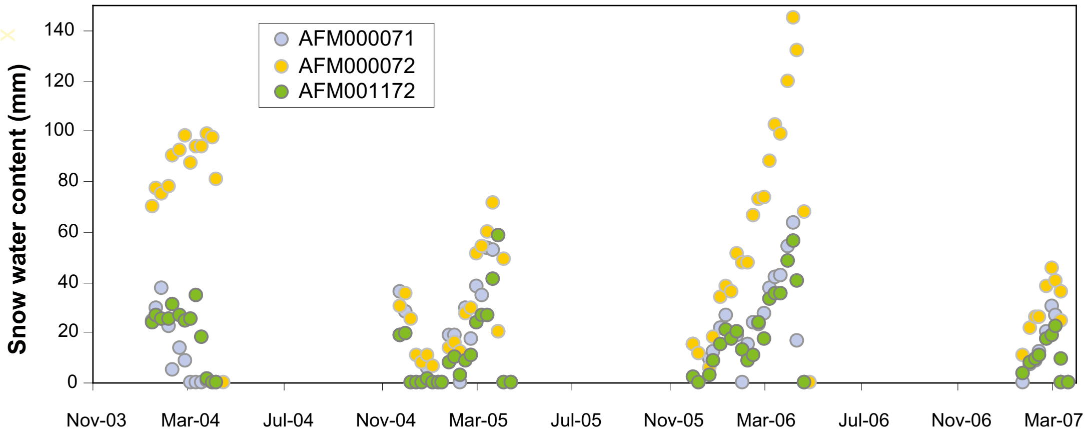


***Figure 2-13.** Average water content in accumulated snow at three locations across the study area.*

The average of mean daily air temperatures from Högmasten and Storskäret is shown in Figure 2-14. The two temperature time series measured at these stations were virtually identical and highly correlated ($R^2 = 0.99$). Monthly average temperature values for Forsmark (average of Högmasten and Storskäret) and surrounding SMHI stations for the period January 2003–March 2007 are shown in Figure 2-15.

The winters are slightly milder on the coast than inland. In Figure 2-16 annual average temperature cycles are shown for the inland station Film and the station at the small island Örskär for the period 1994–2006 and in Figure 2-17 the same cycles are shown for Film, Örskär and Forsmark (average of Högmasten and Storskäret) for the period 2004–2006 (see Figure 2-2 for locations of the stations).

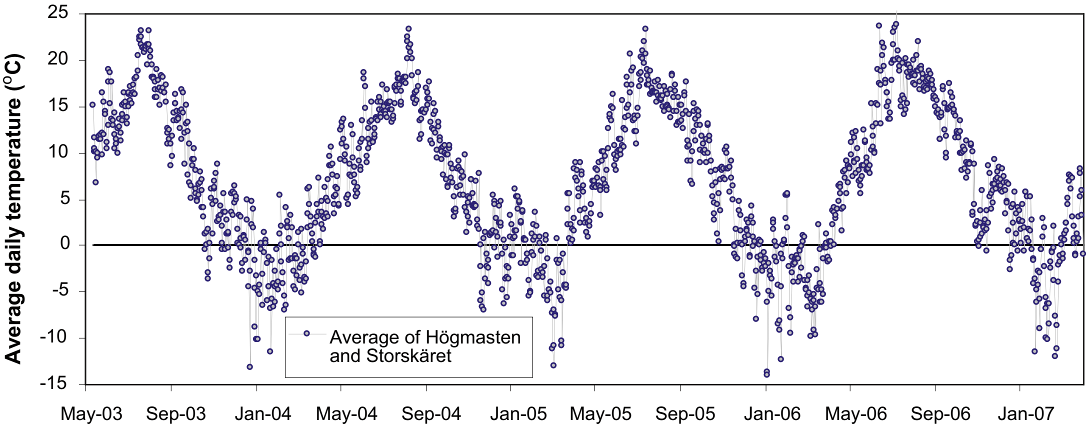


Figure 2-14. Daily average air temperature from measurements at Högmasten and Storskäret. Tick marks on the X-axis indictate the first dates of the labelled months.

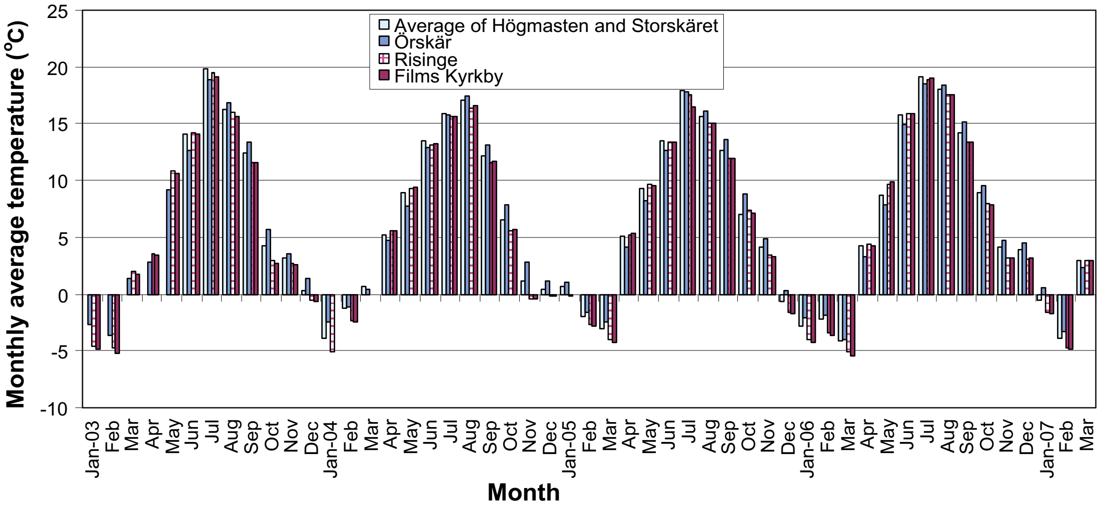


Figure 2-15. Monthly average temperatures from Forsmark (average of Högmasten and Storskäret) and nearby SMHI stations.

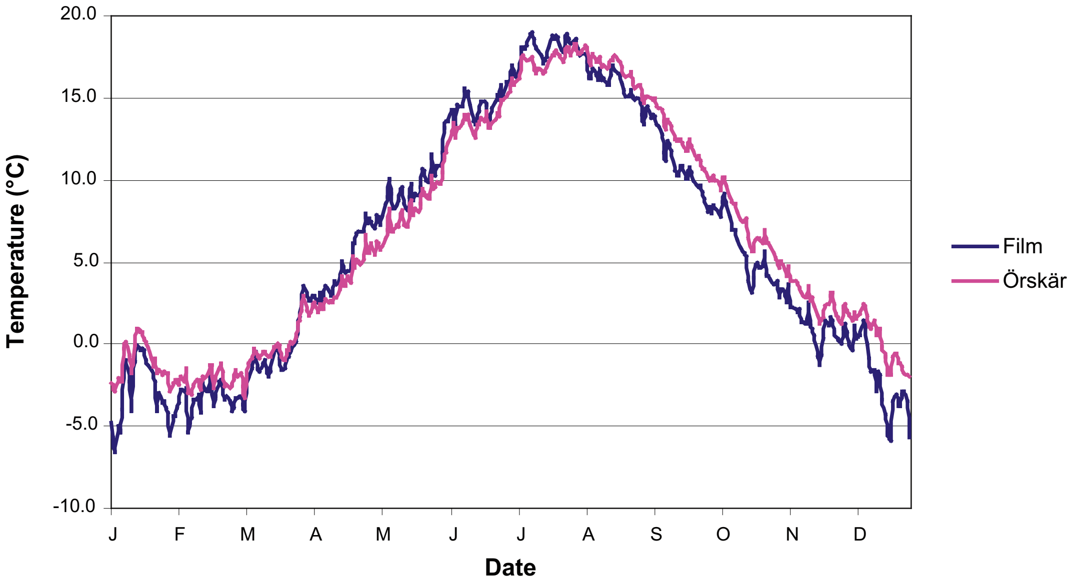


Figure 2-16. Average annual temperature cycles for the SMHI stations Film and Örskär for the period 1961–1990.

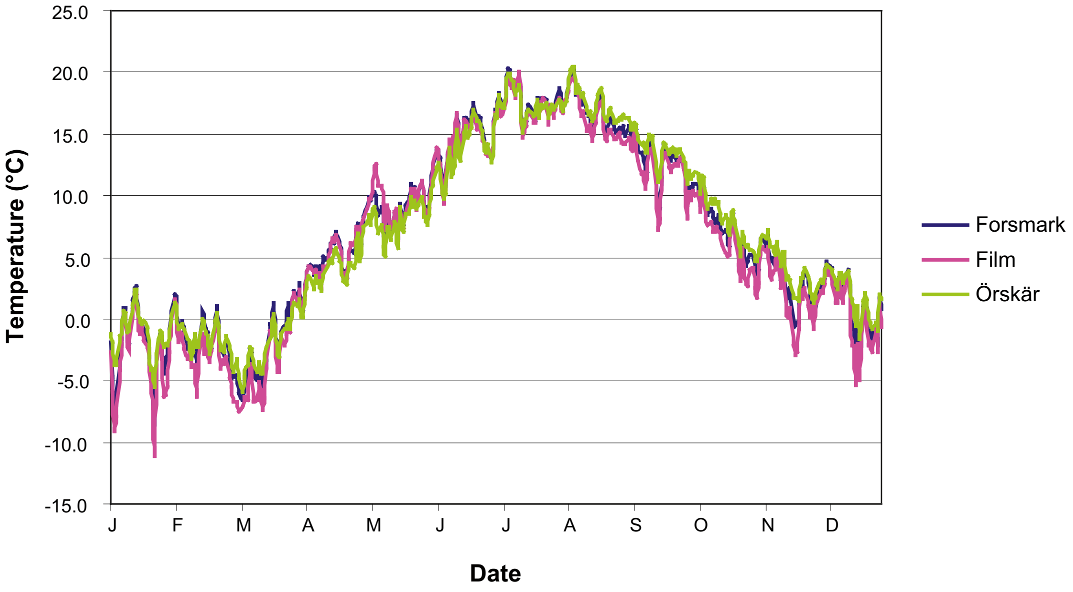


Figure 2-17. Average annual temperature cycles for the SMHI stations Film and Örskär and for Forsmark (average of data for Högmasten and Storskäret) for the period 2004–2006.

The mean annual temperatures at Örskär and Films kyrkby were 5.5 and 5.0°C, respectively for the period 1961–1990. During 2004–2006 the mean annual temperatures were higher, 7.1, 6.9 and 6.1°C at Örskär, Forsmark and Films kyrkby, respectively. The vegetative period, defined as the period with daily mean temperatures exceeding 5°C, was approximately 180 days/year for 1961–1990, which can be compared with the approximately 210 days/year obtained for the years 2004–2006.

Daily mean barometric pressure is shown in Figure 2-18 for Forsmark (Högmasten) and Örskär. The data for the two stations are almost identical. For the period with data available from both stations, the mean barometric pressures were 1,011.9 and 1,011.7, respectively. The minimum and maximum barometric pressures were 970 and 1,045 for Forsmark and 970 and 1,044 for Örskär.

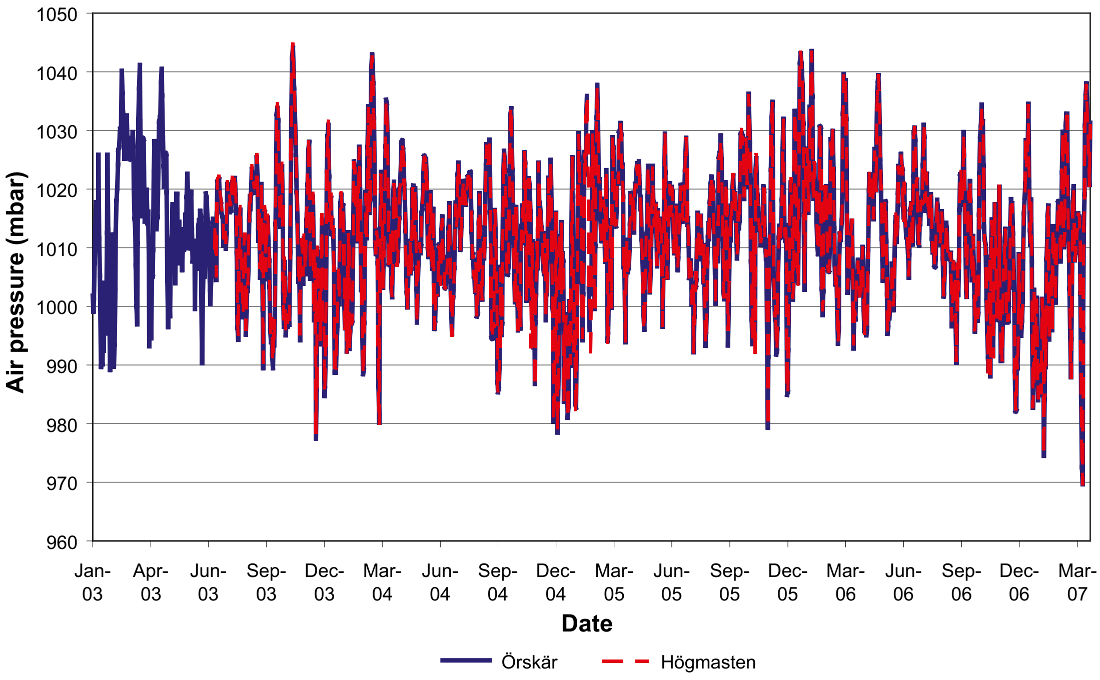


Figure 2-18. Barometric pressure at the SKB station Högmasten and at the SMHI station Örskär.

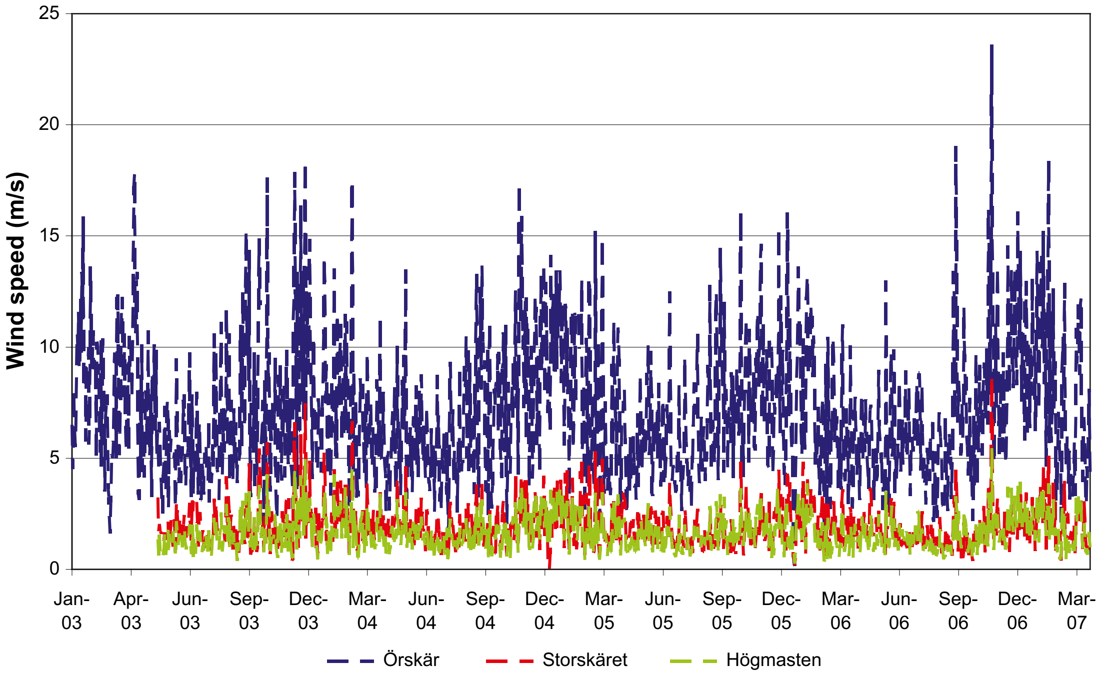


***Figure 2-19.** Wind speed the SKB stations Storskäret and Högmasten, and at the SMHI station Örskär.*

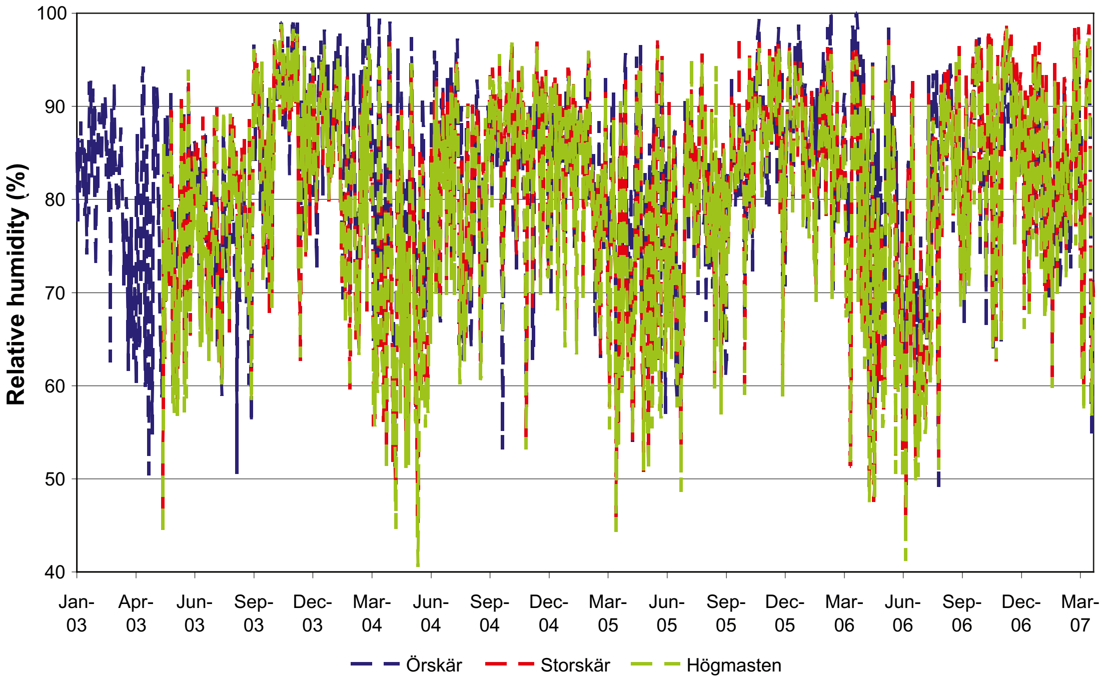


***Figure 2-20.** Relative humidity at the SKB stations Storskäret and Högmasten, and at the SMHI station Örskär.*

The wind speeds at the two Forsmark stations are much lower than at Örskär. The main reason for the big difference is that Örskär has a highly exposed location on a small island. Furthermore, the Forsmark stations were located to represent the conditions above an area dominated by forest for calculation of evapotranspiration. The average daily wind speeds at Högmasten, Storskäret and Örskär were for the period with simultaneous measurements 1.7, 1.9, and 7.1 m/s, respectively. The maximum daily average wind speed was 23.2 for Örskär, while it was only 5.5 m/s for Högmasten and 8.7 m/s for Storskäret.

The dominating wind direction at Forsmark (average of Storskäret and Högmasten) is from south-west, see Figure 2-21.

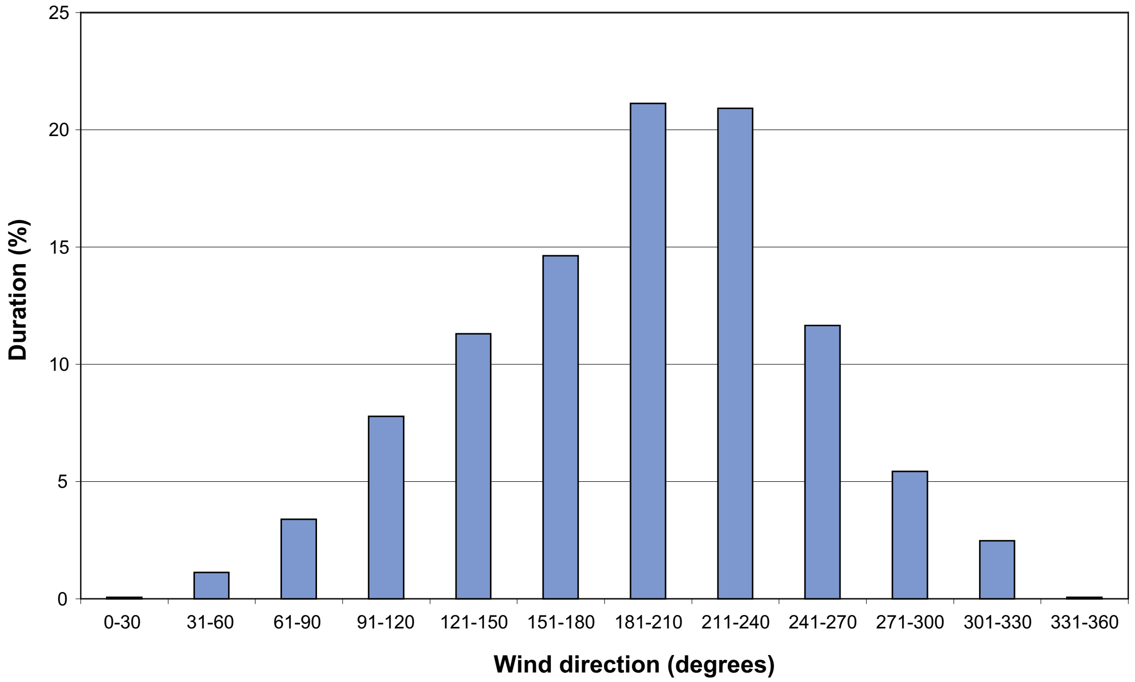


Figure 2-21. *Wind directions at Forsmark. Average of daily data from Storskäret and Högmasten, May 12 2003–March 31 2007, all values < 0.5 m/s removed (wind from north: 0°, east: 90°, south: 180°, west: 270°).*

Monthly means and monthly sums of global radiation for the period 2004–2006 from Forsmark (Högmasten) are shown in Figures 2-22 and 2-23. At Forsmark (Högmasten), the annual global radiation was 949 kWh/m^2 during 2004–2006. As a comparison, based on the synoptic observations, the annual global radiation at Örskär was calculated to be 930 kWh/m^2 for the period 1961–1990.

In Table 2-6 the annual "potential evapotranspiration" for a short crop, calculated by the Penman equation, is given for the same time periods as for the precipitation in Table 2-5. Daily and mean monthly "potential evapotranspiration" values at Forsmark (Högmasten) for the period June 2003 until May 2007 are shown in Figures 2-24 and 2-25, respectively.

During the period of measurements there was a snow cover for 105 days/season and 80 days/season on average in forest land and open land, respectively. In general there was a snow cover from end of November/beginning of December until end of March/beginning of April. However, during some of the seasons there were periods when the snow cover disappeared. The maximum snow depth registered was 48 cm in forest land (at AFM000072) and 25 cm in open land, and the maximum snow water content was 144 and 64 mm, respectively, see Table 2-7. For details on the measurements, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.

Ground frost penetration was measured during three seasons, 2003/04–2005/06, at two sites in forest land and at one site in open land. Ground frost was present during 40 and 80 days/season in forest land open land, respectively. The maximum ground frost depth in open land was 46 cm while the maximum depth in forest land was only 8 cm. For details on the measurements, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.

The ice-cover registrations were made at Lake Eckarfjärden and at a bay of the Baltic Sea close to the Forsmark harbour. Lake Eckarfjärden was considered to be representative for the lakes of the area. This lake was usually covered with ice from November/December until beginning of April, while the Baltic Sea bay was frozen up approximately a month later but had an ice break-up approximately at the same time as the lake. On average Lake Eckarfjärden and the Baltic Sea bay were covered by ice 128 and 98 days/season, respectively. The ice-cover registrations are summarised in Table 2-8. For details on the registrations, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007/.

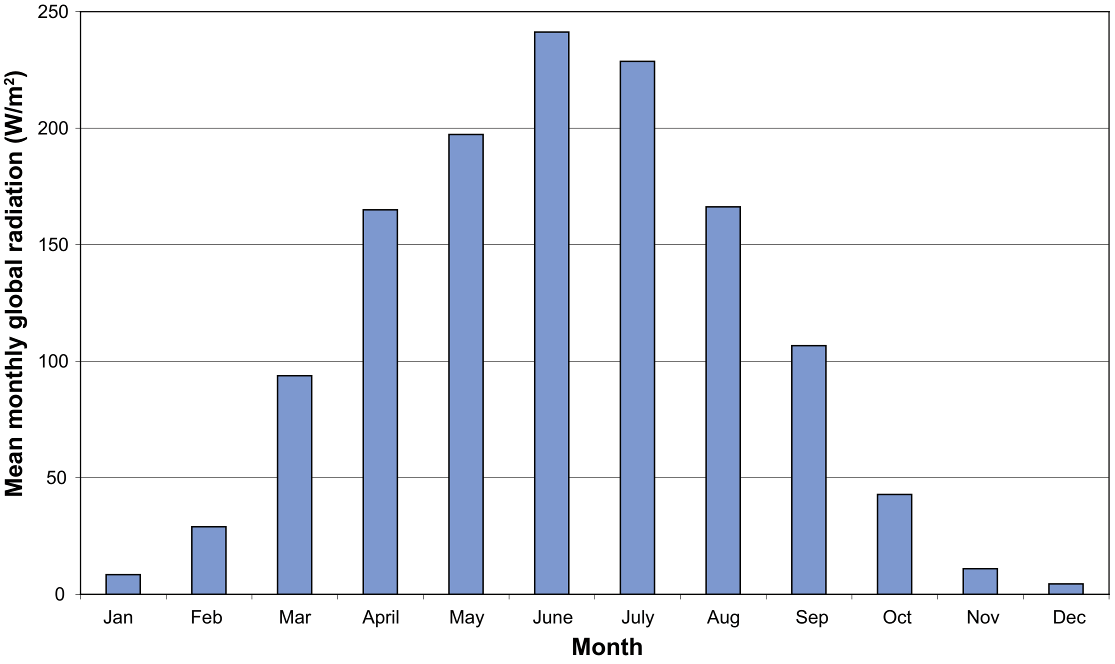


Figure 2-22. Monthly means of global radiation (W/m^2) at Forsmark (Högmasten) for the period 2004–2006.

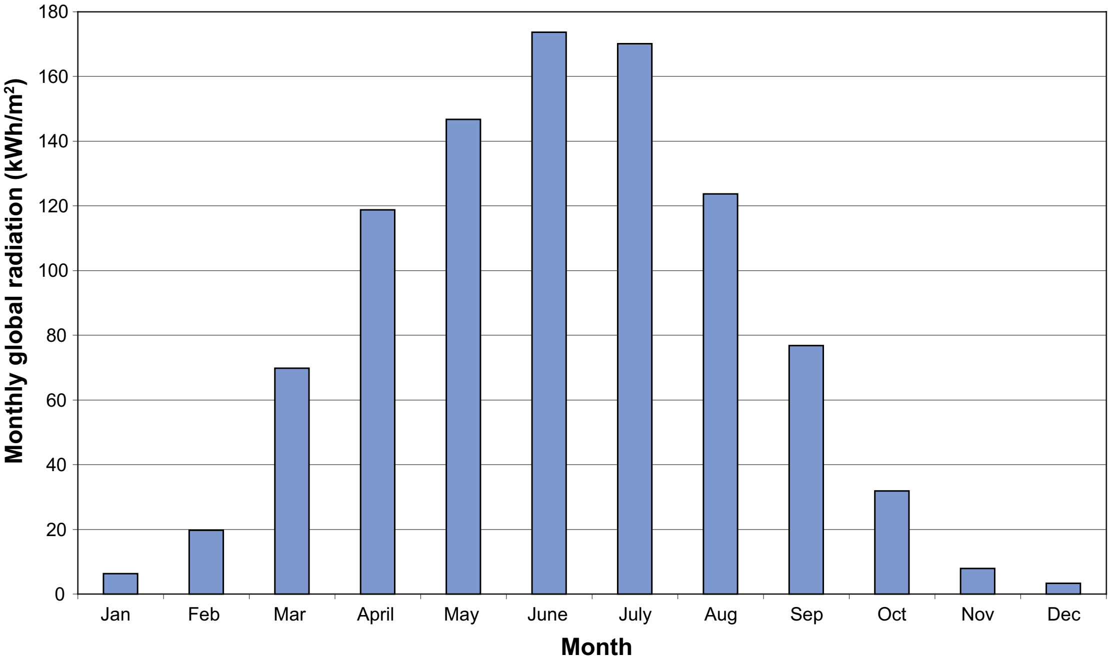


Figure 2-23. Monthly sums of global radiation energy (kWh/m^2) at Forsmark (Högmasten) for the period 2004–2006.

Table 2-6. Calculated "potential evapotranspiration" at Forsmark (Högmasten) for three different time periods.

Time period	Potential evapotranspiration (mm)
Jan. 2004–Dec. 2006	509
Oct. 2003–Sep. 2006	507
June 2003–May 2007	526

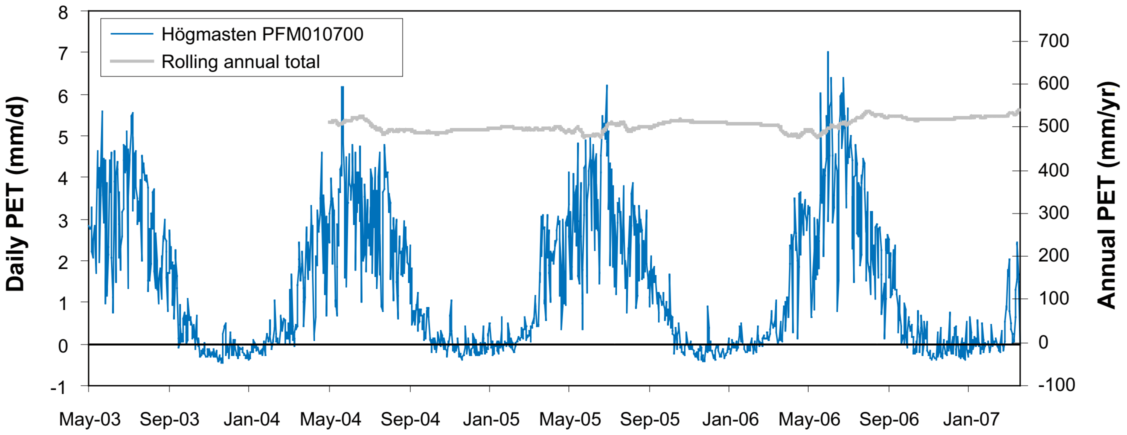


Figure 2-24. *Daily potential evapotranspiration (PET) time series estimated from measured meteorological data at Högmasten, and the rolling annual total PET calculated from the daily time series. Tick marks on the X-axis indictate the first dates of the labelled months.*

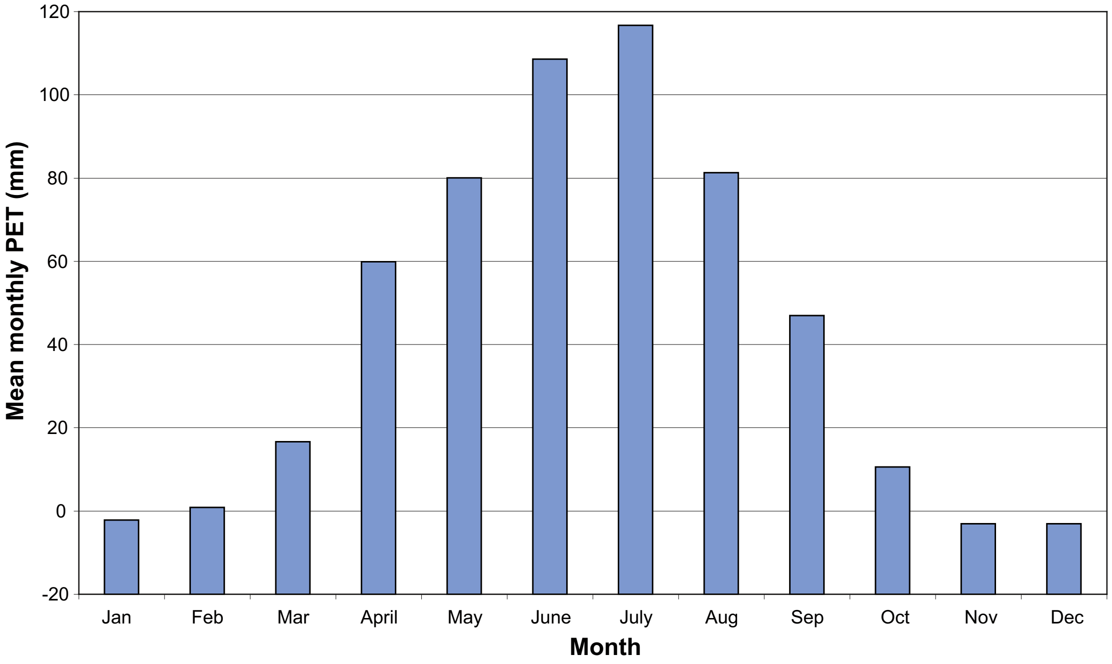


Figure 2-25. *Mean monthly "potential evapotranspiration" at Forsmark (Högmasten) during the period June 2003–May 2007.*

Table 2-7. Summary of snow measurements at Forsmark 2002/03-2006/07.

Open land (AFM000071)	No. of days with snow cover	Maximum snow depth (cm)	Maximum snow water content (mm)
2002/03	85	20	–
2003/04	75	19	37
2004/05	85	21	53
2005/06	120	25	64
2006/07	40	17	30
Forest land (average of AFM000072 and AFM001172)			
2002/03	125	25*	–
2003/04	105	31	65
2004/05	110	25	61
2005/06	133	38	101
2006/07	65	24	34

*Only AFM000072.

Table 2-8. Ice cover at Forsmark 2002/03-2006/07.

Lake Eckarfjärden	Date for ice freeze-up	Date for ice break-up	Period of ice cover (days)
2002/03	2002-11-12	2003-04-02	141
2003/04	2003-12-12	2004-04-06	117
2004/05	2004-11-18	2005-04-09	143
2005/06	2005-11-21 2005-12-12	2005-12-01 2006-04-24	143
2006/07	2006-12-18	2007-03-26	98
Baltic Sea bay at Forsmark harbour (AFM000072 and AFM001172)			
2002/03	2003-01-07	2003-03-31	83
2003/04	2003-12-17	2004-04-13	120
2004/05	2004-12-21 2005-01-17	2005-01-13 2005-04-07	95
2005/06	2005-12-12	2006-04-24	133
2006/07	2007-01-22	2007-03-22	60

2.1.3 Surface water levels

Water levels have been monitored in six lakes and at two locations in the Baltic Sea during the site investigation, see Figure 2-26. The pressure transducers used for the monitoring were installed in stand pipes drilled into the bottom of the lakes and the sea for all locations except for PFM010038. Due to ice-lifting of the stand pipes, the two stations in the sea in Kallrigafjärden (SFM0043) and in Lake Lillfjärden (SFM0066) were abandoned in November 2005 and December 2006, respectively.

A comparison of SKB's and SMHI's sea level measurements (stations PFM010038 and PFM010039, respectively) is shown in Figure 2-27. The SKB and SMHI data show good agreement. Only data from the SKB station PFM010038 are used in the remainder of this report.

The daily average time series from the lake surface water level gauges are presented in Figure 2-28. Figure 2-28a shows all six water level measurements and Figure 2-28b shows a close-up of the four lakes with the lowest water levels together with the sea level. The time series for Lillfjärden (SFM0066) indicates that the lake level is mainly determined by the sea level. The lake levels of Norra Bassängen (SFM0039) and Bolundsfjärden (SFM0040) are also quite low, but these levels seem to be determined mainly by the lake thresholds and the surface water and groundwater inflow from the inland.

Occasionally the sea level rises high enough for direct sea water intrusion to the lower elevation lakes in the site investigation area. During the two major storms in January 2005 and January 2007 (named "Gudrun" and "Per", respectively) the sea water level also rose well above of the level of Lake Fiskarfjärden which has a mean water level of +0.55 m. The two major events of salt water intrusion into Lake Norra Bassängen and Lake Bolundsfjärden coupled to "Gudrun" and "Per" are shown in Figure 2-29.

The highest recorded half-hour value of the sea level, 1.40 m RHB70, was observed during the "Per" storm, which can be compared with 0.94 m during "Gudrun" (the corresponding maximum daily averages were 0.99 and 0.75 m, respectively). For comparison, the mean sea water level during the whole monitoring period was –0.04 m and the minimum recorded half-hour value –0.68 m (minimum daily average –0.55 m).

From GSD-Fastighetskartan © Lantmäteriverket Gävle 2001, Consent M2001/5268
2006-06-08 16:00

Figure 2-26. *Locations of the surface water level gauges.*

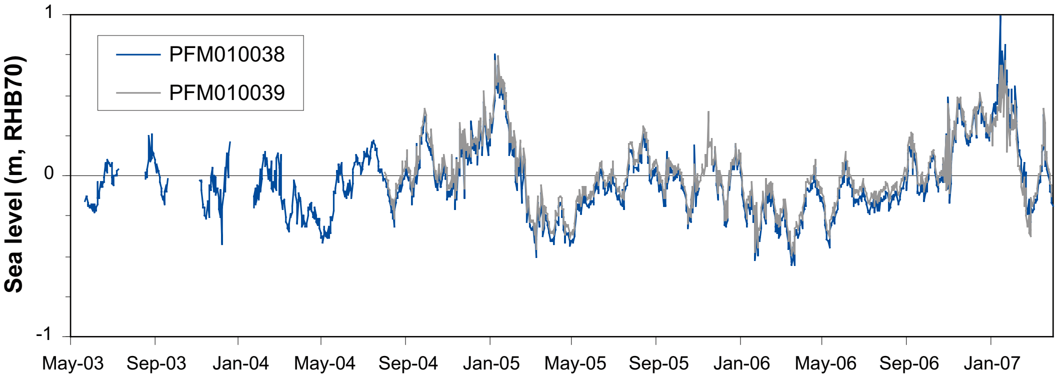


Figure 2-27. *Daily average sea level measured at the SKB and SMHI stations at Forsmark harbour (PFM010038 and PFM010039, respectively).*

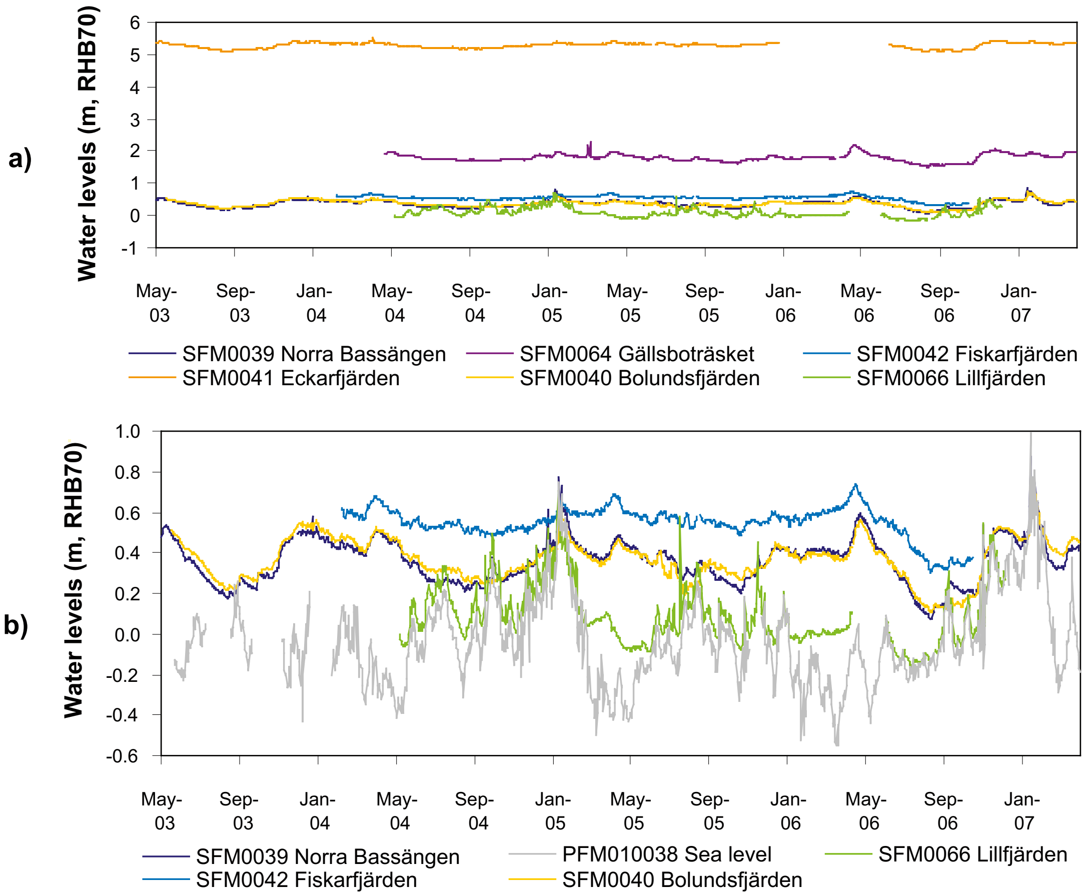


Figure 2-28. *Daily average surface water levels in the Baltic Sea and the larger lakes in the study area shown for all in a) and in close-up for the four lakes with the lowest levels in b). Tick marks on the x-axis indicate the first dates of the labelled months.*

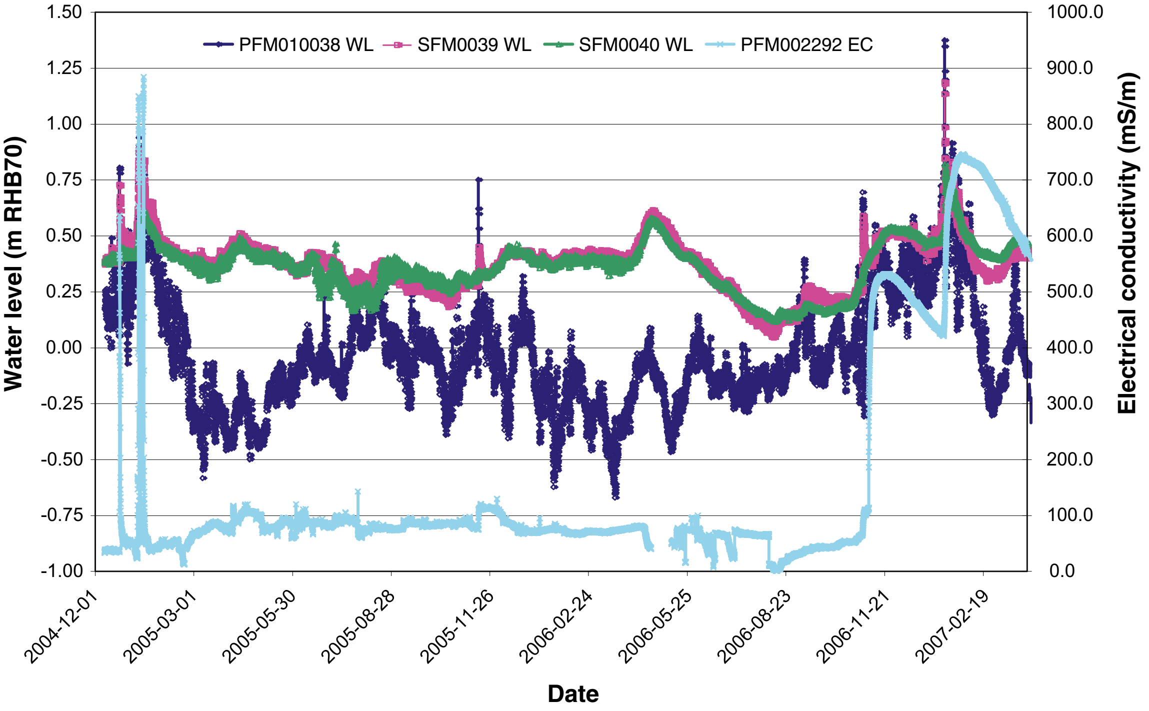


Figure 2-29. *The water levels in the Baltic Sea (PFM010038), Lake Norra Bassängen (SFM0039) and Lake Bolundsfjärden (SFM0040) plotted together with the electrical conductivity in the channel connecting the two lakes (PFM002292).*

From Figure 2-29 it is obvious that the development over time of the electrical conductivity (EC) was quite different in the channel between Lake Norra Bassängen and Lake Bolundsfjärden during the two storms. During "Gudrun" the EC peak was very distinct with a highest value of almost 900 mS/m, which is approximately the same as the EC of the sea water. However, already after less than two days the EC of the flow from Lake Bolundsfjärden to Lake Norra Bassängen was well below 100 mS/m.

This is explained by a distinct density layering in the ice-covered lake during "Gudrun", resulting in only low-salinity water flowing out of the lake. Figure 2-30 complements these observations with electrical conductivity profiles from lake water in Lake Bolundsfjärden taken at three occasions during 2005. The first occasion (January 31, 2005) was approximately 3 weeks after the sea water intrusions and shows the settling of saline waters at the lake bottom. Two months later (March 29, 2005), the conductivity profile was virtually identical. At that time the lake was still covered by ice preventing wind-driven water mixing. However, the summer measurement of August 16 showed profiles indicating well-mixed conditions.

During 2006/2007 the conditions were quite different. A major inflow of sea water appeared already in the beginning of November 2006. The water levels in Lake Norra Bassängen and Lake Bolundsfjärden were at that occasion still low after the very dry summer and early autumn of 2006. Since the lakes were not ice-covered the water body was completely mixed resulting in a continuously high but slowly decreasing EC in the outflow from Lake Bolundsfjärden after this event.

Then another major sea water intrusion took place during "Per". The peak EC was somewhat lower than during "Gudrun", c. 750 mS/m. Based on the water level changes in Lake Bolundsfjärden, information of the bathymetry, and the EC-measurements, the inflow of chloride to the lake has been estimated to c. 40 tonnes during "Gudrun" and considerably more during "Per", c. 250 tonnes (during "Per" the volume of Lake Bolundsfjärden increased by almost 200,000 m^3 in 10 hours). The difference is mainly explained by the considerably higher sea water levels during "Per".

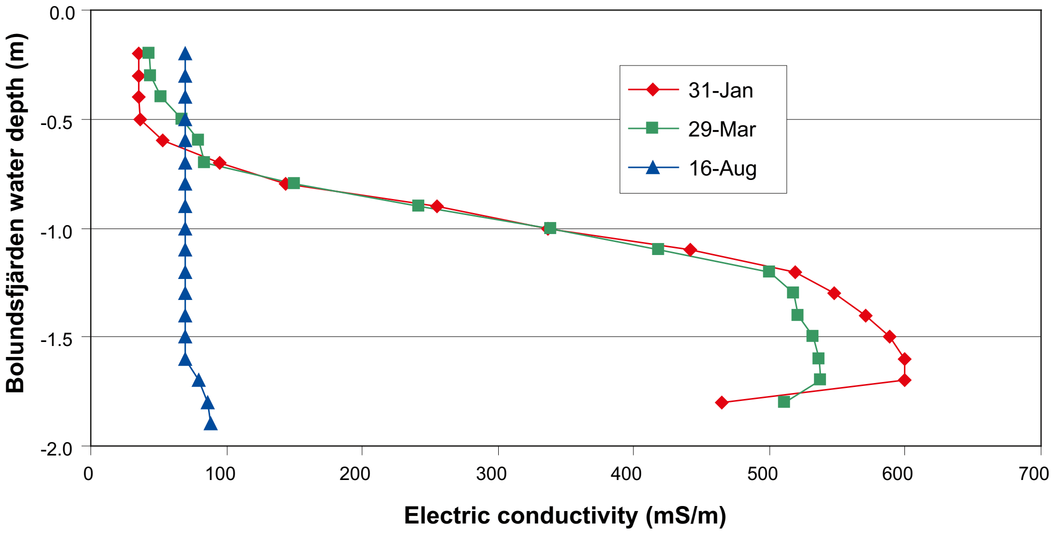


Figure 2-30. Electrical conductivity profiles in Bolundsfjärden measured during winter, early spring, and summer, 2005.

2.1.4 Groundwater levels in the Quaternary deposits

A total number of 74 groundwater wells have been installed in Quaternary deposits (69 monitoring wells and 5 pumping wells). Their locations and at what stage of the investigations they were installed are shown in Figure 2-31. In 51 of these wells the groundwater level has been registered automatically, see Figure 2-32.

In addition, 20 BAT-type filter tips have been installed in low-permeable Quaternary deposits to measure pore pressure and hydraulic conductivity (10), and for water sampling (10), see Figure 2-33. In the seven filter tips for pore pressure measurements belonging to data freeze 2.2, pore pressure was measured twice a month. The number of groundwater wells and BAT-type filter tips installed with regard to the different data freezes is summarised in Table 2-9.

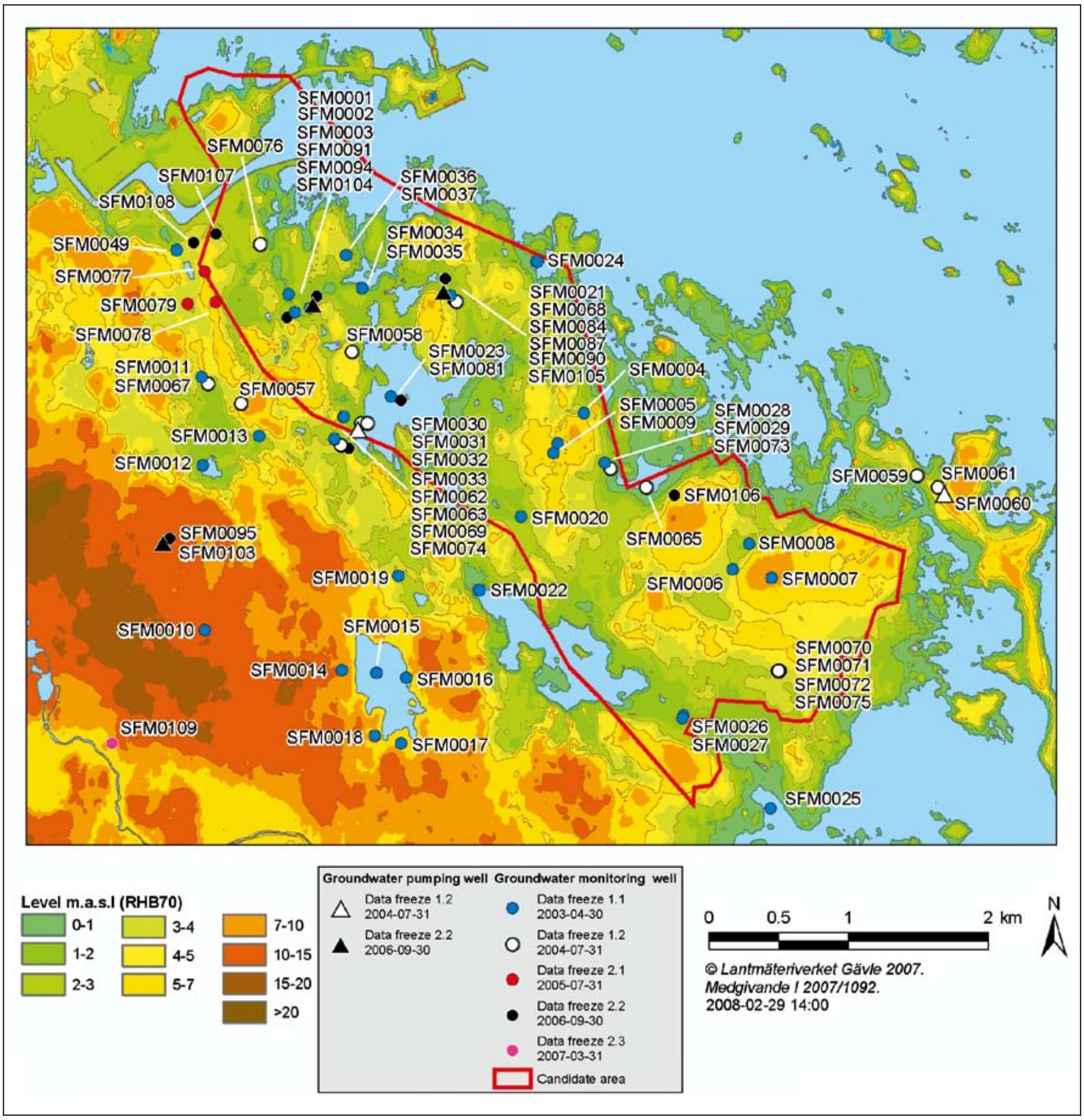


Figure 2-31. Locations of groundwater wells in Quaternary deposits and at what stage of the investigation the wells were installed.

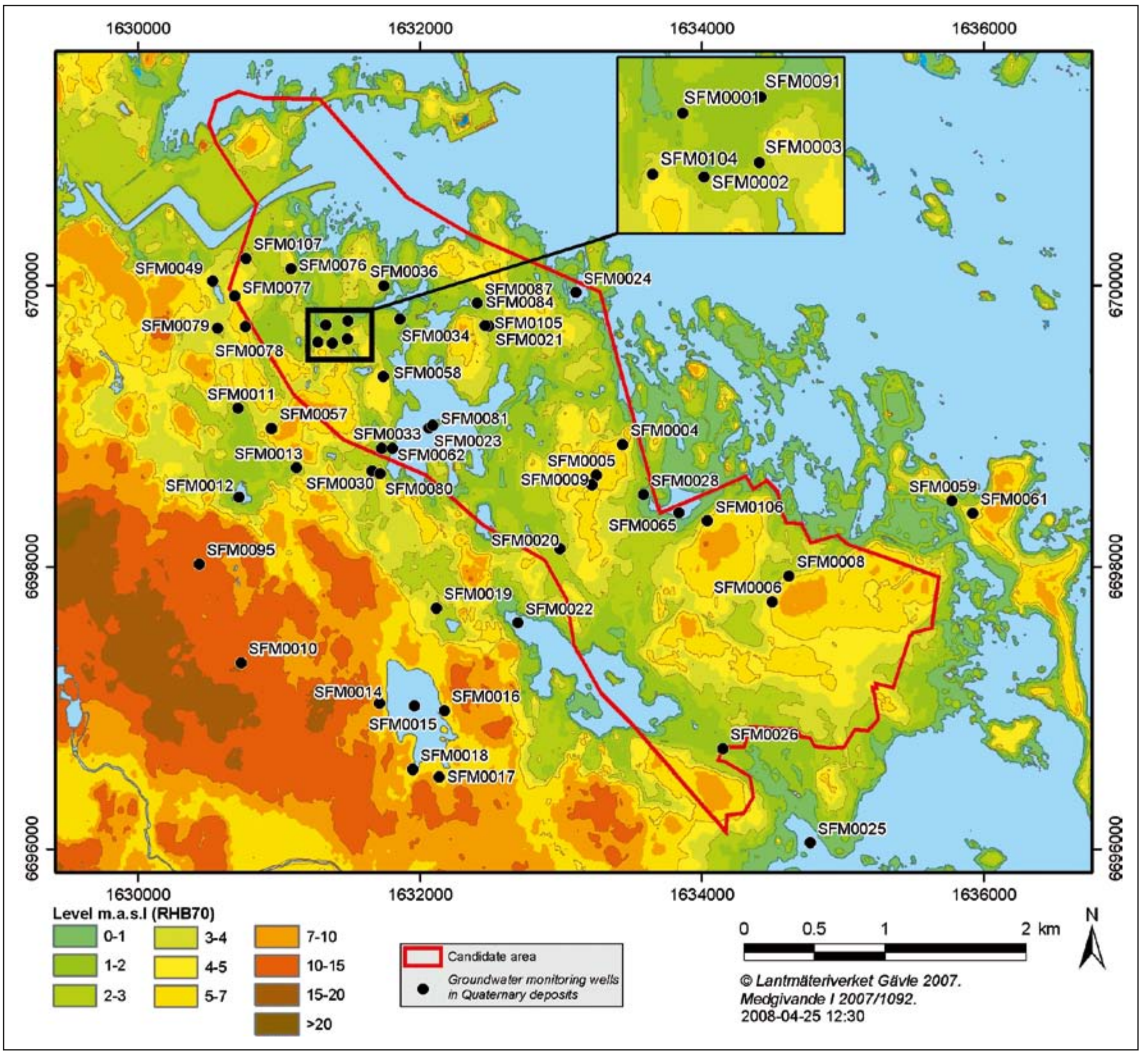


Figure 2-32. *Locations of groundwater monitoring wells in Quaternary deposits with automatic registration of groundwater levels.*

Table 2-9. List of installed groundwater wells and BAT filter tips with regard to the different data freezes (DF) in Forsmark (K denotes hydraulic conductivity).

Type of installation	DF 1.1 2003-04-30	DF 1.2 2004-07-31	DF 2.1 2005-07-31	DF 2.2 2006-09-30	DF 2.3 2007-03-31	Total
Monitoring wells for gw levels and K on land	32	13	3	10	1	59
Monitoring wells for gw levels and K below surface water	6	3	–	1	–	10
Pumping wells	–	2	–	3	–	5
BAT filter tips for pore pressure and K	3	–	–	7	–	10
BAT filter tips for water sampling	3	–	–	7	–	10

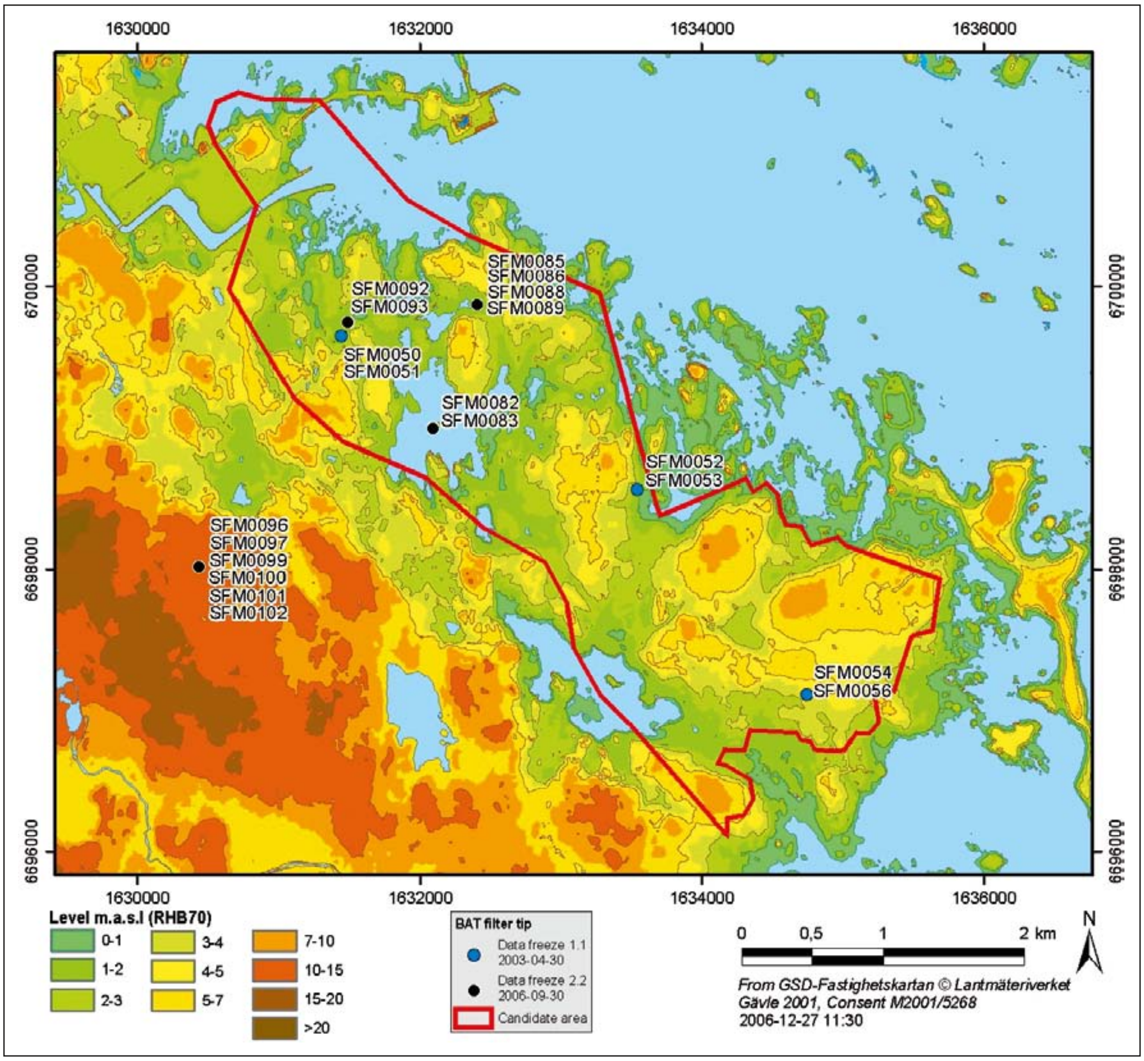


Figure 2-33. *Locations of BAT-type filter tips used in low-permeable Quatarnary deposits to measure pore pressure and hydraulic conductivity, and for water sampling.*

Figure 2-34 presents daily average groundwater levels expressed as a) elevations (RHB70) and b) depth below ground surface for the 42 automatically measured wells situated on land. Measured groundwater elevations in Quaternary deposits range from about –1 m in SFM0030 to +13 m in SFM0010 (Figure 2-34a). However, there is only about a 5.5 m range in groundwater levels when represented as depths below ground surface (Figure 2-34b). The majority of wells form a tight-packed cluster with reported groundwater levels in the range of approximately +0.25 to –1.5 m relative to the surface. These wells typically show a strong uniformity in their responses to drier summer conditions in July and August. Similarly, these wells also display uniformity in response to recharge events following major precipitation and snowmelt events.

SFM0026, which is located in a confined till aquifer at the outlet of Lake Fiskarfjärden, reveals clear artesian conditions with a groundwater level up to approximately one metre above ground. The deepest observed groundwater levels are from two wells situated in Börstilåsen (SFM0059 and SFM0061), which is a glaciofluvial deposit. The wells SFM0006, SFM0008 and SFM0058, which also have relatively deep groundwater levels, are located in till in locally elevated areas, i.e. in typical groundwater recharge areas. The very low groundwater levels during the dry summers of 2003 and 2006 are believed to be caused by root water uptake, indirectly and directly, from the groundwater zone.

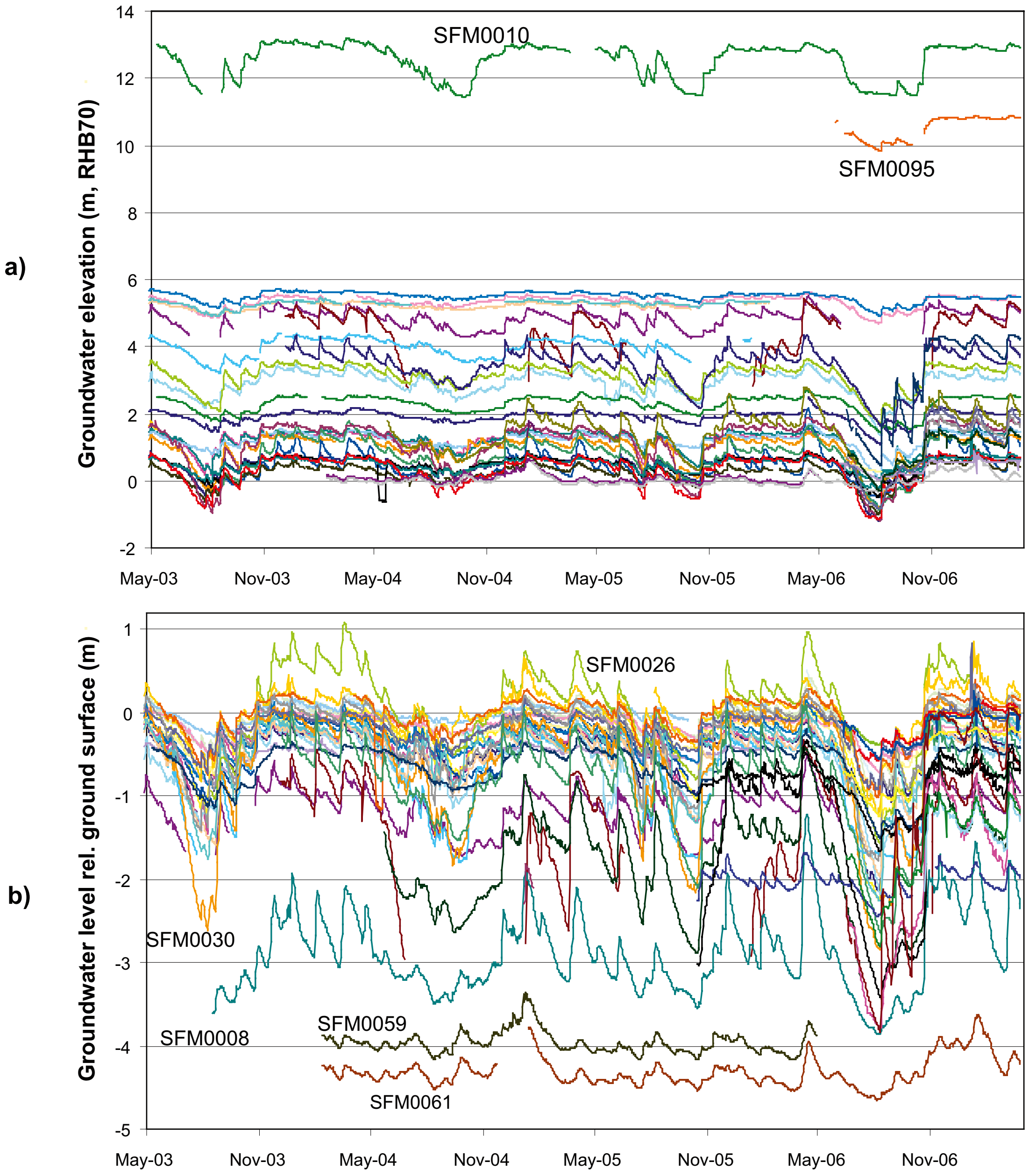


Figure 2-34. *Daily average groundwater levels expressed as a) absolute elevations (RHB70) and b) relative to ground surface for 42 monitoring wells in Quaternary deposits on land.*

Numerous combinations of wells in the Quaternary deposits indicated similar time series responses. The time series from groundwater wells in Quaternary deposits were analysed to identify wells with high covariance ($R^2 > 0.9$) and similar range of variation (± 10%). Sets of wells in close proximity as well as wells further apart demonstrated nearly identical groundwater level variation patterns /Juston et al. 2007/.

Figure 2-35 shows plots of cumulative frequency distributions of the data presented in Figure 2-34b. Two different methodologies for calculating distributions yield two different curves, but they have similar interpretations. If a daily average groundwater level in Quaternary deposits relative to ground surface is first calculated from the 42 well time series (the orange curve in Figure 2-35), the cumulative distribution of that average time series indicates that 80% (between the 10th to 90th percentiles) of the site average groundwater levels were between 0.4 and 1.2 m below ground surface. If instead the cumulative distribution is based on pooled analysis of the 42 individual well time series (the blue curve), then 80% of measured groundwater levels were between 0.0 and 2.2 m below ground surface. In either case, it can be concluded that groundwater in Quaternary deposits is shallow in observation wells across the site investigation area.

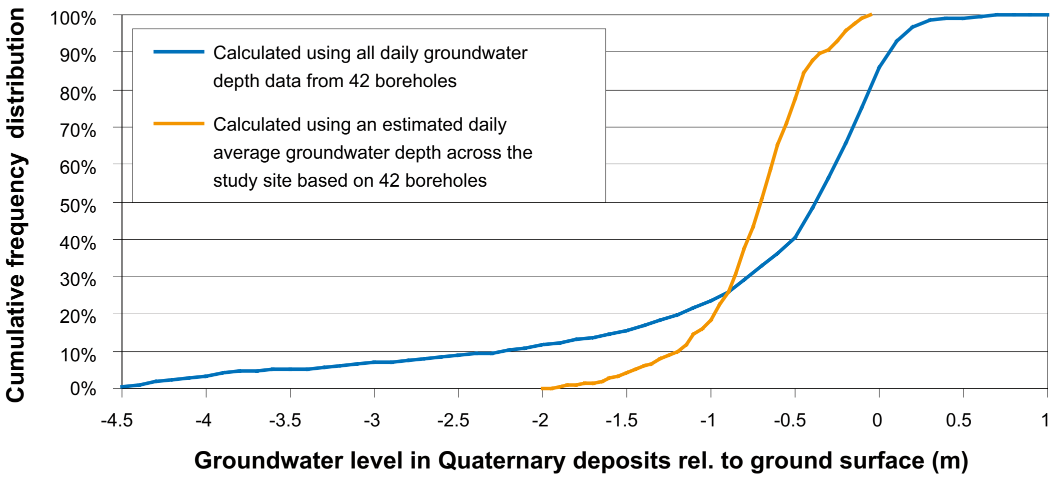


Figure 2-35. *Cumulative frequency distribution of groundwater depth in Quaternary deposits from 42 monitoring wells in the Forsmark site investigation area.*

To facilitate comparisons between well locations, Figure 2-36 shows summaries of the groundwater level in Quaternary deposits time series in terms of means and observed ranges. Figure 2-36a shows the mean and range of groundwater depths in the Quaternary deposits, co-plotted with bedrock depth at each site, and shown ranked according to increasing groundwater depths. In Figure 2-36b the same data are presented ranked according to bedrock depth. Finally, Figure 2-36c shows the mean and range of groundwater elevations, co-plotted with bedrock and ground surface elevations at each site, and shown ranked according to bedrock elevations. All wells exhibited mean groundwater elevations above 0.0 m RHB70. However, 14 of the 40 wells exhibited minimum groundwater elevations less than 0.00 m, with the lowest reported level of –1.18 m in SFM0030.

Figures 2-37 and 2-38 summarise the strong correlation that was observed between mean observed groundwater and ground surface elevations in the Quaternary deposits. It can be stated that the average position of the groundwater level in the Quaternary deposits, with a few exceptions, appears to be largely determined by the local ground surface elevation. In other words, the three-dimensional shape of the groundwater surface in Quaternary deposits appears to generally follow that of the ground surface. There are some outliers indicated by well ID's in Figure 2-37. The most pronounced outliers, SFM0059 and SFM0061, are located below the ridge of the glaciofluvial deposit Börstilåsen, while SFM0008, SFM0058, SFM0077, SFM0080, SFM0104 and SFM0107 are located in till in typical recharge areas and with one exception (SFM0107) in locally elevated areas.

In Figure 2-39 and Figure 2-40 mean groundwater depths are plotted against a field clasification of local geomorphology and groundwater recharge-discharge conditions /Werner et al. 2007/. Figure 2-39 shows that groundwater depth below ground is more variable and generally larger in locally elevated areas, while no clear coupling can be seen between absolute groundwater elevation and local geomorphology. From Figure 2-40 it is obvious that depth to groundwater varies considerably within typical recharge areas, whereas the variations are small and the groundwater level close to the ground surface in discharge areas. No coupling can be seen between groundwater elevation and the classification in recharge-discharge areas. The two figures support the concept that groundwater flow in the Quaternary deposits is mainly governed by local topography and forms small local flow systems.

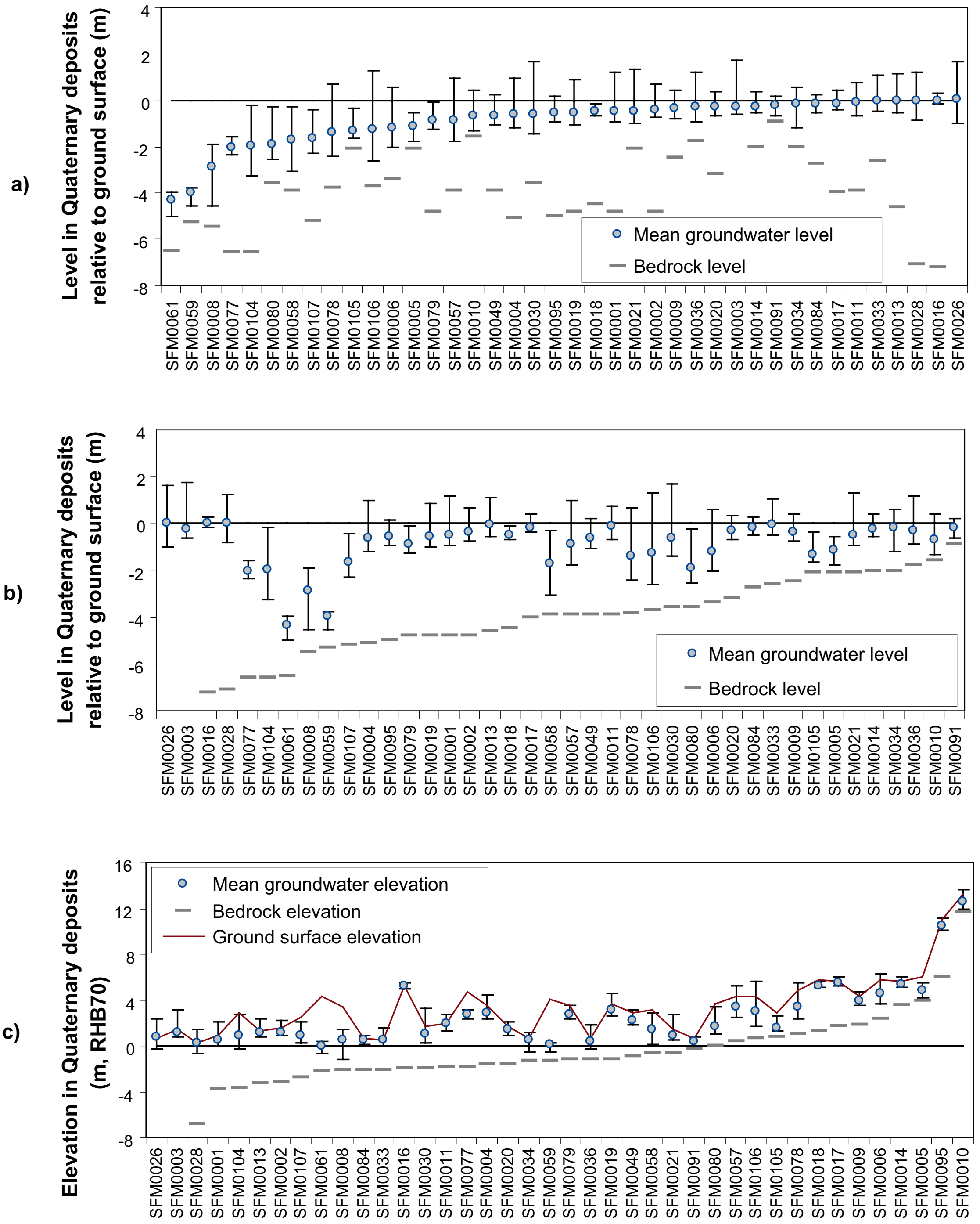


Figure 2-36. *Summary of mean and range of groundwater levels in the Quaternary deposits shown as a) level relative to ground surface ranked accordingly, b) level relative to ground surface ranked by depth to bedrock and c) levels RHB70 ranked by bedrock elevation. In all figures, bedrock surface levels at SFM0026 (–15.4 m RHB70 and 16.1 m below surface) and SFM0003 (–8.7 m RHB70 and 10.2 m below surface) are not shown in order to increase resolution on the remaining data. (Note that wells below open water and wells with time series < 150 days are not included.)*

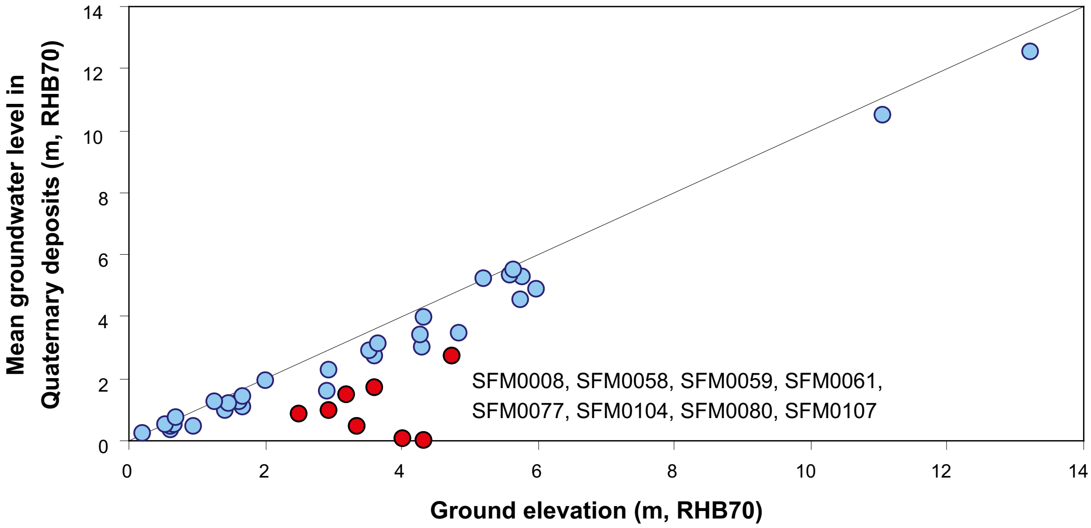


Figure 2-37. *Cross-plot of average groundwater level elevations in Quaternary deposits versus ground elevations. The red dots represent outliers; the well ID's of these are listed in the figure.*

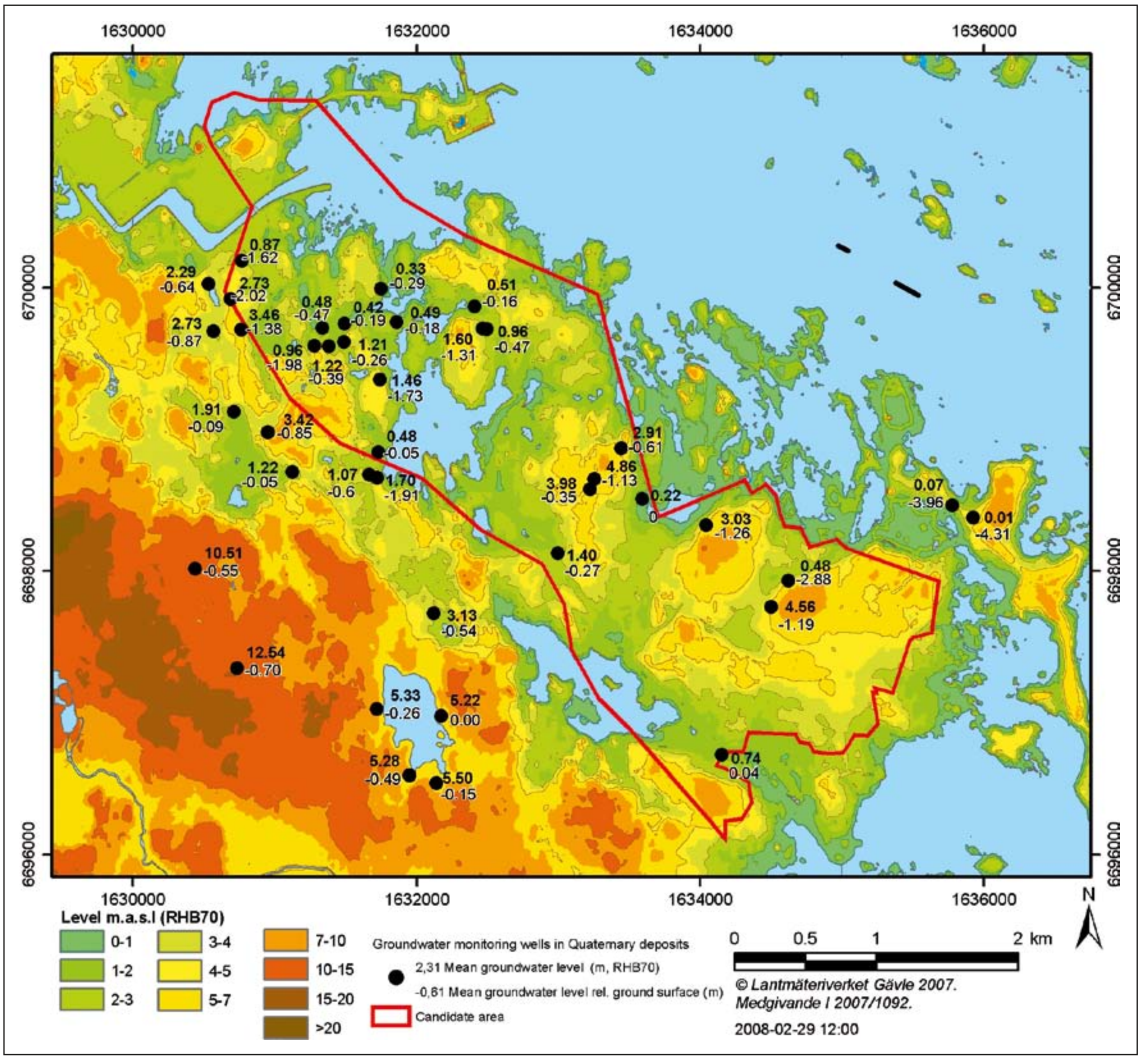


Figure 2-38. *Mean groundwater level elevations (bold figures) and relative to ground surface in monitoring wells in Quaternary deposits.*

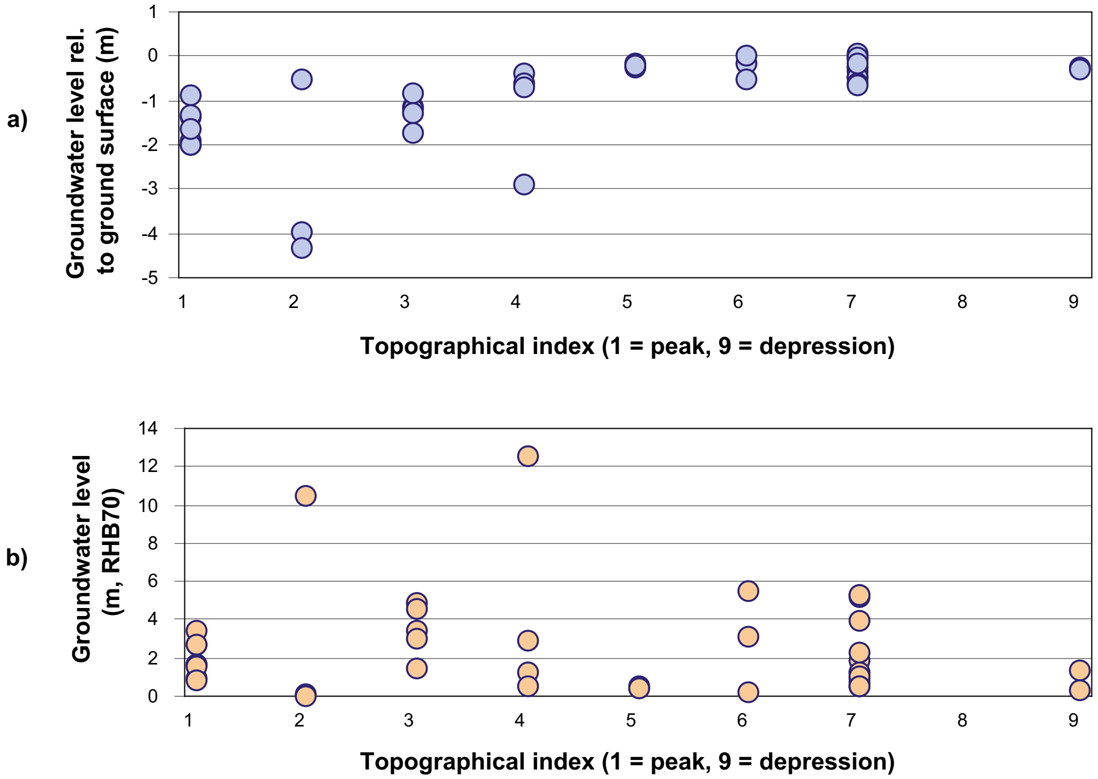


Figure 2-39. *Mean a) groundwater depths and b) elevations as a function of a topographic index based on in-field assessments /Werner et al. 2007/. Numeric categories were defined as follows: 1 = peak, 2 = ridge, 3 = upper slope, 4 = mid slope, 5 = pass, 6 = lower slope, 7 = flat, 8 = channel, 9 = regional depression.*

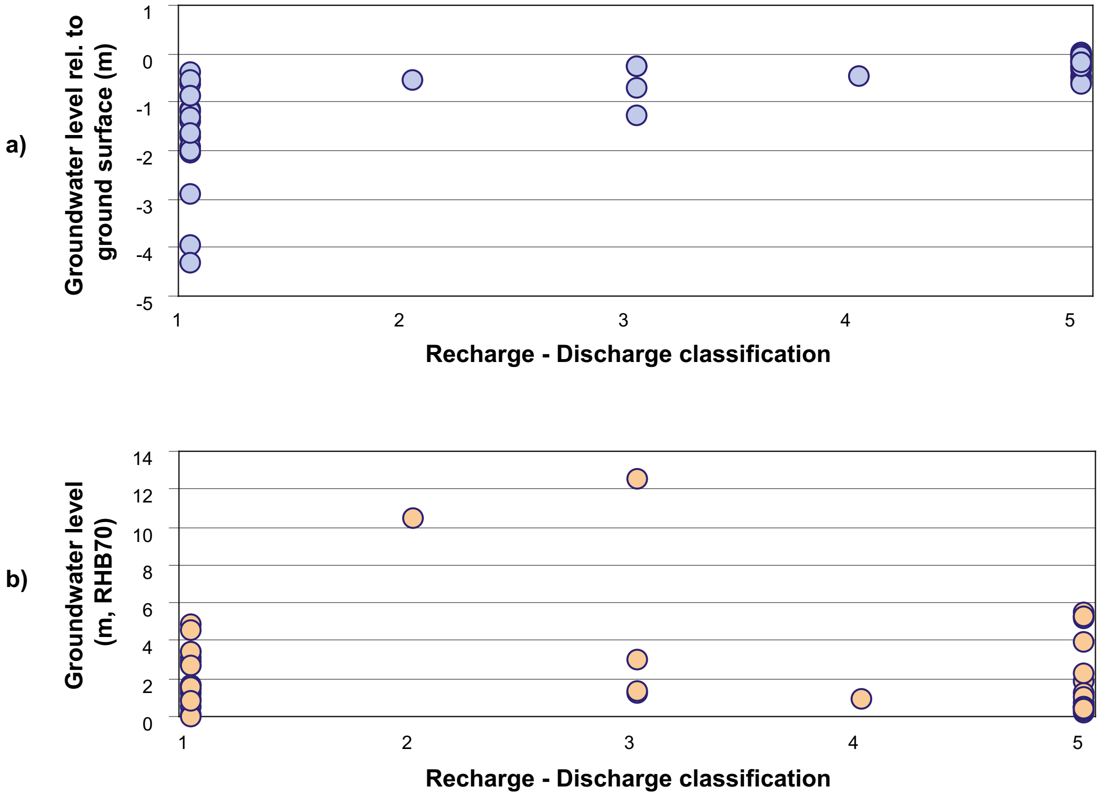


Figure 2-40. *Mean a) groundwater depths and b) elevations as a function of a recharge-discharge classification based on in-field assessments /Werner et al. 2007/. Numeric categories were defined as follows: 1 = recharge area, 2 = probable recharge area, 3 = varying, 4 = probable discharge area, 5= discharge area.*

2.1.5 Groundwater levels in the bedrock

The present report focuses on the near-surface hydrogeology in Quaternary deposits. However, groundwater levels (point water, fresh water and environmental water heads) in the upper c. 150 m of the bedrock are analysed together with groundwater levels in the Quaternary deposits for interpretation of the interaction between groundwater flows in the two flow domains. The locations of the percussion-drilled boreholes are shown in Figure 2-41. For more information on the bedrock hydrogeology the reader is referred to /Follin et al. 2007abc, Follin et al. 2008/.

Groundwater level time series from the percussion-drilled boreholes show frequent intervals of high amplitude disturbances that are related to core drilling and pumping activities. The network of groundwater wells in the bedrock responded differently to activities at different locations, thus suggesting that these disturbance intervals contain valuable information on interconnectivity in the bedrock. Accordingly, these intervals were analysed to identify which wells responded and to what extent for different sources of disturbance.

The disturbances were oscillatory and with high amplitude and tended to obscure more subtle groundwater level changes in response to infiltration and sea level changes. Therefore, a thorough data screening was performed to produce a second "clean" data set with no visible artefacts from disturbing activities.

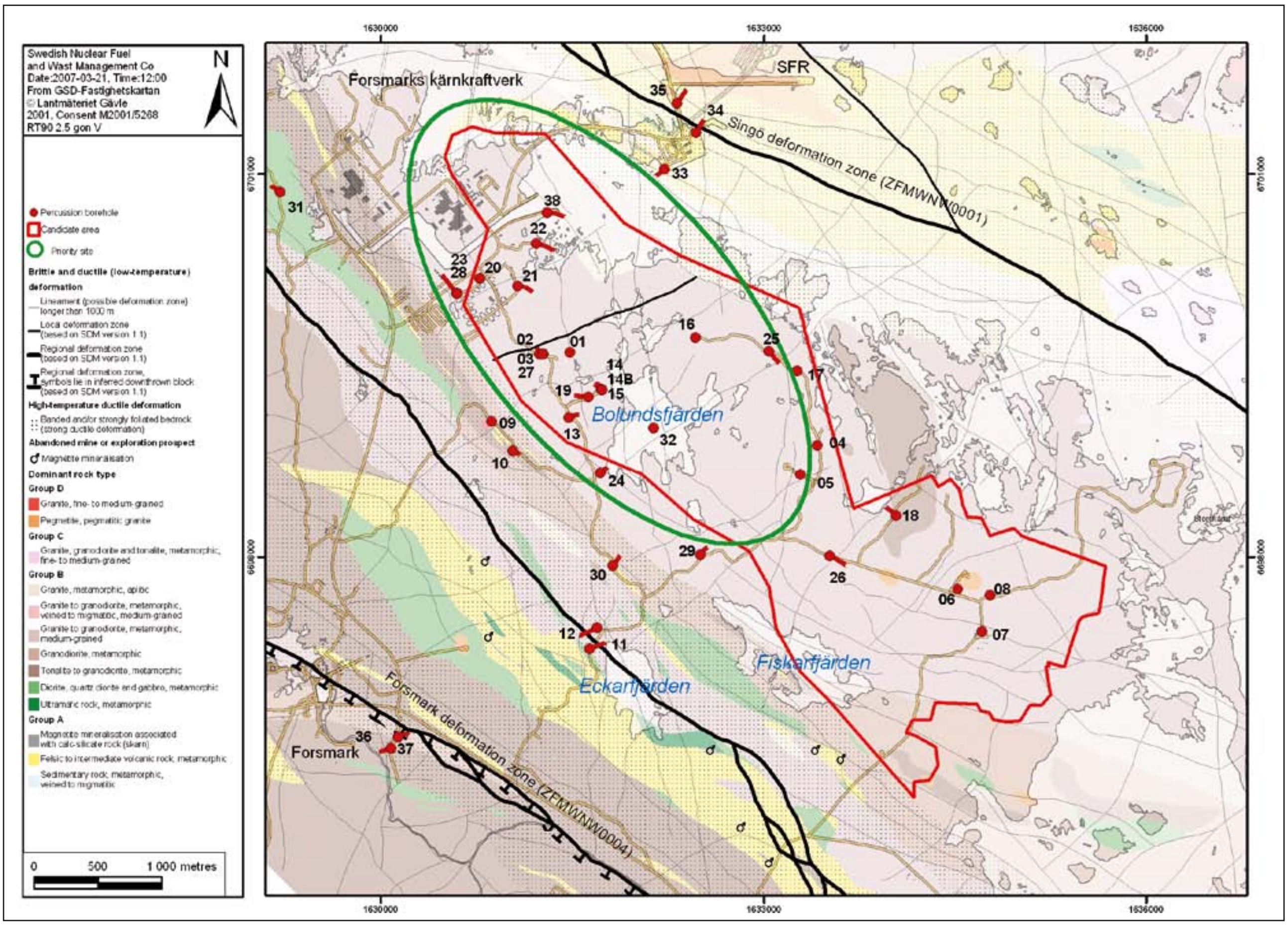


Figure 2-41. Locations of all percussion-drilled boreholes in bedrock; the numbers refer to the ID numbers of the boreholes (e.g. 32 is HFM32).

Point water heads and environmental heads

As mentioned in Section 2.1.1, due to considerable differences in groundwater salinity with depth, and thereby in density, measured groundwater levels in percussion-drilled boreholes in the bedrock should be regarded as point water heads.

The relation between environmental water head and point water head is expressed by:

$$\rho_f H_{in} = \rho_i H_{ip} - Z_i (\rho_i - \rho_a) - Z_r (\rho_a - \rho_f)$$

where

ρ_f	density of fresh water,
H_{in}	environmental water head at *i*,
ρ_i	density of water at *i*,
H_{ip}	point water head at *i*,
Z_i	elevation of point *i*; elevation measured positively upward,
ρ_a	average density of water between and *i*, as defined by $\frac{1}{Z_r - Z_i} \int_{Z_i}^{Z_r} \rho \, dz$
Z_r	elevation of reference point from which the average density of water to point *i* is determined and above which water is fresh; elevation measured positively upward.

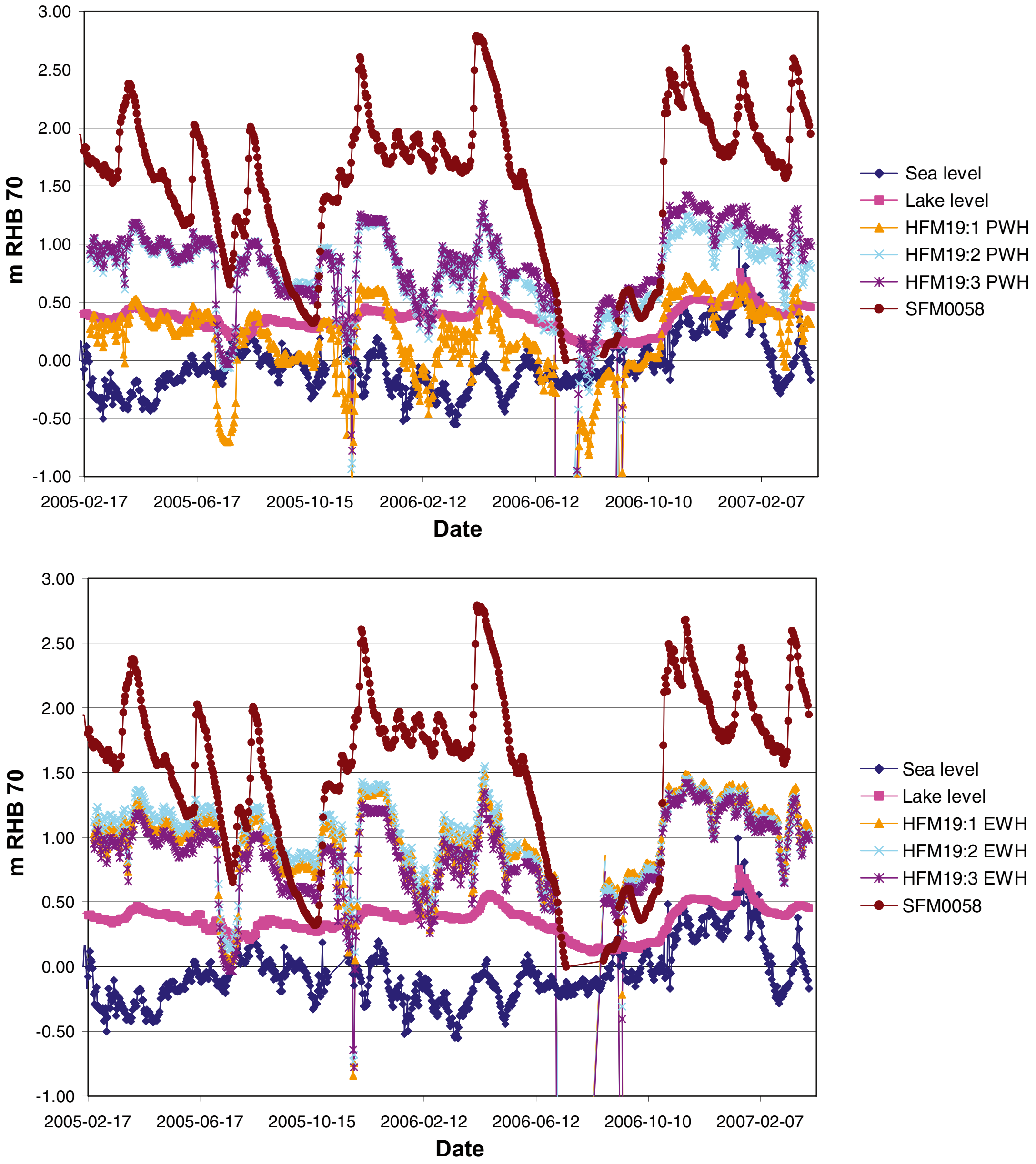
For a detailed discussion on definitions of heads and a description of the method applied for calculation of environmental head from point water head, see /Juston et al. 2007, Johansson 2008/.

In Table 2-10 all the sections in the percussion-drilled boreholes are listed where the difference between mean measured point water heads and calculated environmental water heads is > 0.1 m. The section numbering starts from the bottom of the borehole, which means that the uppermost section just below the Quaternary deposits is that with the highest number in that particular borehole.

Figure 2-42 illustrates measured groundwater levels, i.e. point water heads, and the calculated environmental heads in HFM19 and SFM0058. Both point and environmental water heads suggest that the site is a recharge area for most of the period. The heads in QD are well above the point and environmental water heads in the bedrock borehole sections except during dry summer months. Due to evapotranspiration the groundwater level in the QD during dry summer conditions drops below the point water head in the two uppermost borehole sections HFM19:2 and 19:3 and below environmental water heads in all sections. The groundwater level in QD is also well above the sea water level and the level of Lake Bolundsfjärden except during the dry summer of 2006.

Table 2-10. HFM-borehole sections with a difference between measured point water head (PWH) and calculated environmental water head (EWH) larger than 0.1 m. The section numbering starts from the bottom of the borehole.

HFM-borehole	Section no. (of total)	Difference EWH-PWH (m)
HFM02	1(3)	0.12
HFM08	1(2)	0.68
HFM10	1(2)	0.51
HFM13	1(3)	0.83
HFM19	1(3)	0.76
HFM19	2(3)	0.21
HFM27	1(4)	0.14
HFM27	2(4)	0.12
HFM32	1(4)	0.10



HFM19 (Constant) QD =SFM0058 **Difference EWH-PWH**

Section	Min		Percentil 0.02		Ave		Percentil 0.98		Max		Section	mean
QD	PWHQD	EWHQD	PWHQD	EWHQD	PWHQD	EWHQD	PWHQD	EWHQD	PWHQD	EWHQD	QD	
	-5.63 ↓	-5.63 ↓	-2.5 ↓	-2.5 ↓	-0.8 ↓	-0.8 ↓	0.26 ↑	0.26 ↑	0.44 ↑	0.44 ↑		
3	PWH3	EWH3	PWH3	EWH3	PWH3	EWH3	PWH3	EWH3	PWH3	EWH3	3	0.00
	-0.43 ↓	-0.15 ↓	-0.26 ↓	-0.01 ⟷	-0.07 ↓	0.13 ↑	0.06 ↑	0.26 ↑	0.09 ↑	0.27 ↑		
2	PWH2	EWH2	PWH2	EWH2	PWH2	EWH2	PWH2	EWH2	PWH2	EWH2	2	0.21
	-0.78 ↓	-0.24 ↓	-0.64 ↓	-0.09 ↓	-0.51 ↓	-0.03 ⟷	0.32 ↑	0.08 ↑	0.35 ↑	0.12 ↑		
1	PWH1	EWH1	PWH1	EWH1	PWH1	EWH1	PWH1	EWH1	PWH1	EWH1	1	0.76

Figure 2-42. *Plot of groundwater levels, i.e. measured point water heads (upper graph) and calculated environmental heads (lower graph) in HFM19 and SFM0058, and water levels in the sea and Lake Bolundsfjärden. The inset at the bottom shows the level difference between nearby sections (blue = downward gradient, level diff. > 0.05 m, yellow = level diff. less than 0.05 m, red = upward gradient, level diff. > 0.05 m).*

On average the environmental heads of HFM19:1 and HFM19:2 are 0.76 and 0.21 m higher than the point water heads, respectively, whereas average point and environmental water heads are the same for the uppermost section. When comparing the HFM-sections internally, the deepest section, HFM19:1, always shows the lowest point water head, while the uppermost sections shows the lowest environmental head.

The HFM19 example illustrates the complexity in the interpretation of vertical gradients in an environment with water density varying with depth. If densities are not considered the flow gradient is downward all the way down to the deepest borehole section at a depth of –131 to –144 m RHB70. If the difference in density is taken into account the calculated environmental heads instead indicate that water flows both from above and below to the uppermost borehole sections with its bottom at –81 m. However, it should be noted that the differences between the environmental water heads in the three borehole sections are quite small.

A vital uncertainty in the calculation of environmental heads is the assumption of the density profile in the bedrock outside the borehole compared with that measured in the borehole sections. The fact that a fractured medium is considered implies that water density in a single fracture crossing a borehole section may have a dominating influence on the density obtained for that section. It may also very well be so that there is no continuous vertical hydraulic contact in the bedrock outside the borehole. Furthermore, there is always a risk that the drilling of the borehole, in spite of the packer installations, creates a vertical contact that does not exist naturally. However, if there is a natural vertical contact, the environmental heads should give an indication of the vertical flow direction between the frequent horizontal and sub-horizontal fracture zones existing in the upper c. 150 m of the bedrock in the candidate area. This information is of major interest in discussions of groundwater recharge and discharge.

Groundwater levels

From Table 2-8, listing the 9 borehole sections where the difference between measured point water head and calculated environmental head is larger than 10 cm, it is clear that for most borehole sections the difference is small and will not influence the interpretation of vertical groundwater flow gradients. In the following, the presented groundwater levels are measured point water heads unless otherwise stated.

Groundwater level time series from the percussion-drilled boreholes, raw data and a second “clean” data set with no visible artefacts from disturbing activities are shown in Figure 2-43.

Natural conditions

Figure 2-44 shows summaries of undisturbed groundwater levels in the bedrock in terms of means and observed ranges. Note that it is difficult to establish meaningful comparisons of time series summary statistics when the time series themselves are so unevenly populated (Figure 2-43b). For this reason, the summary values shown in Figure 2-44 should be considered “best available”. In the figure only data series with more than 150 days are presented. The data points are colour-coded to indicate the variable populations used in the mean and range calculations. In the notations used for the percussion-drilled boreholes, HFMXX.Y, XX is the borehole number and Y is the borehole section number, with the numbering of the sections starting from the bottom of the borehole.

Figure 2-44a shows the mean and range of groundwater point water heads in the bedrock (topmost section of HFM-borehole or open borehole), co-plotted with bedrock and ground surface elevations at each site, and shown ranked according to increasing bedrock elevations. Two well sections exhibit mean groundwater point water heads below 0.0 m RHB70 (HFM34.3: –0.47 m and HFM35.4: –0.72 m). Four more wells show minimum values extending below 0.0 m RHB70 (HFM07, HFM17, HFM27 and HFM32). The number of wells with means and minimums below 0.0 m RHB70 is not changed if point water heads are transformed to environmental water heads.

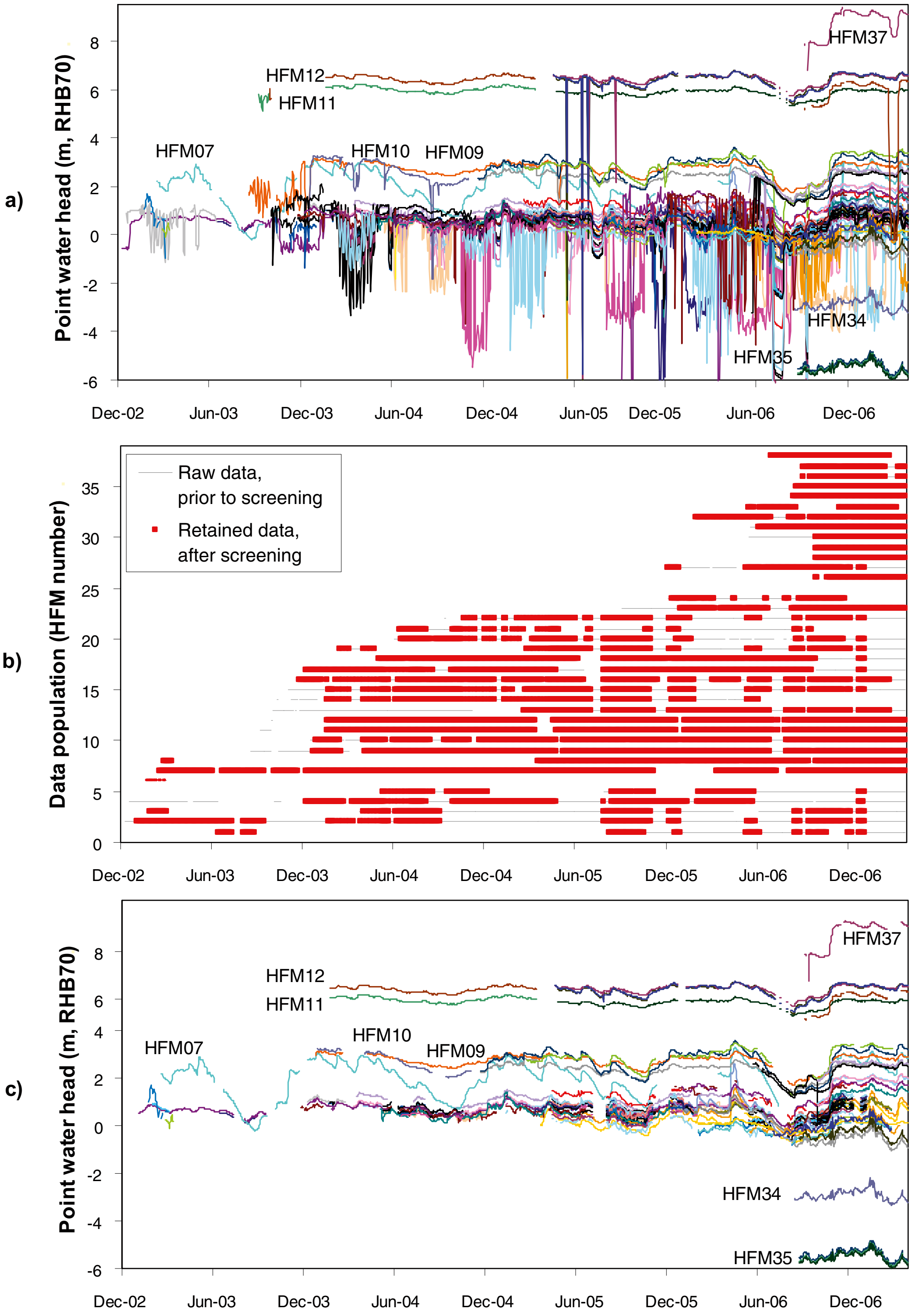


Figure 2-43. *Daily averages of point water heads in 37 percussion-drilled boreholes in bedrock. Raw data is shown in a) and include numerous disturbance intervals. Data population is shown in b) with data judged as undisturbed by site investigation activities marked in red. In c) the retained data set after the screening is shown.*

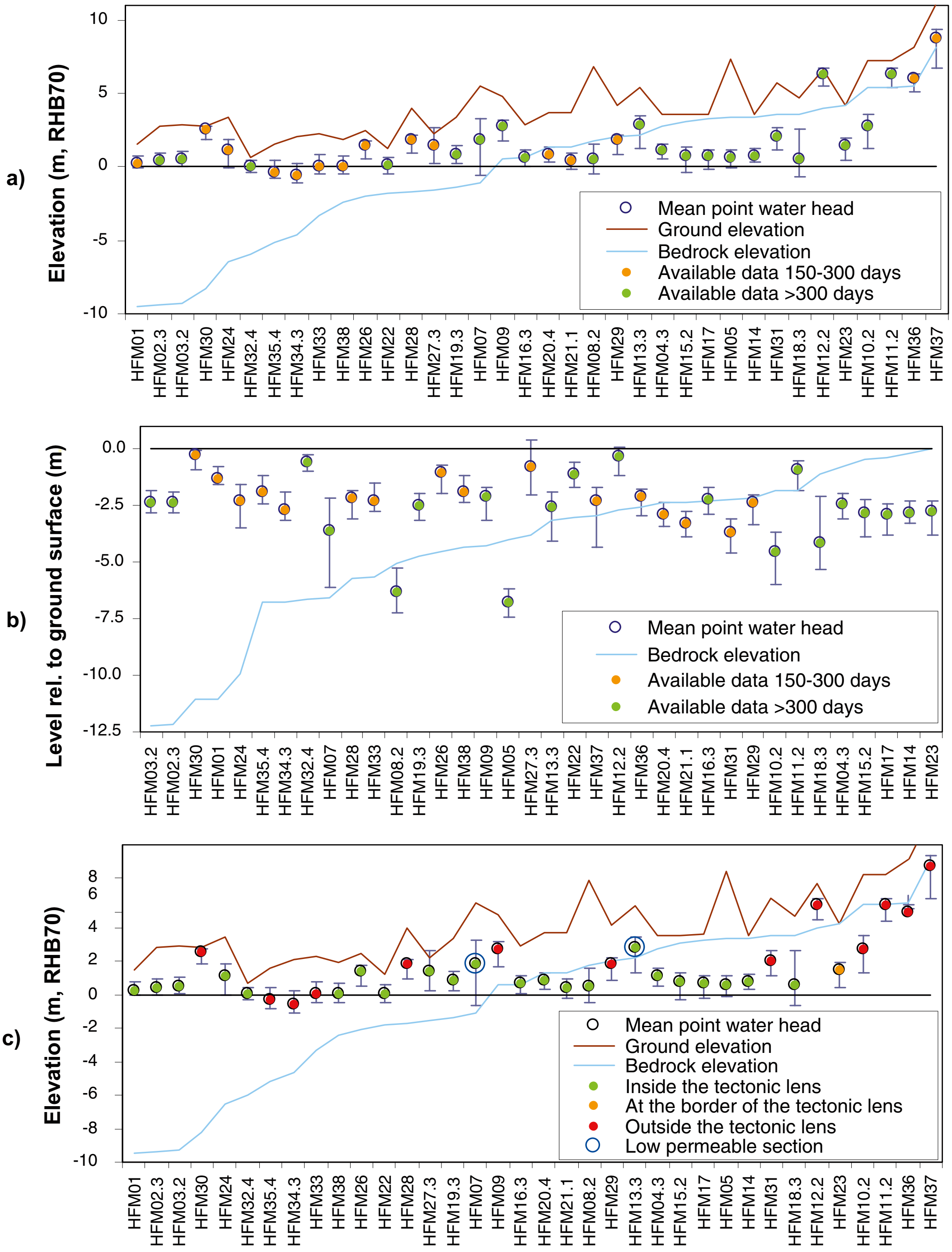


Figure 2-44. *Mean groundwater point water heads in bedrock with observed ranges based on available "clean" data plotted as a) point water head elevations ranked according to bedrock elevations, b) point water head relative to ground surface ranked by depth to bedrock, and c) point water heads ranked according to bedrock elevation as in a) but with colour-coding to show the well location related to the tectonic lens. Data are from the topmost section in wells with packers and open boreholes for wells with no packers.*

For the conceptual modelling, it is interesting to note that 23 of the 36 boreholes demonstrate point water heads above local bedrock levels. As was evident in the undisturbed time series (Figure 2-43c), most wells had mean point water heads within a close range (between 0.0 and 1.0 m RHB70). Of the wells located within the geologic tectonic lens constituting the candidate area, all wells but two have mean point water heads below 1.5 m RHB70. These two borehole sections (HFM07 and HFM13:3) have very low transmissivity and do not appear to be affected by any of the highly transmissive sub-horizontal fracture zones, see Figure 2-44c.

Figure 2-44b shows these same data plotted as point water heads in relation to ground surface, co-plotted with bedrock depth below ground surface, and ranked according to decreasing depth to bedrock. It is obvious that the strong coupling between groundwater level and topography found for the wells in till does not exist for the point water heads in bedrock. This is illustrated in Figures 2-45 and 2-46.

Figure 2-47 shows multiple point water head time series measured in HFM04 in sections separated by packer installations. These data suggest downward vertical gradients in point water heads in the bedrock penetrated by HFM04 (in this borehole there is no salinity gradient which means that point and environmental water heads are the same).

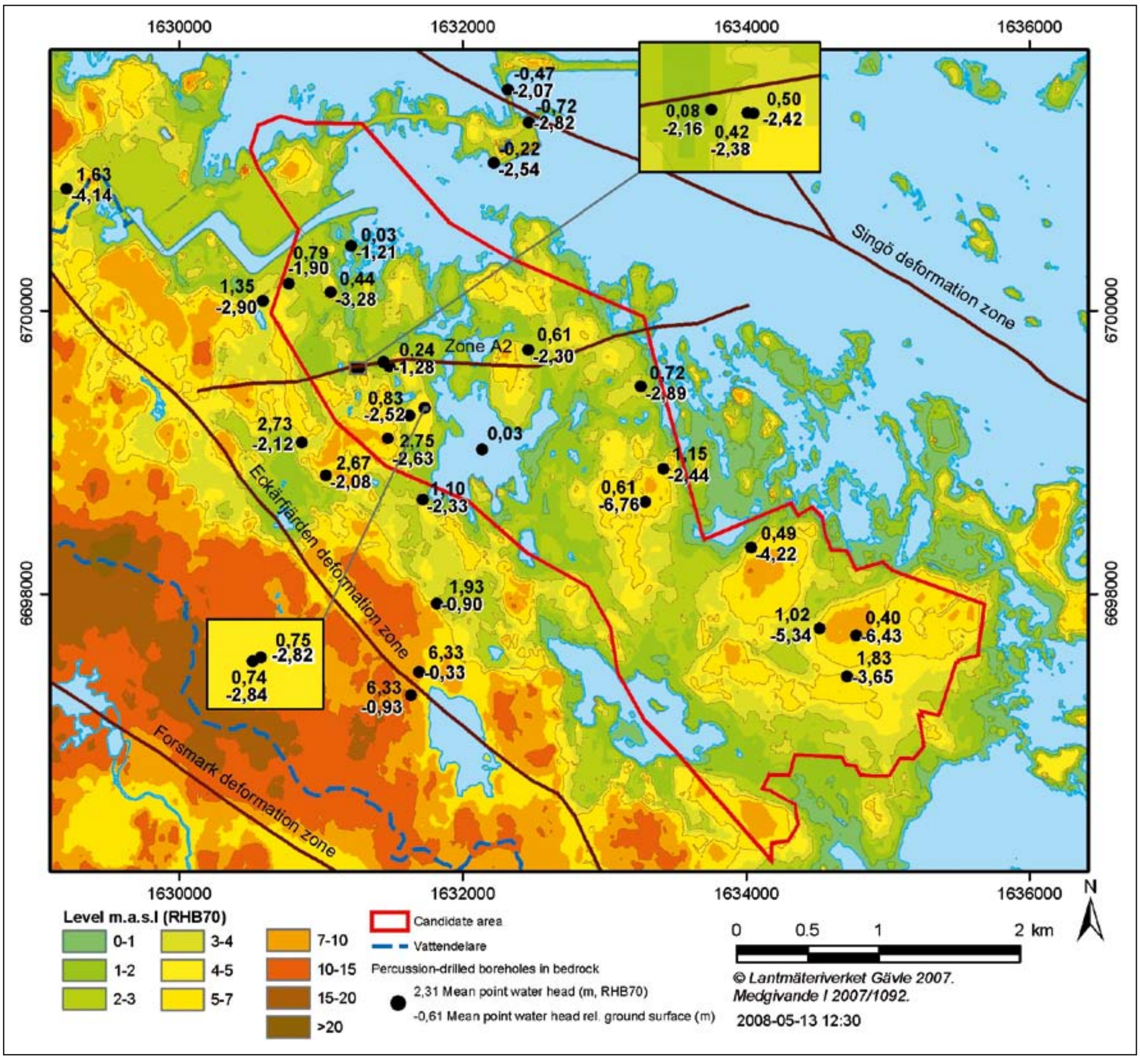


Figure 2-45. Map indicating the mean point water heads in bedrock (RHB70) and the corresponding groundwater head depths below ground surface.

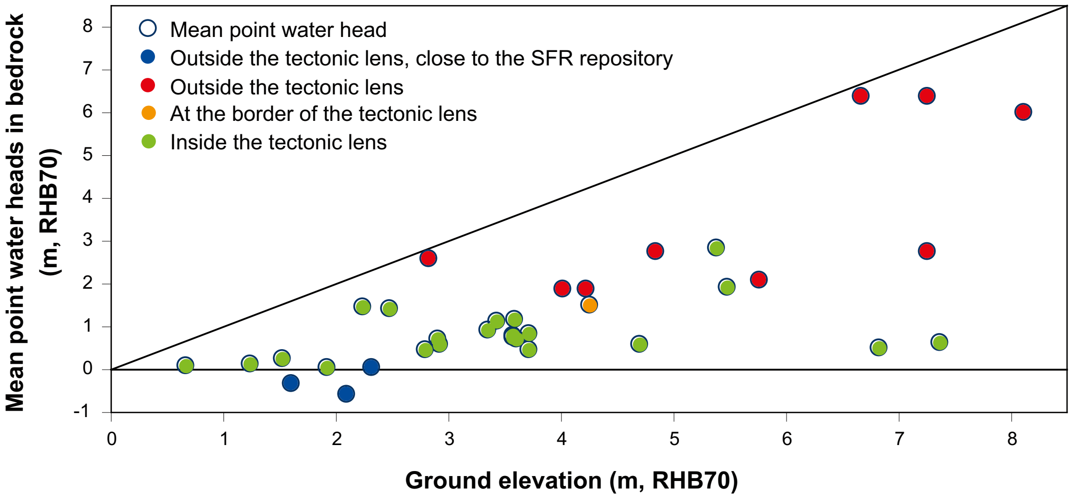


Figure 2-46. *Cross-plot of mean groundwater point water heads in bedrock versus ground surface elevations.*

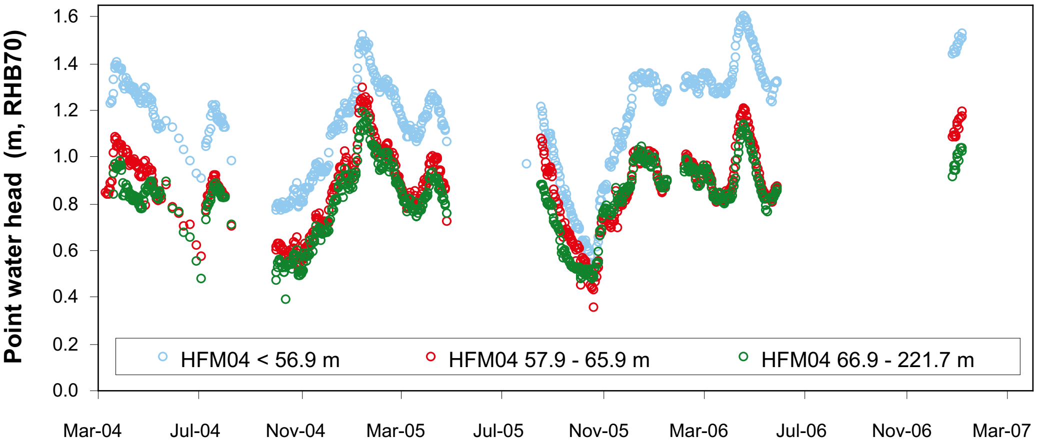
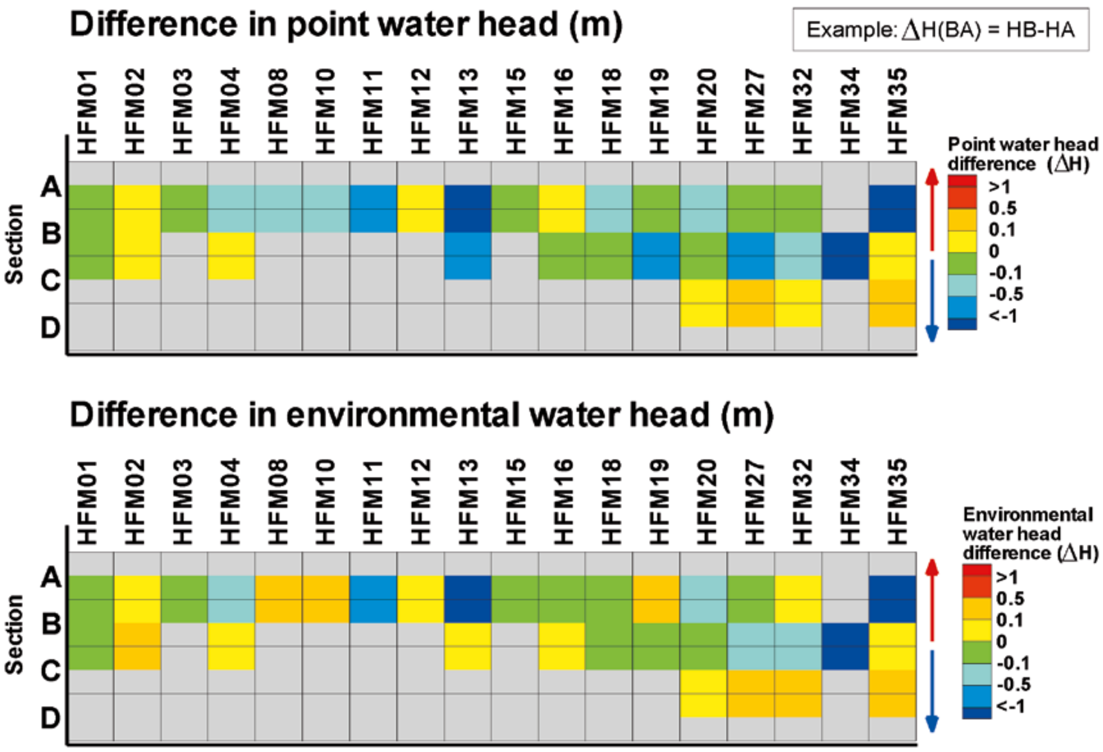


Figure 2-47. *An example of vertical groundwater point water head differences in three sections in HFM04.*

Figure 2-48 shows average differences in mean point water heads between neighbouring sections for the boreholes that have multiple sections (packers); the borehole locations are shown in Figure 2-41. In most wells there is a downward gradient between the two uppermost borehole sections (for point water heads in 14 of 17 wells and for environmental heads in 11 of 17 wells). In six of the boreholes there are differences in vertical direction of the gradient in one or more sections if point and environmental water head data are compared (HFM08, HFM10, HFM13, HFM16, HFM19 and HFM32). If environmental heads are considered, there is a continuous downward gradient in six wells (HFM01, HFM03, HFM11, HFM15, HFM18 and HFM34) while there is a continuous upward gradient in four wells (HFM02, HFM08, HFM10, HFM12).

Disturbed conditions

In Figures 2-49 and 2-50 the responses in groundwater levels in bedrock wells in the central part of the site investigation area to pumping by c. 6 L/s in HFM14 during 3 weeks in the summer of 2006 are shown /Gokall-Norman and Ludvigson 2007a/. The widespread and fast responses indicate very high transmissivities in combination with low storativities.



Difference in point water head (m)

Difference in environmental water head (m)

Figure 2-48. Summary of a) mean difference in point water head and b) environmental water head in the percussion-drilled boreholes with packers separating the boreholes into several intervals.

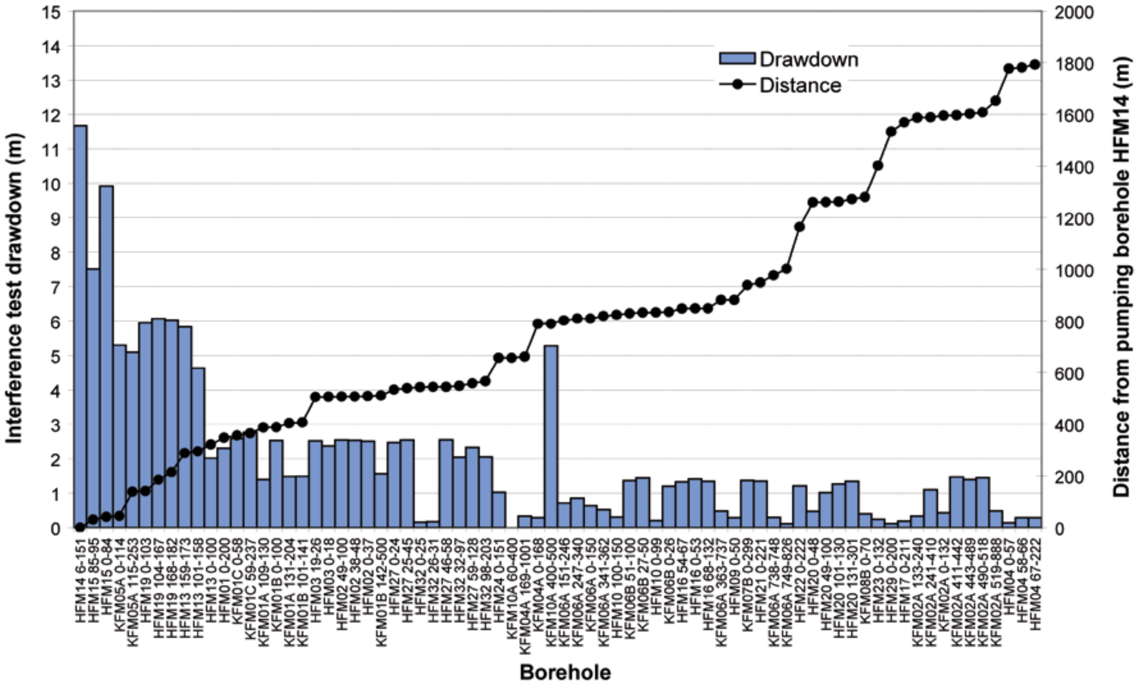


Figure 2-49. Plot of observed drawdowns at the end of the 2006 interference test in HFM14. The monitoring intervals are sorted by distance from the abstraction well /Follin et al. 2007a/.

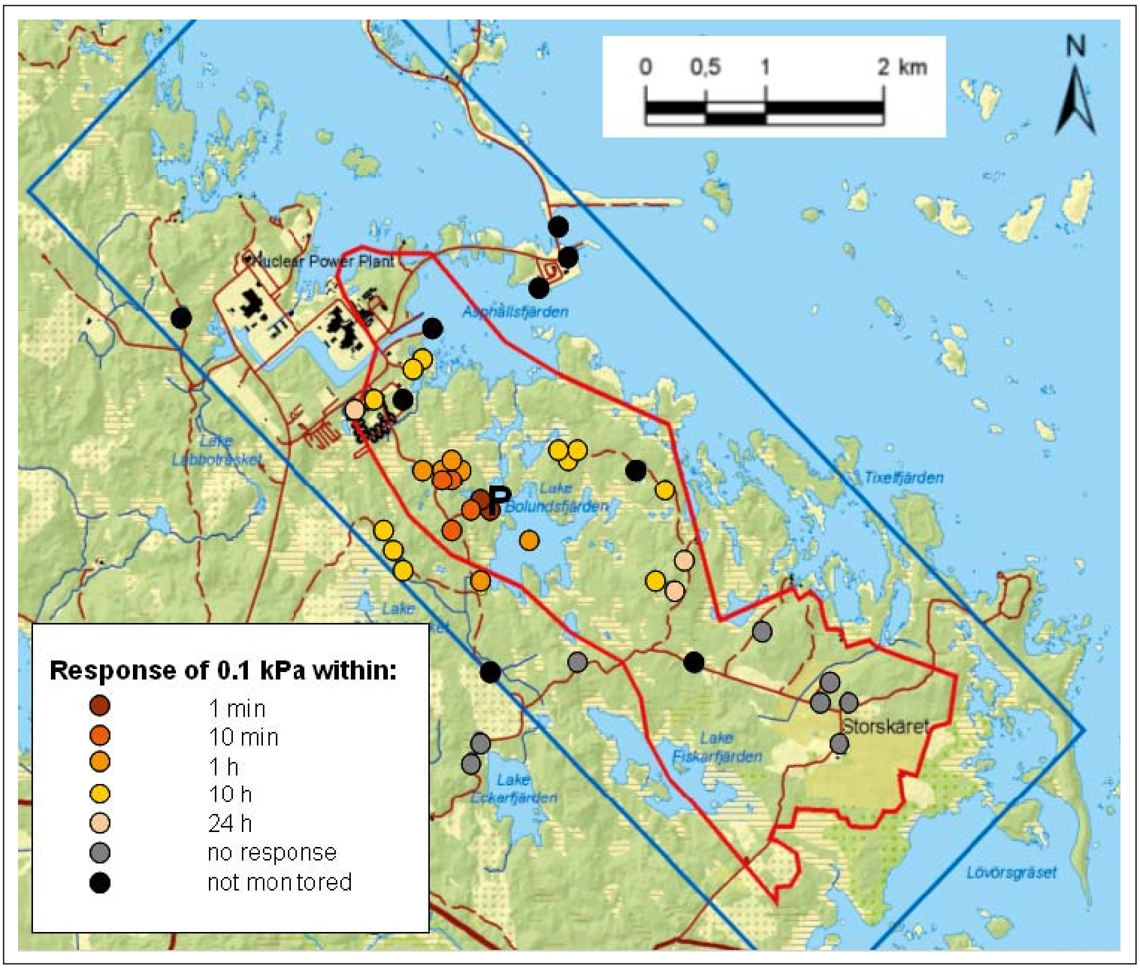


Figure 2-50. Map showing response times in the bedrock to the 2006 interference test conducted in HFM14. The test responses were monitored at 71 "observation points". In boreholes with more than one section, the section with the fastest response is shown /Follin et al. 2007a/.

2.1.6 Surface discharge

Four surface water discharge gauging stations were installed in the central part of the site investigation area (Figure 2-51) /Johansson 2005a/. Long-throated flumes were selected for the discharge measurements, mainly due to the limitations set by the flat landscape, the need for accurate measurements, and the desire to avoid migration obstacles for the fish. Long-throated flumes give accurate measurements over relatively wide flow ranges and work under a high degree of submergence. At three of the four discharge gauging stations, two flumes, with different measurement ranges, were installed to obtain good accuracy data over the full flow range. At all four stations water levels, electrical conductivities, temperatures and discharges were monitored. Water electrical conductivity was measured at one additional station, at the outlet of Lake Bolundsfjärden (PFM002292), see Figure 2-51.

Measurements of water levels, electrical conductivities and temperatures were made every 10 minutes. However, if the difference from the previous measurement was small, not all data were stored. In most cases, the storing interval was less than one hour and at least one value was stored every two hours.

For the calculation of discharge, quality assured water level data from the flumes were taken from Sicada database. The calculation procedure included consolidation of the time series to hourly averages, screening of data for removal of short-term spikes, noise and other data that were judged erroneous. Data gaps were filled by manual measurements when available. After the calculations were performed, the results were delivered to Sicada. The procedure for calculation of discharge is described in detail in /Johansson and Juston 2007/. The sizes of the catchment areas associated to the four discharge gauging stations are given in Table 2-11.

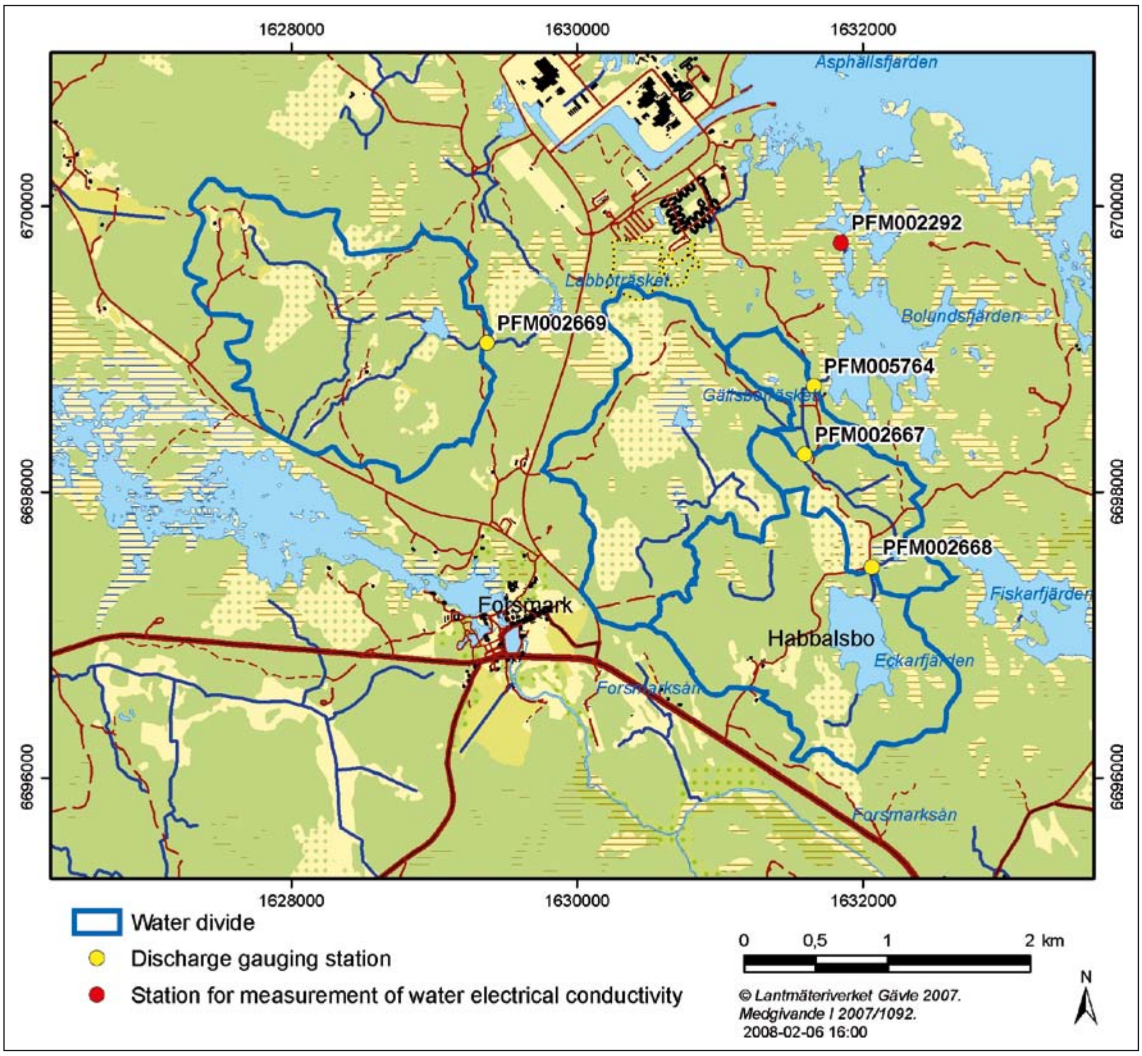


Figure 2-51. *Map showing locations of the four surface water discharge gauging stations, their associated catchment areas, and the station for continuous measurements of electrical conductivity only.*

Table 2-11. Sizes of catchment areas associated with the automatic discharge gauging stations.

Gauging station ID-code	Catchment area ID-code	Catchment area (km^2)
PFM005764	AFM001267	5.59
PFM002667	AFM001268	3.01
PFM002668	AFM001269	2.28
PFM002669	AFM001270	2.83

Time series of surface water discharge at the four installed gauging stations are shown in Figure 2-52.The highest recorded discharge from the catchments at stations PFM005764, PFM002667, PFM002668 and PFM002669 were 212 L/s (38.0 L/s/km^2), 131 L/s (43.4 L/s/km^2), 75.9 L/s (33.3 L/s/km^2), and 183 L/s (64.5 L/s/km^2), respectively. All stations had zero discharge for relatively long periods in late summers and early autumns, especially during 2006.

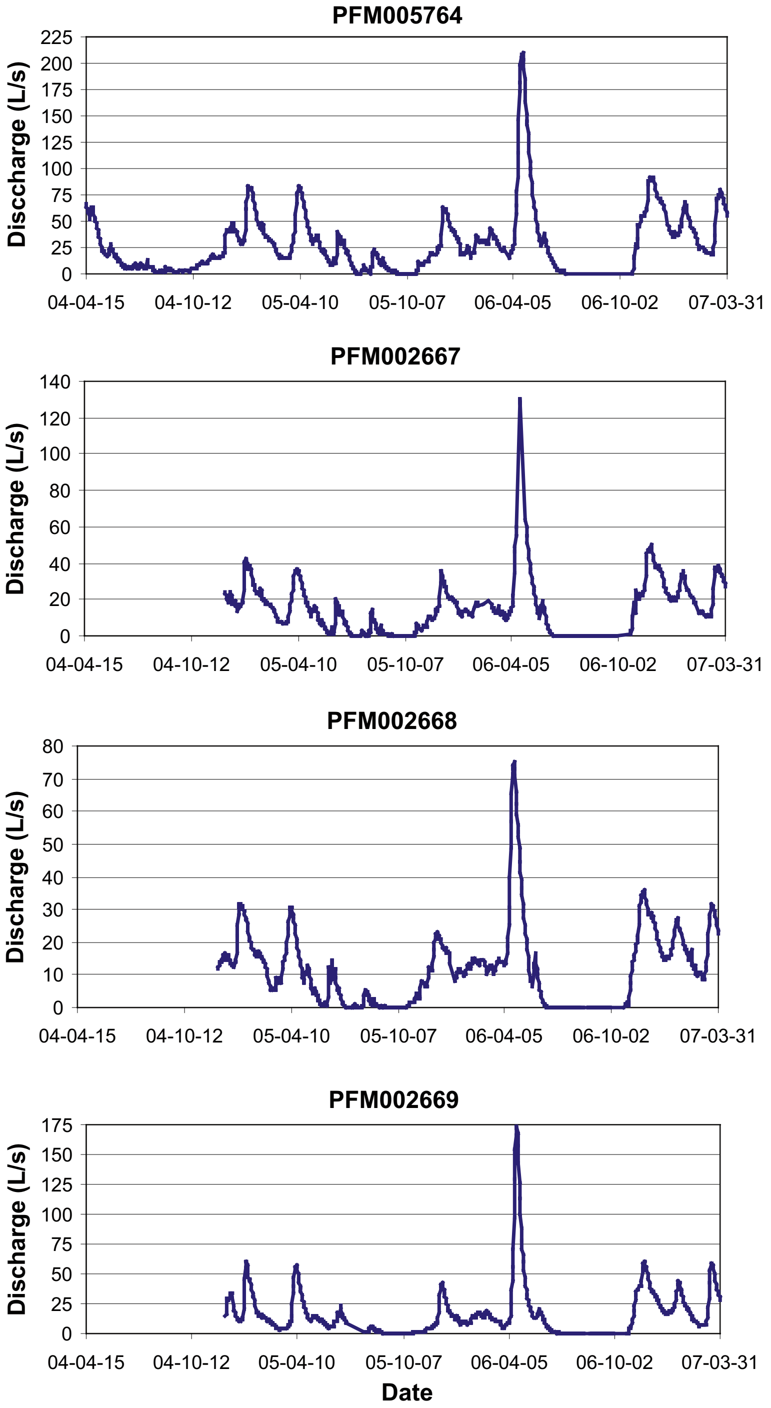


Figure 2-52. *Surface discharge time series at the four automatic gauging stations (daily means). Note the different scales of the discharge axes.*

The relatively short time series available imply that it is difficult to draw any definite conclusions on long-term mean specific discharge. This is illustrated by the mean values for various time periods presented in Table 2-12. The mean specific discharge for the largest catchment, which had a time series spanning 35.5 months, was 4.87 L/s/km^2 (154 mm/year). The variation of specific discharge for a specific station for the time periods selected for comparison was 24–33%, whereas the variation between stations for the same time period was 9–13%.

The results of the automatic monitoring of the electrical conductivity of the discharge at the stations are summarised in Table 2-13. Generally, discharge and EC were inversely correlated, i.e. EC was low during high discharge and vice versa. A co-plot of discharge and EC at PFM005764 is shown in Figure 2-53.

Table 2-12. Discharge characteristics for the four gauging stations for various time periods (* total available time series for PFM00576, ** total available time series for PFM002667, PFM002668 and PFM002669).

	PFM005764	PFM002667	PFM002668	PFM002669
Apr 15, 2004-Mar 31, 2007*				
Mean discharge (L/s)	27.2			
Min. discharge (L/s)	0.00			
Max. discharge (L/s)	212			
Specific discharge (L/s/km^2)	4.87			
Specific discharge (mm/yr)	154			
Dec 8, 2004-Mar 31, 2007**				
Mean discharge (L/s)	31.0	15.6	11.6	15.8
Min. discharge (L/s)	0.00	0.00	0.00	0.00
Max. discharge (L/s)	212	131	75.9	183
Specific discharge (L/s/km^2)	5.54	5.19	5.07	5.57
Specific discharge (mm/yr)	175	164	160	176
Jan 1-Dec 31, 2005				
Mean discharge (L/s)	25.2	12.1	9.09	11.6
Min. discharge (L/s)	0.00	0.00	0.00	0.00
Max. discharge (L/s)	85.3	43.7	31.8	60.7
Specific discharge (L/s/km^2)	4.51	4.01	3.99	4.10
Specific discharge (mm/yr)	142	127	126	129
Jan 1-Dec 31, 2006				
Mean discharge (L/s)	32.9	17.1	12.1	17.4
Min. discharge (L/s)	0.00	0.00	0.00	0.00
Max. discharge (L/s)	212	131	75.9	183
Specific discharge (L/s/km^2)	5.89	5.67	5.31	6.13
Specific discharge (mm/yr)	186	179	167	193
Oct 1, 2004-Sep 30, 2005				
Mean discharge (L/s)	24.7			
Min. discharge (L/s)	0.00			
Max. discharge (L/s)	85.3			
Specific discharge (L/s/km^2)	4.42			
Specific discharge (mm/yr)	139			
Oct 1, 2005-Sep 30, 2006				
Mean discharge (L/s)	27.3	14.3	10.3	14.1
Min. discharge (L/s)	0.00	0.00	0.00	0.00
Max. discharge (L/s)	212	131	75.9	183
Specific discharge (L/s/km^2)	4.88	4.74	4.53	4.96
Specific discharge (mm/yr)	154	149	143	157

Table 2-13. Electrical conductivity (EC) at the automatic discharge gauging stations.

Gauging station ID-code	Catchment area ID-code	Average EC (mS/m)	EC Range (mS/m)
PFM005764	AFM001267	37	21–47*
PFM002667	AFM001268	26	14–40
PFM002668	AFM001269	25	10–40
PFM002669	AFM001270	37	22–55

* Some very high values, mostly at very low discharges, were considered not representative and removed.

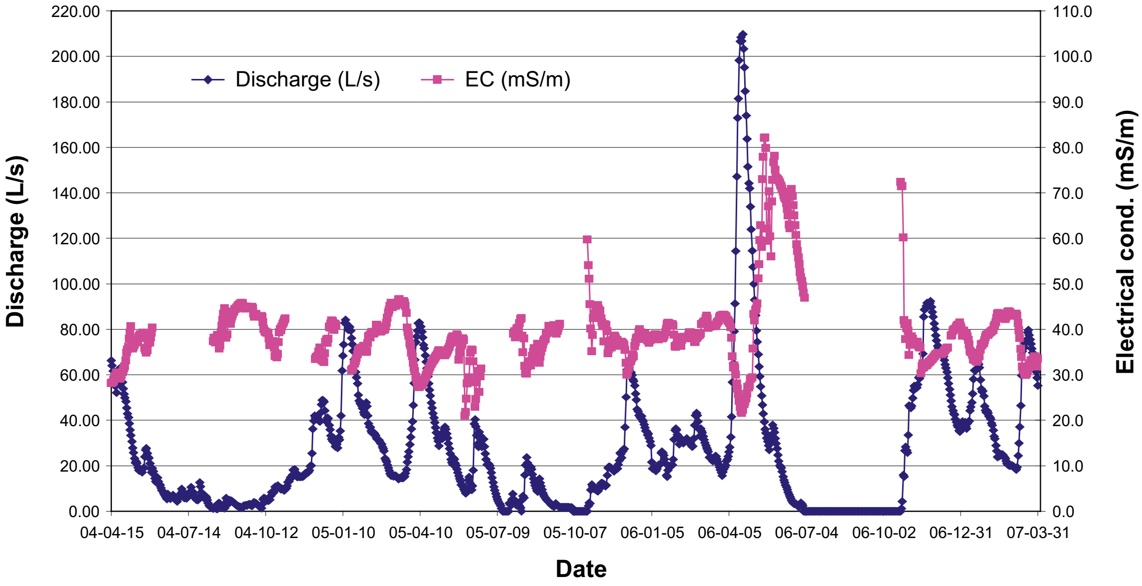


Figure 2-53. *Co-plot of discharge and electrical conductivity (EC) at PFM005764.*

3 Hydrological relationships between datasets

3.1 Site average rainfall/snowmelt time series and monthly precipitation – potential evapotranspiration budget

A simple snow accumulation and melt model was used to derive a rainfall/snowmelt time series from the precipitation time series. The model assumptions were:

- Precipitation that occurred on days with mean daily air temperatures above –0.4°C was rainfall that infiltrated the ground surface.
- Snow accumulated on the ground surface from precipitation occurring on days with mean daily air temperatures equal and below –0.4°C.
- The accumulated water content in the frozen above-ground storage melted on days when the mean daily air temperature was above –0.8°C. The melt rate was estimated using a standard degree-day formulation and a calibrated rate constant of K = 0.8 mm/degree above –0.8°C.

The input to the model was the daily average precipitation time series from Högmasten and Storskäret (Figure 2-7) and the daily average air temperature from the same stations (Figure 2-14). Calibration was based on the average of measured snow water content at the two sites located in forest (AFM000072 and AFM001172, see Figures 2-4 and 2-13). The site located on agricultural land was excluded since forest is totally dominating in the central parts of the site investigation area. The output from the model was a simulated time series for water storage in snow, Figures 3-1. The snow routine model appeared to adequately capture the site-average dynamics for water storage in snow ($R^2 = 0.83$).

Figure 3-2 shows rainfall and estimated snowmelt events separately. This time series are used in subsequent sections to develop hydrological relationships in groundwater level and surface discharge time series.

It will also be useful to consider a monthly rainfall/snowmelt minus potential evapotranspiration differential in subsequent evaluations of time series. Figure 3-3 shows monthly rainfall/snowmelt and potential evapotranspiration time series based on monthly totals from the rainfall/snowmelt (Figure 3-2) and potential evapotranspiration time series (Figure 2-24).

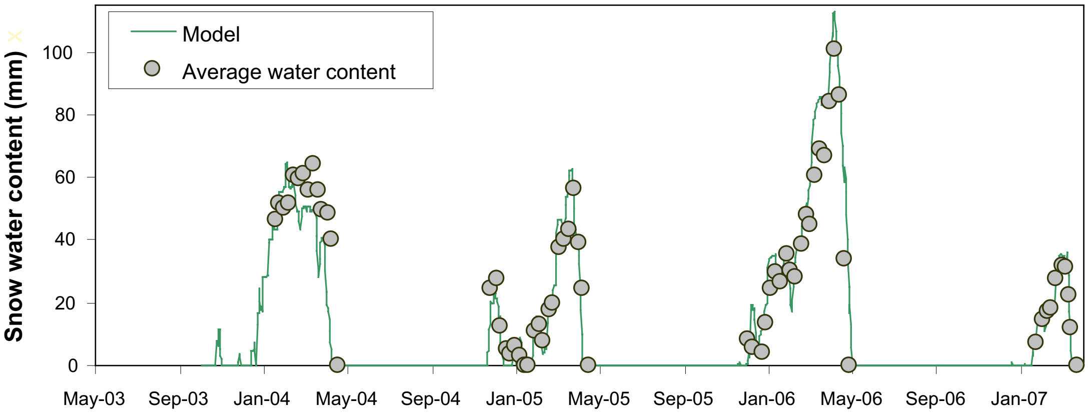


Figure 3-1. *Comparison of measured and simulated site-average snow water content based on a simple degree-day snowmelt model.*

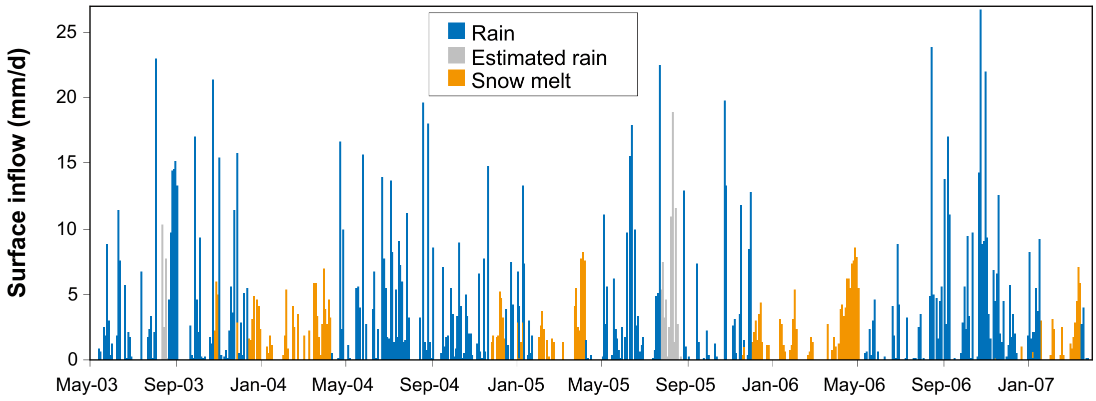


Figure 3-2. *The site-average rainfall/snowmelt record.*

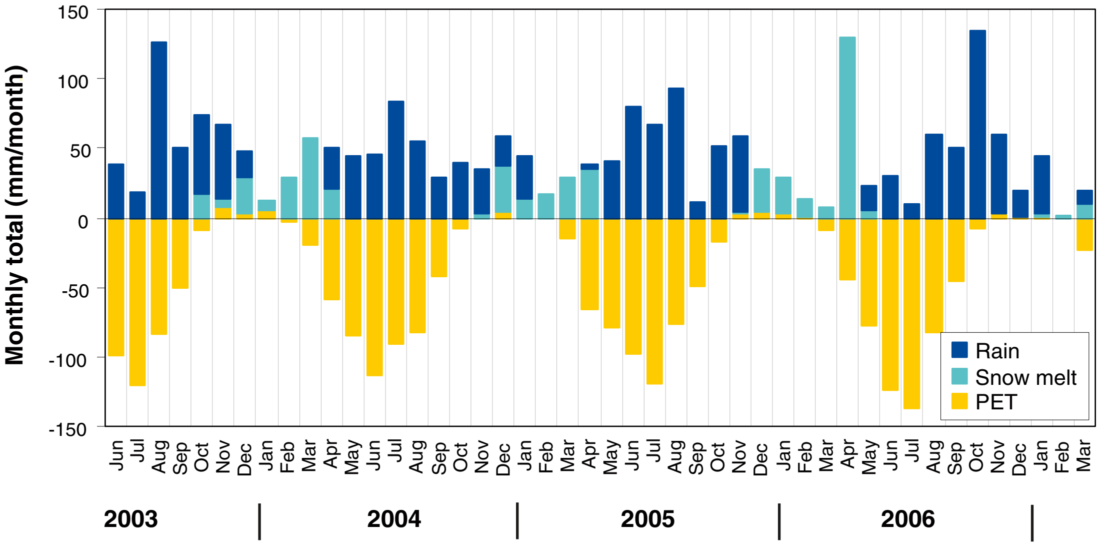


Figure 3-3. *Monthly total R+S (rainfall+snowmelt) and PET (potential evapotranspiration).*

3.2 Relationships between groundwater levels and precipitation, snowmelt events and evapotranspiration

The influence of rainfall, snowmelt, and evapotranspiration are clearly evident in groundwater level and surface discharge time series, in terms of both long-term cycles and short-term event-driven responses. Figure 3-4 shows co-plots of time series for rainfall plus snowmelt minus potential evapotranspiration, groundwater levels relative to ground surface in Quaternary deposits, point water head elevations in bedrock, and surface water discharge. The rainfall plus snowmelt minus potential evapotranspiration data are shown with monthly totals (Figure 3-4a) to emphasize the overall trends. There is a strong seasonal cycle in rainfall/snowmelt minus potential evapotranspiration that is reflected in the overall shape of many of the groundwater responses in both the Quaternary deposits and in the bedrock.

In Figure 3-5 the accumulated sum of rain and snowmelt (R+S) minus potential evapotranspiration is plotted together with the average groundwater level in all wells in till. The direct response on rainfall and strong impact of evapotranspiration can be clearly seen. The very fast and strong responses of the groundwater level to rainfall also when the level is relatively deep below the ground and the unsaturated zone deficit could be assumed to be relatively large, as in the summer/autumn of 2005 and 2006, indicate some kind of by-pass flow and/or a quite small specific yield.

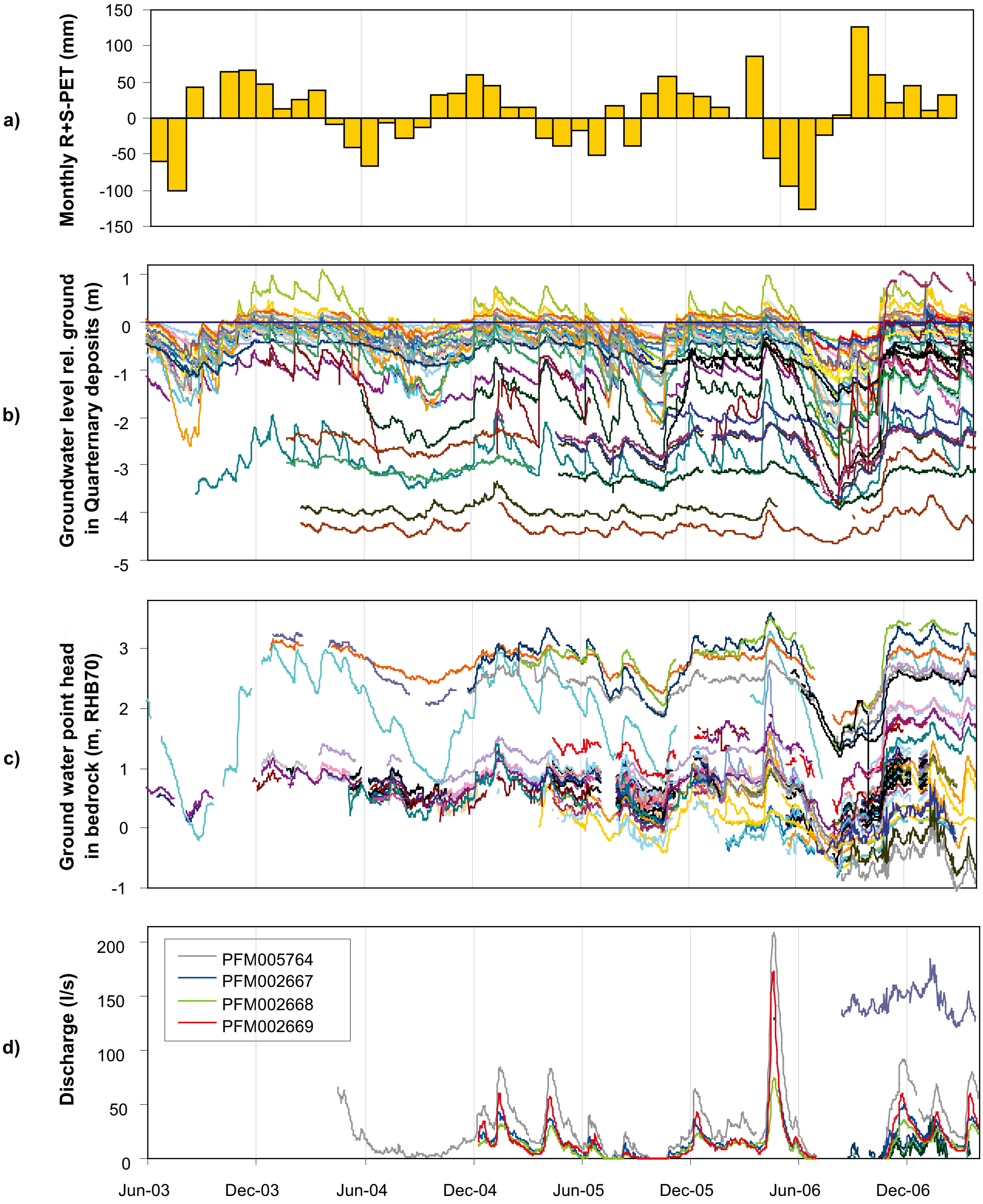


Figure 3-4. *Time series comparisons for monthly rainfall plus snowmelt minus potential evapotranspiration (a), daily groundwater levels in Quaternary deposits relative to ground surface (b), daily groundwater point water head elevations in the bedrock (c), and daily surface water discharge (d). Not all wells are shown in c) in order to provide better resolution on the overall trends (HFM11, HFM12, HFM34.2, HFM35.1-3, HFM36 and HFM37 are excluded).*

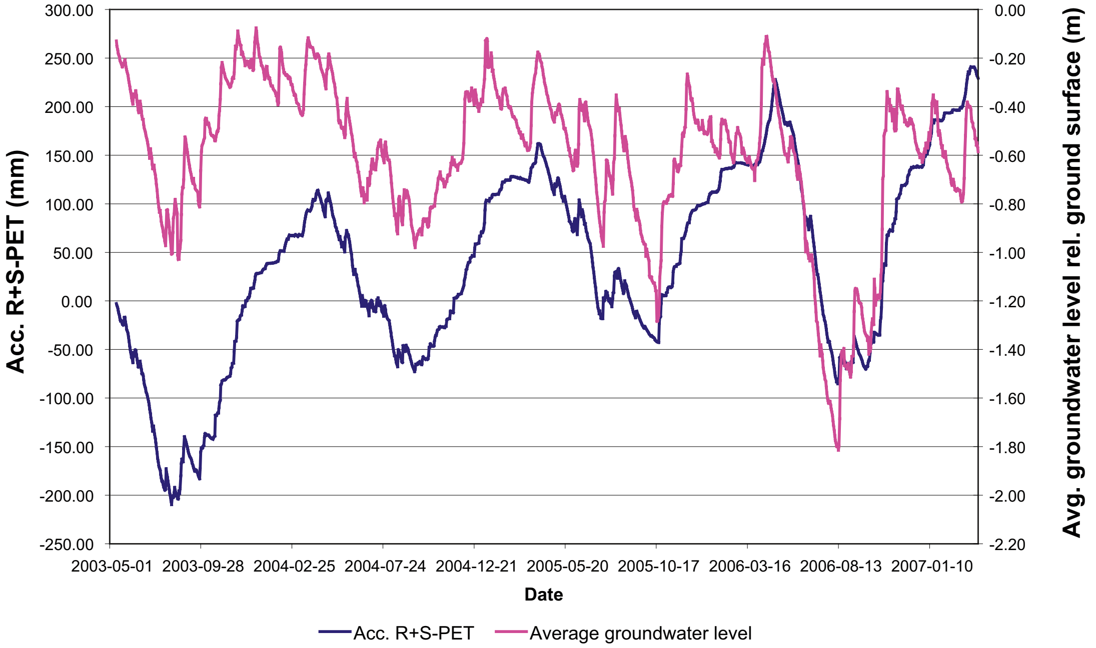


Figure 3-5. *Rain and snowmelt (R+S) minus potential evapotranspiration PET is plotted together with the average groundwater level in all wells in till.*

Figure 3-6 shows coefficients of determination (R^2) for groundwater levels in Quaternary deposits (excluding wells below lakes) compared to the rainfall plus snowmelt minus potential evapotranspiration time series. The correlations were estimated using monthly average groundwater levels to help eliminate the influence of short-term dynamics. Month-to-month correlations were typically low in most wells (< R^2 = 0.30), with the exception of SFM0059 and SFM0061. However, correlations of monthly groundwater levels to the average of the antecedent two months rainfall/snowmelt minus potential evapotranspiration deficit was substantially higher in almost all wells (R^2 = 0.60–0.80), with the exceptions of SFM0005, SFM0006, SFM0059, and SFM0061.

The time series for the wells with ID codes SFM0080 and higher are quite short and the results for these wells should be seen as preliminary. SFM0006 was the only well that showed poor correlation to both month-to-month and antecedent two months R+S-PET. SFM0059, which is located in a glaciofluvial deposit, was the only well with higher correlations to month-to-month R+S-PET values compared to the antecedent two months average.

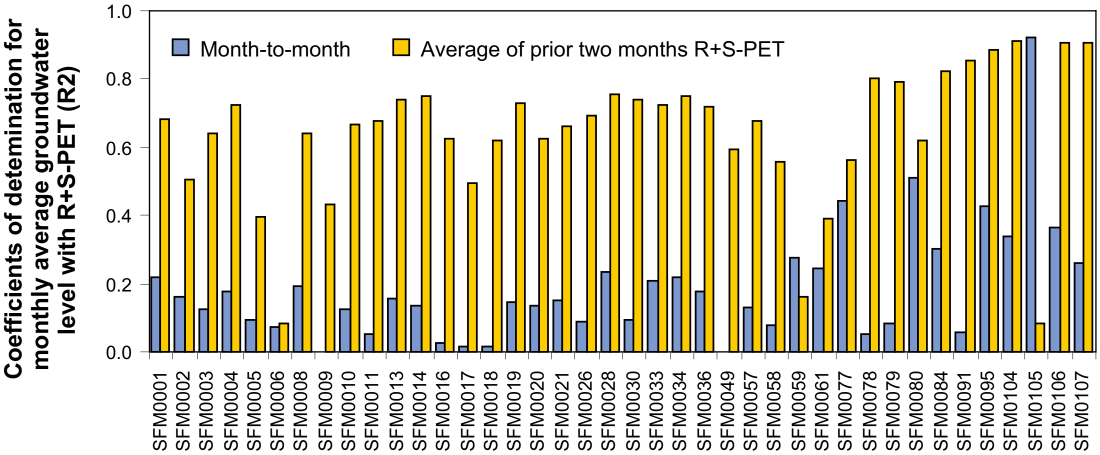


Figure 3-6. *Correlation of monthly average groundwater levels in Quaternary deposits with monthly and bi-monthly rainfall/snowmelt-potential evapotranspiration differentials (R/S-PET). See Figure 2-32 for the locations of the wells.*

Figure 3-7 shows the coefficients of determination (R^2) for monthly change in groundwater levels in Quaternary deposits (change between the first and last day of the month) and rainfall plus snow melt minus potential evapotranspiration for the same month. Compared with the month-to month correlations with absolute levels presented in Figure 3-6, the coefficients of determination are considerably higher. In general these results suggest that rainfall/snowmelt minus potential evapotranspiration cycles to a great extent explain the monthly average variations in groundwater levels in most wells.

The time series for point water heads in the bedrock show similar trends as the groundwater levels in the Quaternary deposits (Figure 3-4c). However, correlations to rainfall plus snowmelt minus potential evapotranspiration were not as high as with groundwater in Quaternary deposits. Figure 3-8 shows coefficients of determination for monthly average groundwater point water heads in bedrock

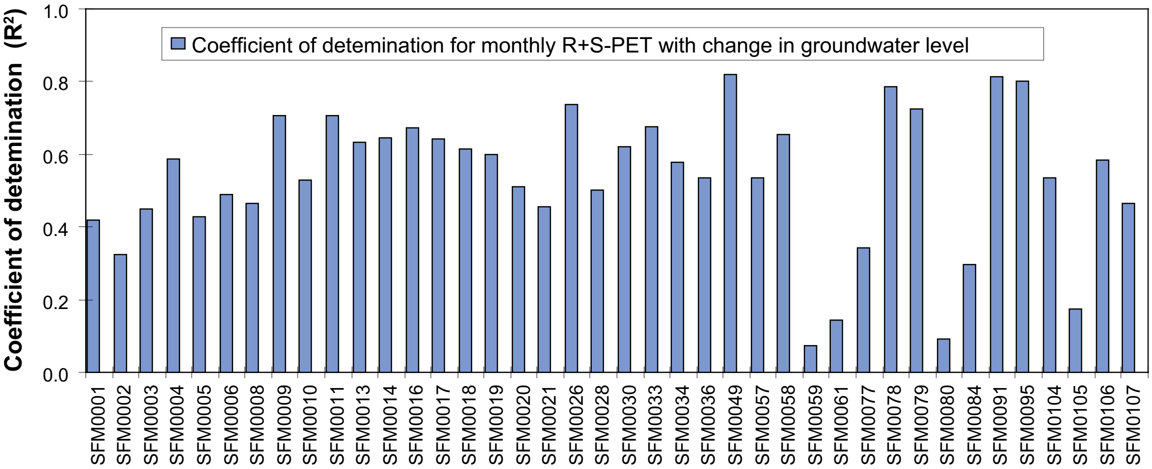


Figure 3-7. Coefficients of determination (R^2) for monthly change in groundwater levels in Quaternary deposits (change between the first and last day of the month) and rainfall plus snow melt minus potential evapotranspiration (R+S-PET) for the same month. See Figure 2-32 for the locations of the wells.

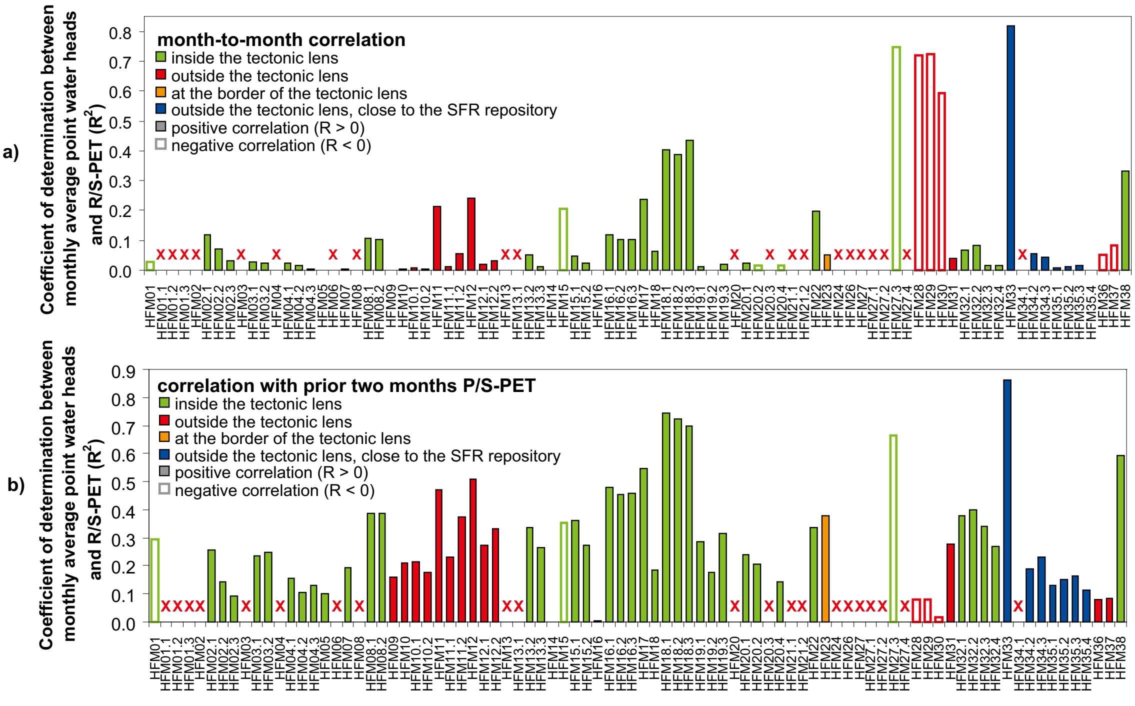


Figure 3-8. *Correlations for monthly average groundwater point water heads in bedrock to a) monthly average and b) average of prior two-months rainfall/snowmelt minus potential evapotranspiration (R+S-PET) time series. X's indicated wells that had less than 6-months months of available data with at least 15 days of data in each month. See Figure 2-41 for the locations of the wells.*

compared to monthly rainfall/snowmelt minus potential evapotranspiration. Coefficients of determination are shown for all packer sections, as correlations varied in different sections of the same well. Note that the correlations between monthly average point water heads and monthly average R+S-PET (Figure 3-8a) were negative for some wells.

In general, correlations between point water heads and rainfall plus snowmelt minus potential evapotranspiration were weak and inconsistent in the bedrock. The highest observed positive correlation to the monthly average data was by far at HFM33 and was $R^2 = 0.82$. HFM33 also had the highest correlation to the two-month prior average of R+S-PET and that value was $R^2 = 0.86$. The correlation to the two-month prior average was actually higher than to the month-to-month correlation for all HFM wells. Results from a principal component analysis (PCA) that further investigated relationships between groundwater point water heads in bedrock and meteorological variables (R+S-PET), were presented in /Juston et al. 2007/.

Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, were evident in the data from many of the groundwater wells in Quaternary deposits. Figure 3-9 shows two examples of diurnal ET-driven cycles for the wells SFM0033 and SFM0030 with very shallow and somewhat deeper groundwater levels, respectively; one-hour resolution data for a three-week period in August 2006 (see Figure 2-32 for the location of the wells). As would be expected, the well with shallower groundwater depth exhibited a stronger diurnal response (~10 cm), as compared to the location with deeper groundwater (~5.0 cm). Additionally, the shallow system exhibited a sharper response to the precipitation beginning on August 15. During the period August 15–17 the total rainfall was 35 mm.

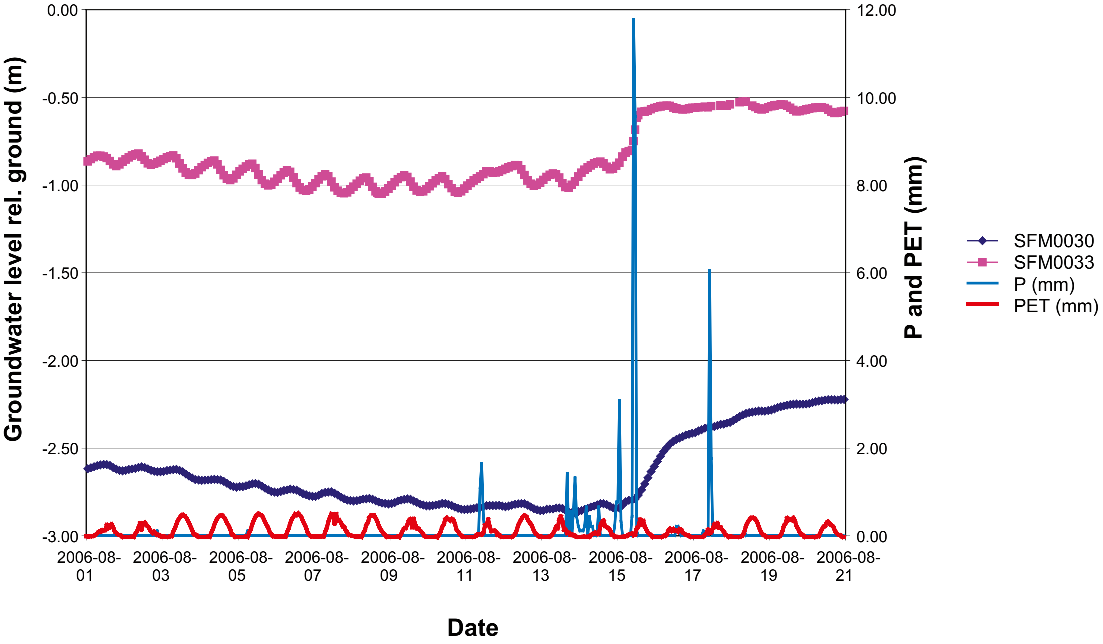


Figure 3-9. *Diurnal groundwater level fluctuations in an area with very shallow groundwater (represented by well SFM0033) and in an area with somewhat deeper groundwater (represented by well SFM0030).*

3.3 Relationships between groundwater levels and the sea level

In Figure 3-10 sea levels are plotted with groundwater levels in QD and bedrock. The correlations between the three data sets have been investigated by several methods, including linear regression of mean values for different time intervals and displacements in time, principal component analysis (PCA), independent component analysis (ICA) and partial least squares modelling (PLS) /Juston et al. 2007/. In Figures 3-11 and 3-12 the regression coefficients for the QD and bedrock wells, respectively, are shown. The time intervals and displacements in time demonstrating the highest regression coefficients are shown.

As anticipated the regression coefficients for the groundwater levels in QD with the sea were very low, with exception of the two wells SFM0059 and SFM0061 located in glaciofluvial material (Börstilåsen) within 100 m from the sea. The coefficients of determination for the bedrock boreholes were also quite low except for those obtained for the boreholes located at the SFR-peninsula, i.e. HFM33, -34 and -35 (Figure 3-12). The time series in these boreholes are comparatively short. However, it is assumed that the coefficients of determination of these wells will remain high also when longer time series become available.

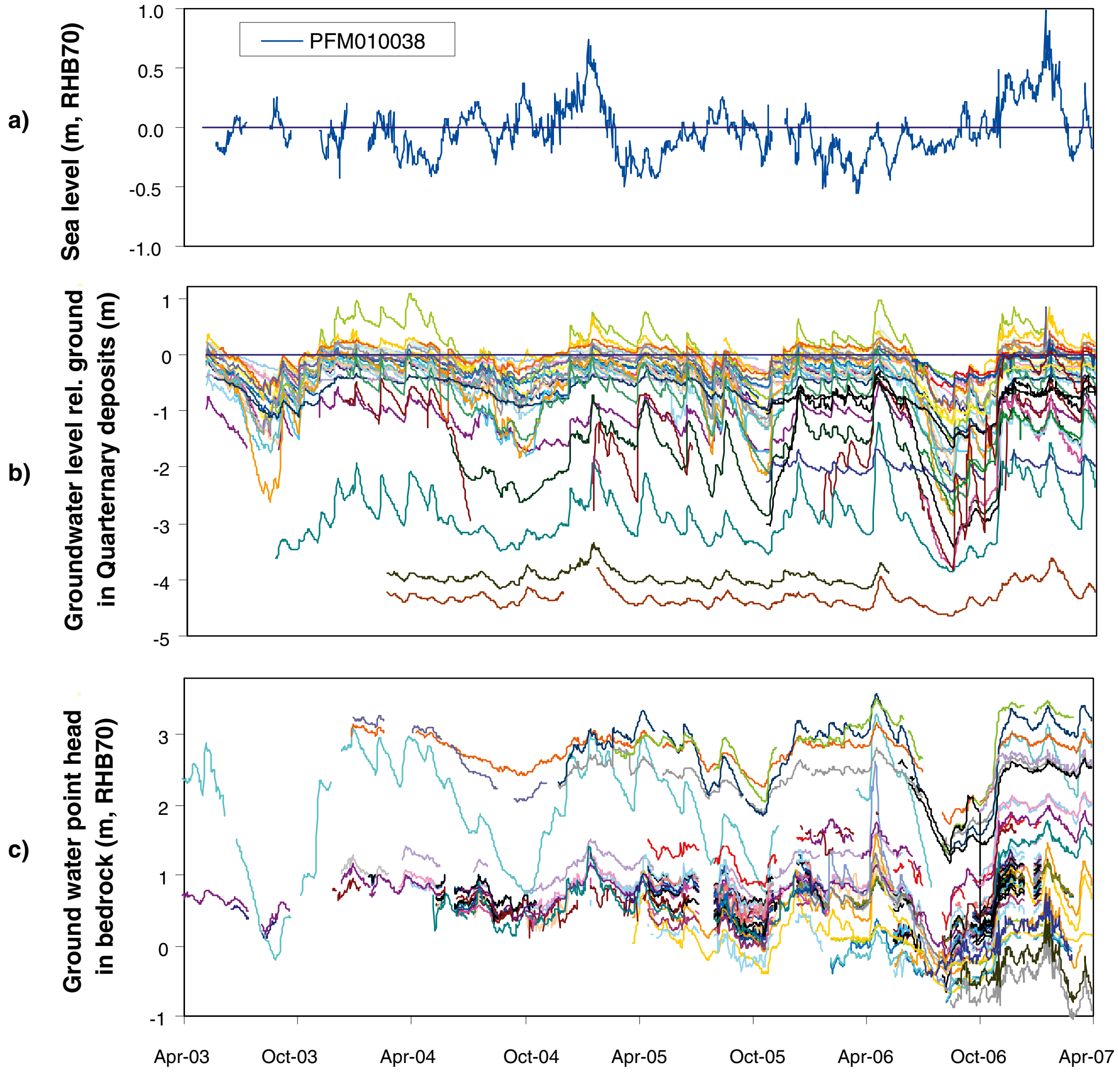


***Figure 3-10.** Comparison of sea water levels (a) and groundwater levels in QD (b) and in bedrock (c). In c) HFM11, 12, 34:2, 35:1–3, 36 and 37 have been excluded to enable a better resolution of the y-axis.*

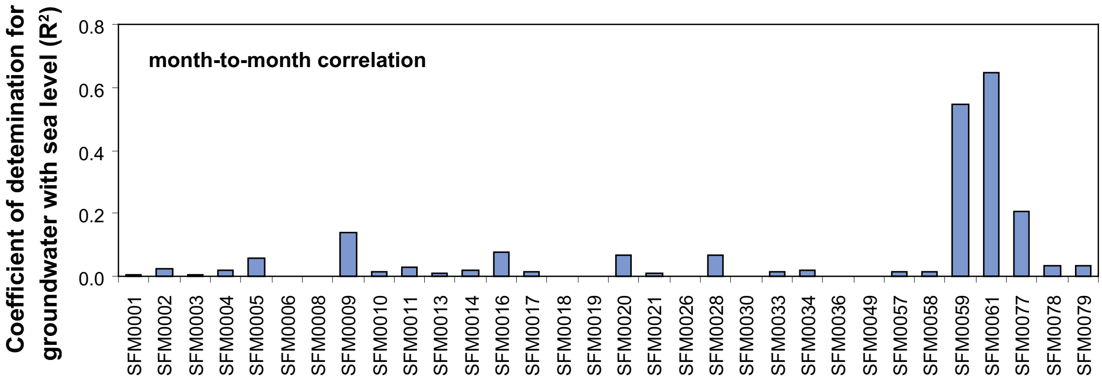


Figure 3-11. Correlation between sea water level and groundwater levels in monitoring wells in QD on land with more than one year of data.

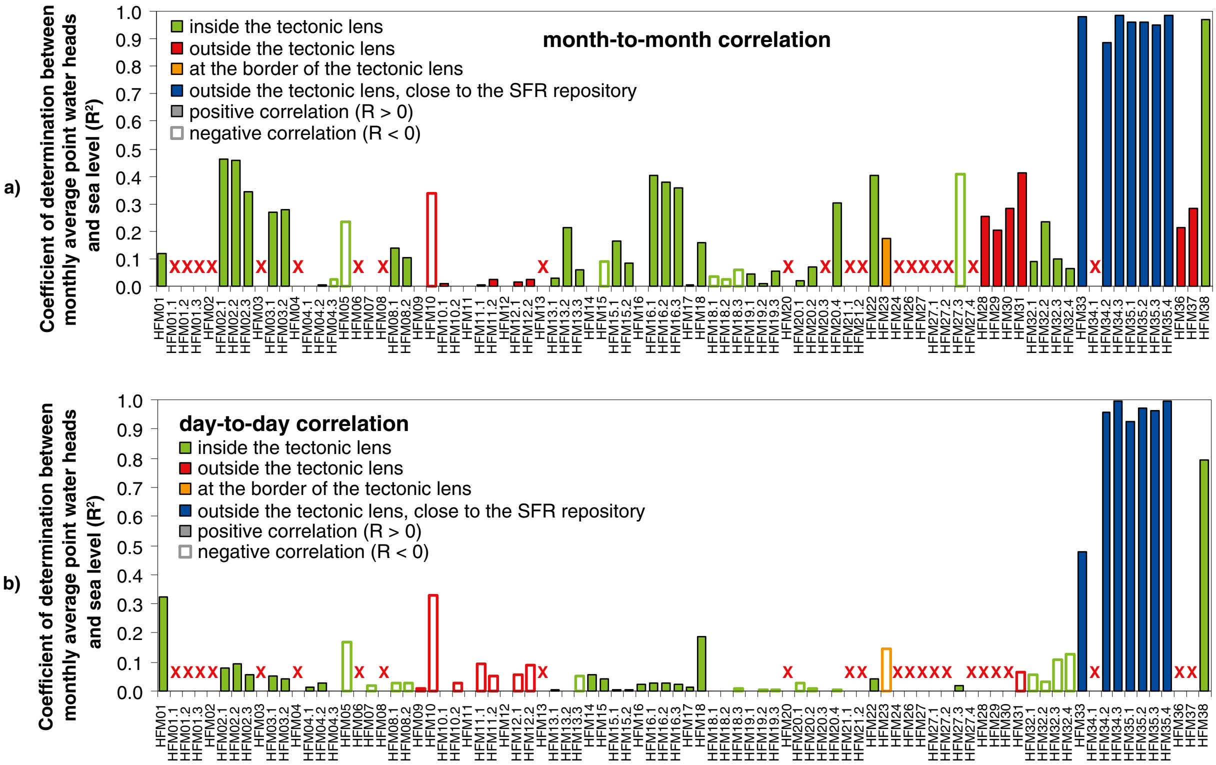


Figure 3-12. Correlation between sea water level and point water heads in bedrock (HFM-borehole sections). The month to month correlation is presented for sections with more than 6 months of data with at least 15 days of data per month. For the day-to-day correlation, sections with more than 6 months of data are included.

The very low coefficients of determination for most of the bedrock boreholes were not expected. To further explore the relationship between the sea level and the groundwater levels in the bedrock PCA (Principal Component Analysis), ICA (Independent Component Analysis) and PLS (Partial Least Squares) analyses were conducted. The PCA and ICA analyses indicated that the seasonal rain+snowmelt and evapotranspiration variations describe about 80% of the total variation, while the sea water level explains less than 10% of the variation /Juston et al. 2007/. However, the fact that the sea water level covariates with the occurrence of low pressures and accompanying precipitation makes the correlation difficult to elucidate.

Figure 3-13 shows the sea water level plotted together with the mean of measured groundwater levels in all HFM-boreholes and a groundwater level simulated by a simple tank model. The level in the groundwater storage was assumed to be a function of daily infiltration (corrected precipitation and difference in snow storage minus potential evapotranspiration), and an outflow function proportional to the groundwater level. A constant of the outflow function was calibrated to meet the assumption of zero change of groundwater storage during March 2005 to February 2007. There is a good match between the modelled groundwater level (green) and the mean variation in all percussion boreholes (red) according to Figure 3-13, indicating that the annual cycle is mostly controlled by variations in evapotranspiration.

The PLS regression technique, which is a multivariate regression technique related to PCA and suitable to explore the correlation structure between two matrices, was applied on selected time series of groundwater point water heads, sea level, air pressure and modelled groundwater level. Here, one matrix contains the time series of sea level, air pressure and modelled groundwater level, and the second matrix the time series of groundwater point water heads.

The resulting components of the PLS-model reveal underlying factors common to both matrices (i.e. common to both sea level, air pressure and modelled groundwater level, and groundwater point water heads), and may have an explicit interpretation. In all models the first component describes the overall seasonal pattern closely coupled to the modelled groundwater level (Gwmod), whereas the second component is mainly coupled to variations in sea level and air pressure. The graphical output of these multivariate models is analogous to the "loading plot" of the PCA, in the respect that variables located close to each other are correlated, whereas variables located on opposite sides of the origin are inversely correlated. Variables located close to the origin show little connection to the selected components.

In order to describe the relative influence of the sea level (SeaLev), air pressure and (Gwmod) on the observed groundwater level variation in each borehole, the distance to SeaLev and GWmod was calculated according to the schematic picture in Figure 3-14. This projected measure (ζ) is used to summarise all models in Table 3-1 and finally to achieve a compact spatial visualisation of the relative influence of the variations in sea level in Figure 3-15. See /Juston et al. 2007/ for a more detailed description of the applied methodology.

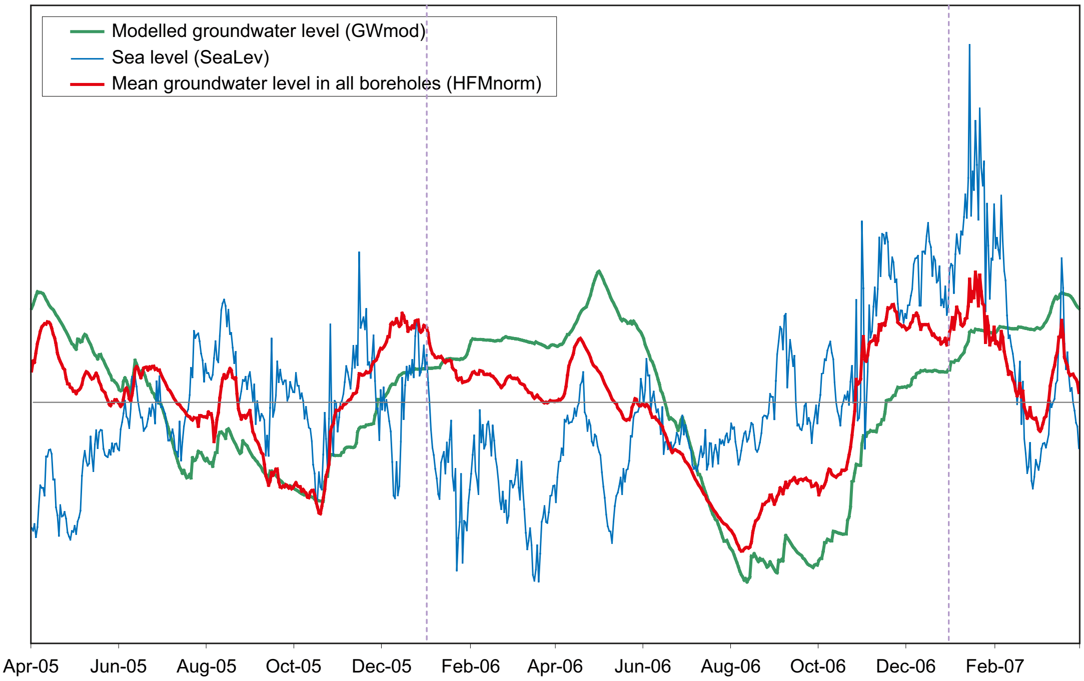


Figure 3-13. *Time-series showing sea level and modelled groundwater level together with the mean groundwater level in all percussion-drilled boreholes (HFM) (mean of individually normalised time series). All time series are standardised to zero mean and equal variance.*

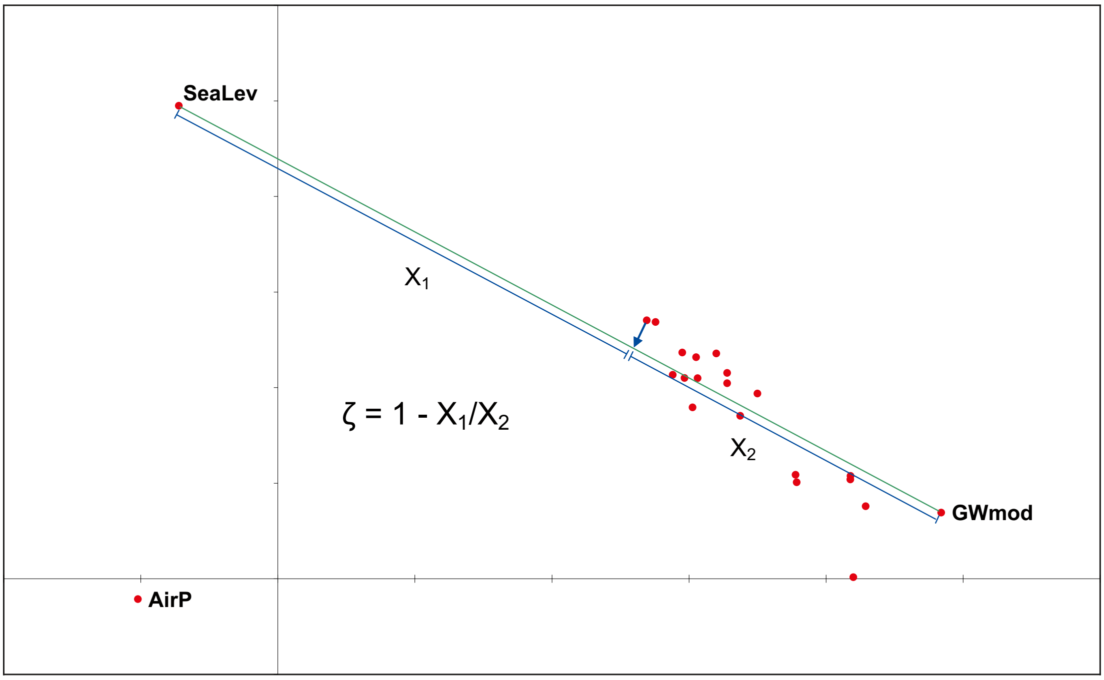
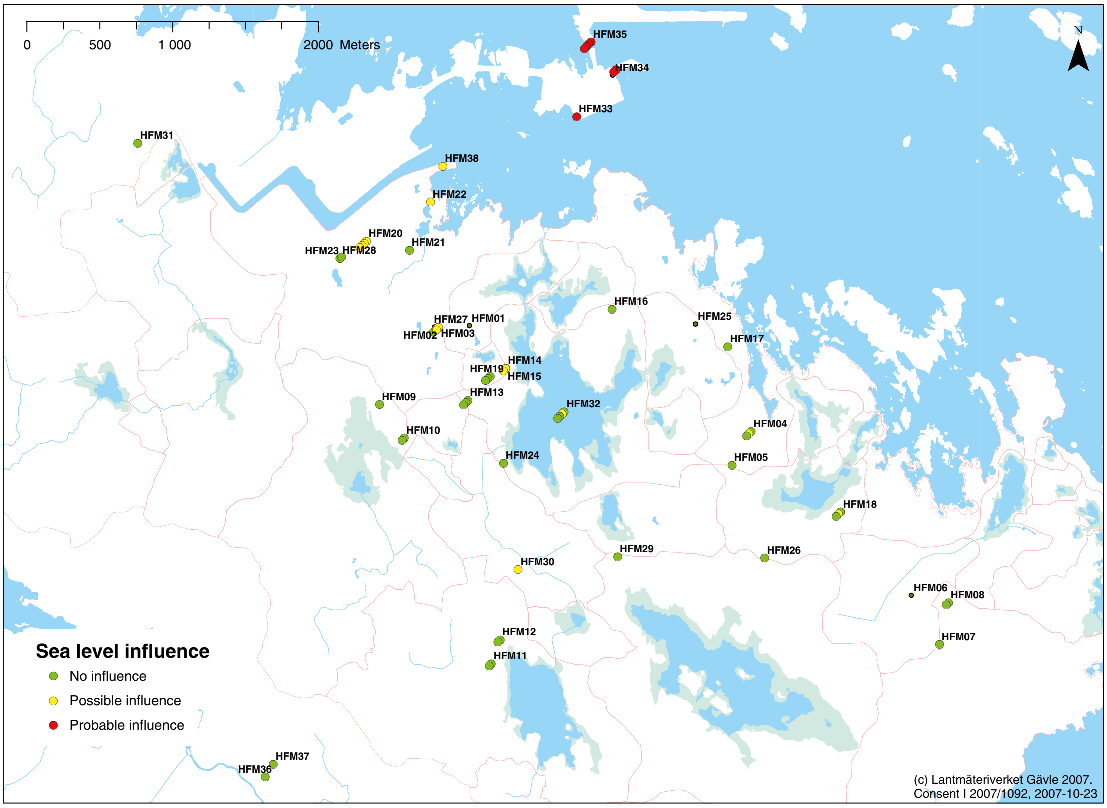


Figure 3-14. *Schematic description of how the relative distance to the SeaLev "pole" (ζ) is calculated from the perpendicular projection to the line that connects SeaLev and GWmod.*



(c) Lantmäteriverket Gävle 2007.
Consent I 2007/1092, 2007-10-23

Figure 3-15. *The spatial distribution of the three classes representing "no influence", "possible influence" and "probable influence" from variations in sea water level. In case of several sections per borehole, the uppermost section is plotted on top and the deepest section at the bottom of the pile.*

Table 3-1. Compilation of results from the correlation analysis of sea water level influence on percussion-drilled boreholes. The analysis has been conducted on individual borehole sections (denoted HFMXX.Y with the section numbering (Y) starting from the deepest section). The ζ-parameter ranging from 0 to 1 represents the relative association with the SeaLev and GWmod variables (1 indicates strong association with SeaLev). To facilitate interpretations three colour coded classes denoted 'no influence' (green), 'possible influence' (yellow) and 'probable influence' (pink) have been marked in the table. A0-G are sub-series of data used to make maximum use of available data.

Borehole	Data selection										Classification	
Idcode	**A0**	**B0**	**C0**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Mean**	**Class**
HFM02.1			0.40				x				0.40	Possible influence
HFM02.2			0.63				x				0.63	Possible influence
HFM02.3			0.32				x				0.32	No influence
HFM03.1			0.43				x				0.43	Possible influence
HFM03.2			0.42				x				0.42	Possible influence
HFM04.1	0.27				0.30						0.28	No influence
HFM04.2	0.27				0.40						0.34	Possible influence
HFM04.3	0.20				0.16						0.18	No influence
HFM05					0.17						0.17	No influence
HFM07	0.11	0.02	0.00	0.01			x	0.27	0.14		0.09	No influence
HFM08.1		0.07		0.15	0.29	0.37	x	0.39	0.26	0.29	0.26	No influence
HFM08.2		0.07		0.15	0.30	0.35	x	0.41	0.24	0.27	0.25	No influence
HFM09	0.09	0.06	0.00	0.11	0.16	0.11	x	0.26	0.11	0.12	0.11	No influence
HFM10.1	0.08	0.07	0.00	0.11	0.15	0.10	x	0.26	0.11	0.13	0.11	No influence
HFM10.2		0.02		0.07	0.11	0.14	x	0.21	0.09	0.12	0.11	No influence
HFM11.1	0.29	0.01	0.00		0.13	0.08	x	0.30	0.11	0.11	0.13	No influence
HFM11.2			0.00		0.21	0.17	x	0.37	0.17	0.16	0.18	No influence
HFM12.1	0.17	0.10			0.23	0.16	x	0.34	0.14	0.14	0.18	No influence
HFM12.2					0.16	0.08	x	0.37	0.15	0.16	0.18	No influence
HFM13.1		0.23		0.35			x				0.29	No influence
HFM13.2		0.31		0.29			x				0.30	No influence
HFM13.3		0.21		0.26	0.17	0.18	x		0.17	0.17	0.19	No influence
HFM14	0.34	0.33	0.42	0.42							0.38	Possible influence
HFM15.1	0.36	0.24	0.40	0.33			x				0.33	Possible influence
HFM15.2		0.31		0.41			x				0.36	Possible influence
HFM16	0.32	0.25	0.37								0.31	No influence
HFM17	0.23		0.25		0.32	0.19	x				0.25	No influence
HFM18	0.39	0.13	0.54	0.32			x				0.35	Possible influence
HFM18.1						0.32	x				0.32	No influence
HFM18.2						0.35					0.35	Possible influence
HFM18.3						0.32					0.32	No influence
HFM19.1		0.24		0.36							0.30	No influence
HFM19.2		0.23		0.34							0.29	No influence
HFM19.3		0.20		0.30							0.25	No influence
HFM20.1		0.60		0.30			x				0.45	Possible influence
HFM20.2		0.47					x				0.47	Possible influence
HFM20.3		0.42					x				0.42	Possible influence
HFM20.4		0.33					x				0.33	No influence
HFM21.1				0.25			x				0.25	No influence
HFM22		0.65		0.33			x				0.49	Possible influence
HFM23						0.29	x	0.33	0.31		0.31	No influence
HFM24						0.03					0.03	No influence
HFM26							x	0.25			0.25	No influence
HFM28							x	0.27			0.27	No influence
HFM29								0.23			0.23	No influence
HFM30								0.35			0.35	Possible influence
HFM31							x	0.20			0.20	No influence
HFM32.1						0.19	x		0.27		0.23	No influence
HFM32.2						0.31	x		0.35		0.33	Possible influence
HFM32.3						0.12					0.12	No influence
HFM32.4						0.07		0.32	0.16		0.19	No influence
HFM33								1.00			1.00	Probable influence
HFM34.2							x	1.00			1.00	Probable influence
HFM34.3							x	0.96			0.96	Probable influence
HFM35.1							x	1.00			1.00	Probable influence
HFM35.2								1.00			1.00	Probable influence
HFM35.3							x	1.00			1.00	Probable influence
HFM35.4							x	0.97			0.97	Probable influence
HFM36								0.05			0.05	No influence
HFM37								0.21			0.21	No influence
HFM38							0.63				0.63	Possible influence

In all analyses, two-component PLS-models are used, where about 70–80% of the variation in groundwater point water heads are explained by the selected variables. In Table 3-1 a rough statistical classification in three classes denoted “no influence”, “possible influence” and “probable influence” is introduced to facilitate interpretations. It should be noted that both limits and denominations of these classes are chosen rather arbitrarily.

With the selected class limits there is a tendency of stronger sea level influence in the northern and north-western part of the Forsmark area. This pattern is most evident near the SFR repository (note the red points at the peninsula in the north), where all observations are classified as “probable influence” from sea level fluctuations (HFM33, HFM34, HFM35). Also a number of boreholes located on the mainland show “possible influence“ indicating that groundwater in the bedrock in this area is influenced from sea level fluctuations, e.g. HFM02, HFM03, HFM14, HFM15, HFM20, HFM22 and HFM38.

Except for the boreholes in the northwest, there are a two boreholes near the coast (HFM04 and HFM18) that are classified as “possible influence”, as well as one borehole (HFM30) located more distant from the sea. In the case of HFM18 there are several indications of “possible influence” that strengthen the conclusion, whereas the classification of the latter borehole, HFM30, which is only represented in one time-series, most probably is a coincidence.

It should be noted that there are many uncertainties associated with the analysis and precise conclusions should not be drawn about specific boreholes. There are several examples of borehole sections that are classified both as “no influence” and “possible influence” depending on which of the sub-series of data used in the analysis, e.g. HFM08, HFM11 and HFM12, indicating that there is a substantial noise in the classification. General spatial trends shown by several boreholes based on different time series may on the other hand give indications that there is a real phenomenon behind the pattern rather than a coincidence. For example, this is the case in the north-western part of the area. The spatial pattern formed by the boreholes in the north-western part of the area, demonstrating possible influence from sea water fluctuations according to the correlation analysis (e.g. HFM02, HFM03, HFM14, HFM15, HFM20, HFM22 and HFM38), may reflect structural properties of the bedrock in this area.

3.4 Relationships between lake levels and groundwater levels

3.4.1 Vertical gradients between lake levels and wells in till below

Groundwater levels in the till below lake surfaces were measured where surface water levels were measured in Lake Eckarfjärden, Lake Gällsboträsket, Lake Fiskarfjärden, Lake Bolundsfjärden, and Lake Lillfjärden, but not at Lake Norra Bassängen. Surface water levels and groundwater levels below lakes are shown in Figure 3-16 for Eckarfjärden, Gällsboträsket, Fiskarfjärden, Bolundsfjärden, and Lillfjärden. Figure 3-17 shows the same data represented as level differentials, where positive values indicate upward gradients from groundwater to surface water, and negative values indicate downward gradients from surface water to groundwater.

Level gradients were variable and typically small (a few centimetres) and often within uncertainties of the measurements (levelling and level measurements uncertainties), although Lillfjärden often had downward gradients of higher magnitude (10–30 cm), probably due to the periodically direct influence of the sea water level. All lakes showed both upward and downward gradients. Some single peaks with large downwards gradients are caused by water sampling in the groundwater wells (see for example the time series from Lake Bolundsfjärden), while some others are suspected measurement errors. Differentials in some lakes exhibited higher downward gradients during late summer and early autumn, such as Lake Eckarfärden, Lake Fiskarfjärden, and Lake Bolundsfjärden during the dry summer of 2006 (Figure 3-17ad).

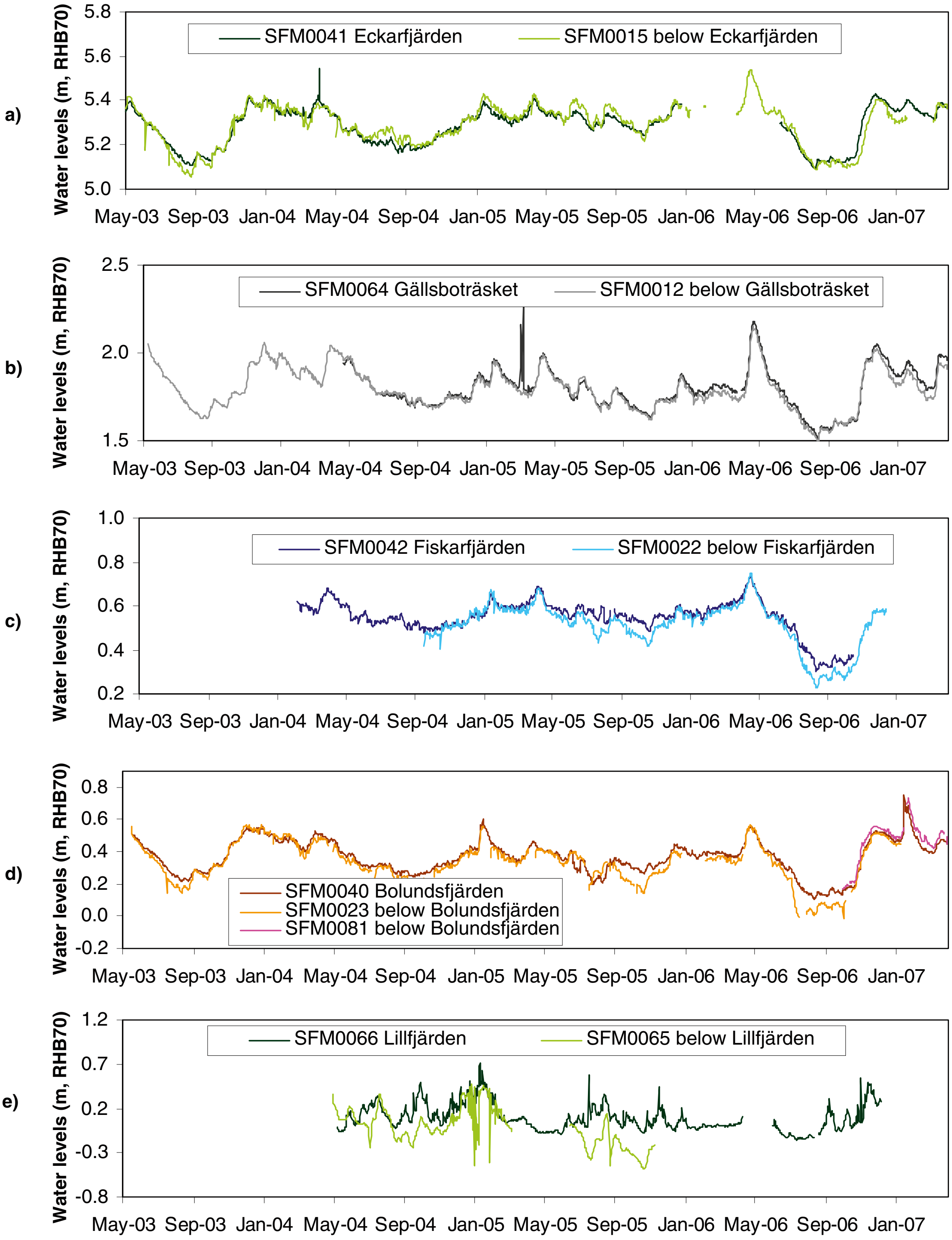


Figure 3-16. *Lake water levels and groundwater levels (m, RHB70) below the lakes for a) Lake Eckarfjärden, b) Lake Gällsboträsket, c) Lake Fiskarfjärden, d) Lake Bolundsfjärden, and e) Lake Lillfjärden.*

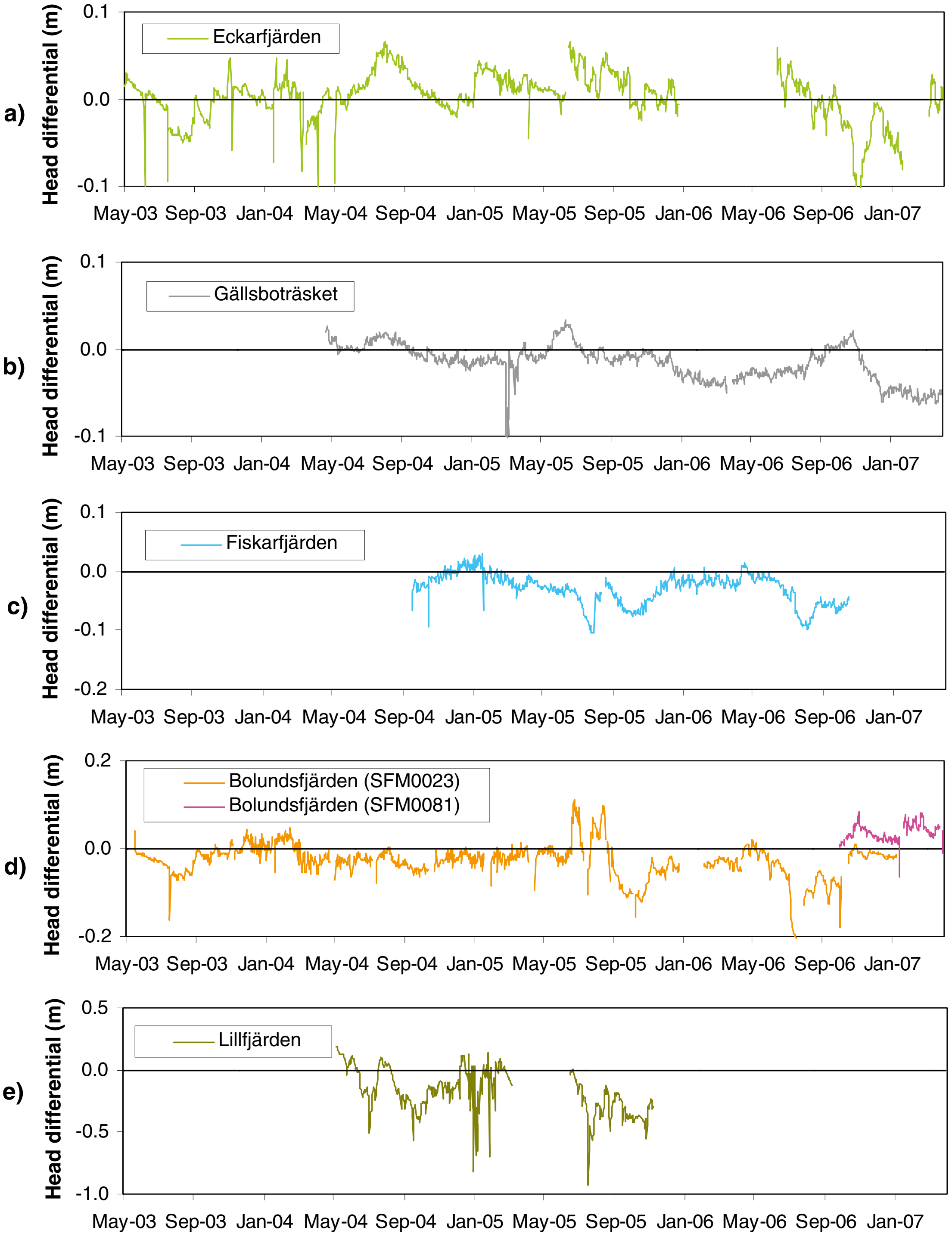


Figure 3-17. *Level differentials between surface water and below-bottom wells in five lakes in the site investigation area. Negative differentials indicate downward gradients (groundwater recharge), while positive differentials indicate upward gradients (groundwater discharge).*

3.4.2 Gradients between lake levels and local groundwater wells

This section presents time series data for the Eckarfjärden, Bolundsfjärden, and Fiskarfjärden areas, combining lake level data with data from local groundwater wells. There were insufficient data for similar compilations at the other lake locations. For locations of groundwater wells in Quaternary deposits and bedrock, see maps in Figure 2-32 and Figure 2-41, respectively.

Figure 3-18 shows the time series of both wells in Quaternary deposits and in bedrock in and near Lake Eckarfjärden compared with the lake water level. In Figure 3-19, the bedrock wells are excluded for better resolution in levels. As would be expected, the lake water level (SFM0041) showed the smallest amplitude, followed by the below water well (SFM0015). The lake water level appears to provide a buffering effect on groundwater level amplitudes close to the lake. This helps explain why the amplitudes in SFM0014, 16, 17 and 18 were amongst the lowest reported for groundwater wells in Quaternary deposits (Figure 2-36).

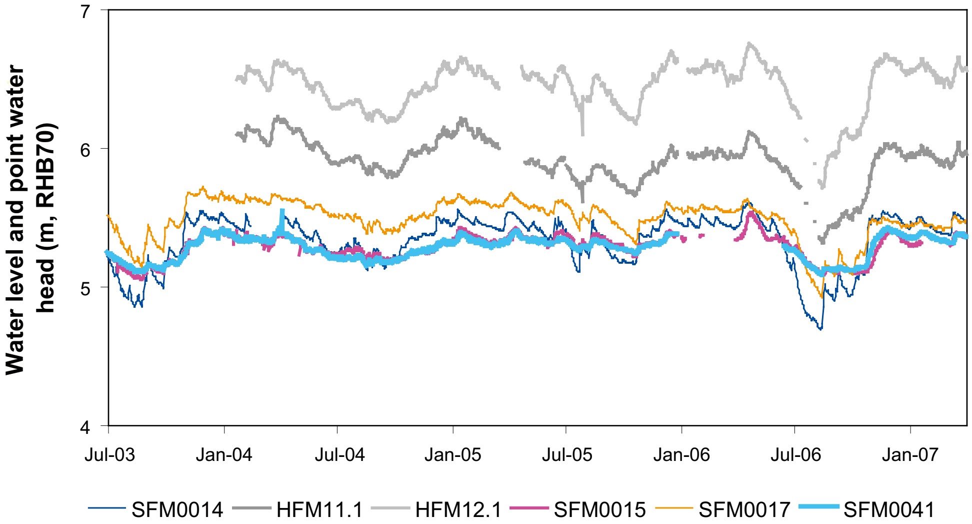


***Figure 3-18.** Lake water level, groundwater levels in Quaternary deposits, and groundwater point water heads in bedrock from wells in and close to Lake Eckarfjärden. SFM0041 is the lake level, SFM0015 a well in till below the lake, SFM0014 and SFM0017 wells in till close to the lake, and HFM11 and HFM12 are wells in bedrock. See Figures 2-32 and 2-41 for the locations of the wells.*

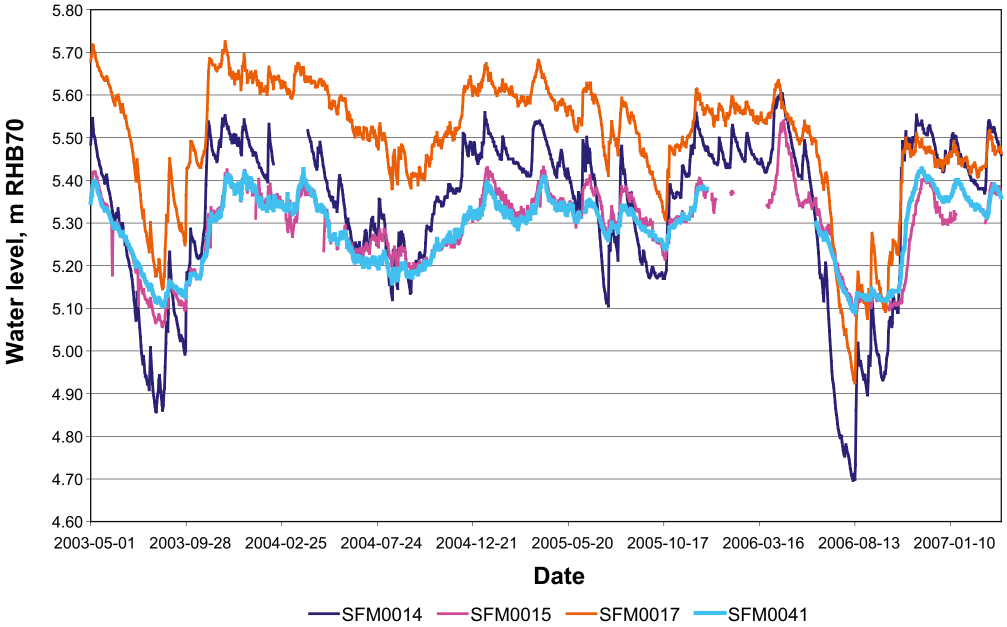


***Figure 3-19.** Lake water level and groundwater levels at Lake Eckarfjärden. SFM0041 is the lake level, SFM0015 a well in till below the lake, and SFM0014 and SFM0017 are wells in till approximately 50 and 80 m from the lake shore, respectively. See Figure 2-32 for the locations of the wells.*

The three wells located in closest proximity to the lake shore (HFM0014, 16, and 18) all had periods (mostly in summer) when groundwater levels were well below the lake water level. These periods typically coincided with intervals when the groundwater level below the lake (SFM0015) was lower than the surface water level, therefore providing complementary evidence of select periods of groundwater recharge from the lake. The groundwater point water heads in the wells in bedrock closest to the lake (HFM11.1 and HFM12)were well above the lake water level at all times, most often in the range of +1 to +1.5 m.

Figure 3-20 shows similar data for wells in the vicinity of Lake Bolundsfjärden. Once again, the higher lake surface elevations compared with local groundwater elevations in Quaternary deposits during dry summers suggest that the lake acts as a source of groundwater recharge to the local shallow aquifers during these periods. During other periods, the higher groundwater levels suggest the lake acts as a discharge area for the surrounding shallow aquifers. As with the wells close to Eckarfjärden, SFM0033 (excluding the disturbance in May 2004) and SFM0034 had amongst the lowest reported amplitudes in groundwater wells (Figure 2-36). However, SFM0030 which is located a little more than one hundred meters southwest of the lake had the highest reported amplitude of all wells. The very low groundwater levels in this well during the summers 2003 and 2006 indicate a strong influence of evapotranspiration on the groundwater level.

Figure 3-21 shows lake water levels and a profile of groundwater levels in the vicinity and below Lake Bolundsfjärden under average winter conditions and dry summer conditions. During a period of average winter conditions there is a groundwater flow gradient towards the lake. The gradient is reversed during dry summer conditions.

The lake water level of Lake Fiskarfjärden (SFM0042) is shown in Figure 3-22 together with the groundwater level in till below the lake (SFM0022), and in a well in till below clay approximately 150 m south-east of the lake along the outlet brook (SFM0026). At SFM0026 the groundwater level is often well above the ground surface, which is at 0.70 m RHB70.

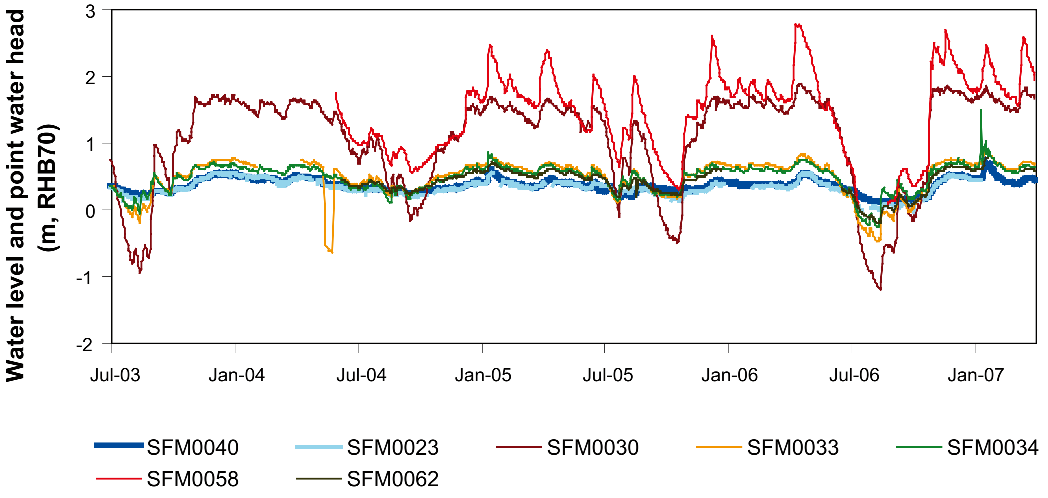


__Figure 3-20.__ Surface water level and groundwater levels in Quaternary deposits from wells in and close to Lake Bolundsfjärden. SFM0040 shows the lake water level, SFM0023 is the well in till below lake sediments in the middle of the lake, and SFM0062 is a well in till below lake sediments but close to the shore, see Figure 2-32.

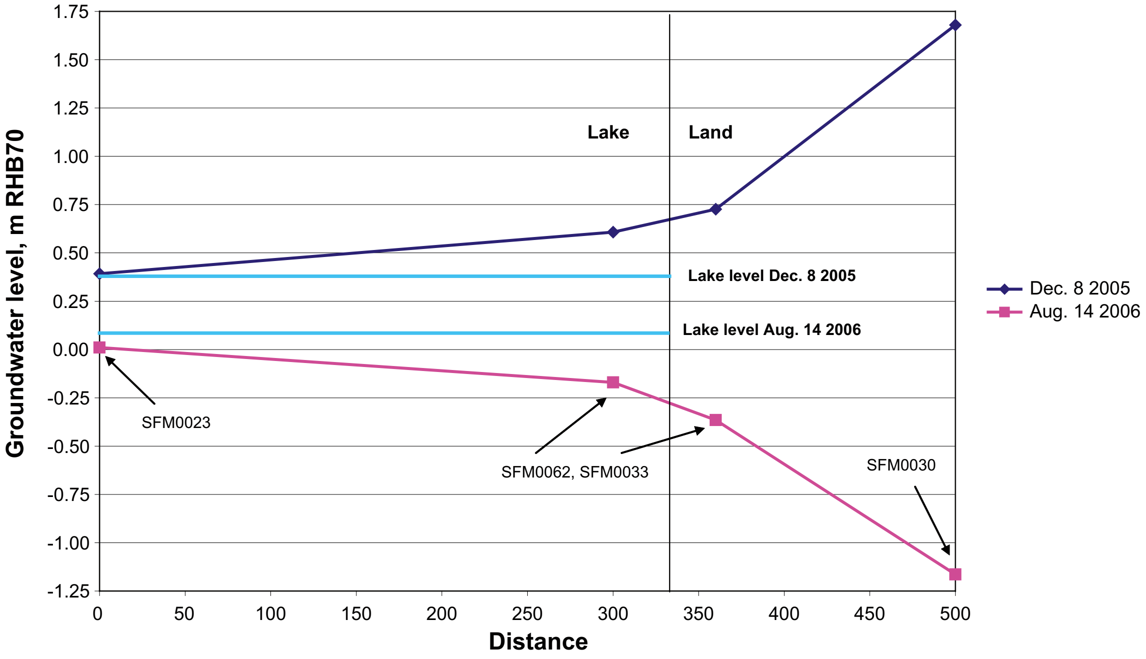


***Figure 3-21.** Lake water level and groundwater profiles in the Bolundsfjärden area from an average winter situation (December 8, 2005) and from dry summer conditions (August 14, 2006). See Figure 2-32 for the locations of the wells.*

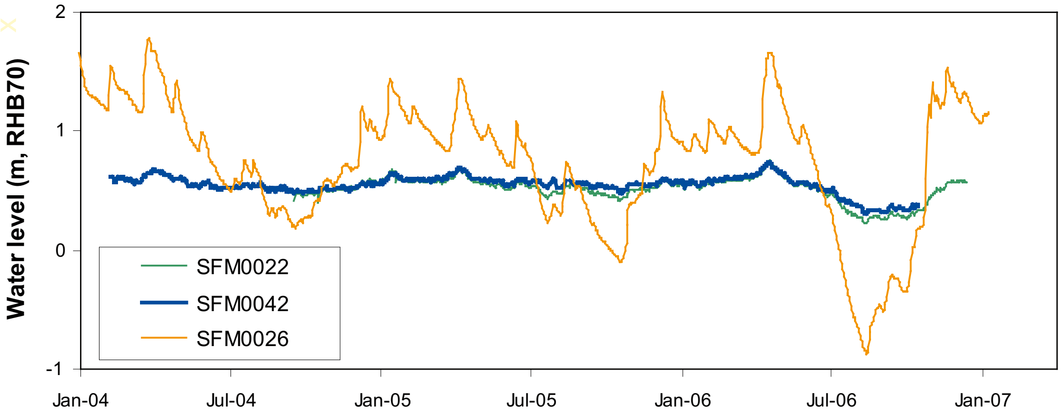


***Figure 3-22.** Lake water level and groundwater levels in Quaternary deposits in wells close to Lake Fiskarfjärden. SFM0042 shows the lake level, SFM0022 is the well in till below the lake, and SFM0026 is a well in till below clay 150 m southeast of the lake along the outlet brook.*

3.5 Relationships between groundwater levels in the Quaternary deposits and point water heads in the bedrock

Interesting observations were made in groundwater level time series from nearby wells in till and bedrock, as illustrated in Figures 3-23 to 3-37. Specifically, the groundwater level in the till seems to be considerably higher than that in the bedrock in the central part of the site investigation area (within the tectonic lens). This difference exists even though most of the screens of the wells in till are installed at or across the QD/rock interface. The differences between the levels in till and rock are generally much larger than between different sections in the bedrock boreholes sealed off by packers. However, the groundwater levels in the presented bedrock boreholes are still above the QD/rock interface under undisturbed conditions, indicating that no unsaturated zone exists below the interface.

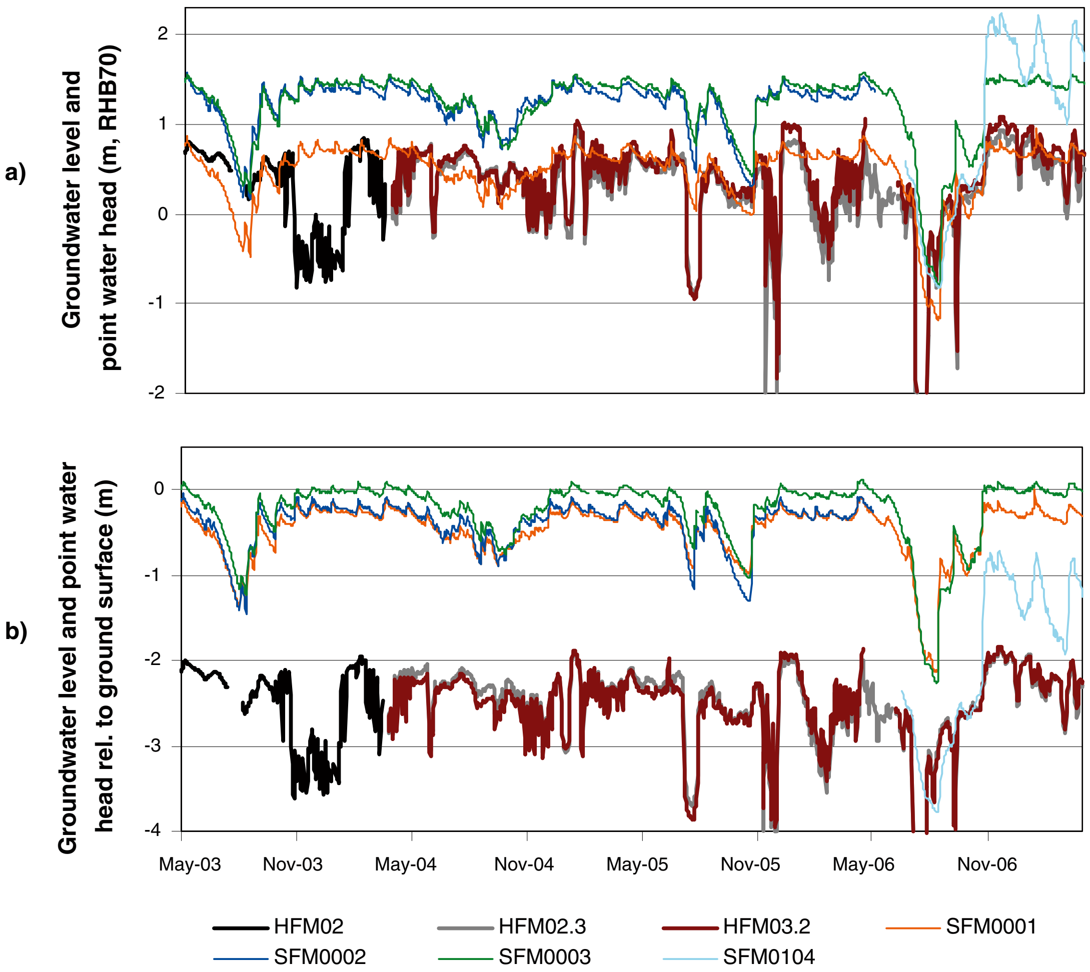


***Figure 3-23.** Comparison of groundwater levels in wells in Quaternary deposits (SFM0001-3 and SFM0104) and point water heads in bedrock (HFM02 and HFM03) at Drill site 1 in terms of a) metres above sea level and b) depth below ground surface (see Figures 2-32, 2-41 and 3-24 for the locations of the wells). Data from the shallowest HFM-sections are shown (the head differences between sections are within a few centimetres). In addition data for the open borehole HFM02 are shown together to prolong the HFM02-time series.*

3.5.1 Drill site 1

In Figure 3-23, the groundwater levels in wells in QD and bedrock at Drill site 1 are shown. The locations of the wells are shown on the detailed map in Figure 3-24. Absolute groundwater levels in QD are well above the point water heads in bedrock except during dry summer conditions (see the summers of 2003 and 2006).

In the summer of 2006, a pumping test was performed in HFM14, situated at Drill site 5 approximately 400 m to the southeast of Drill site 1. The bedrock wells (HFM02 and HFM03) responded to the pumping, but no impact could be seen in the QD-wells. In general, there is no discernable response in the groundwater levels in QD to disturbances in the groundwater levels in the bedrock. On the other hand, both groundwater levels in QD and bedrock are correlated to rainfall+snowmelt and evapotranspiration.

Figure 3-25 shows a close-up of groundwater levels at Drill site 1 during the July and September 2006 pumping tests in HFM14. The drawdown response in the bedrock wells is clearly evident, but the response in the Quaternary deposits during July appears to be more related to dry conditions. During the September test the groundwater levels in Quaternary deposits are rising due to rainfall.

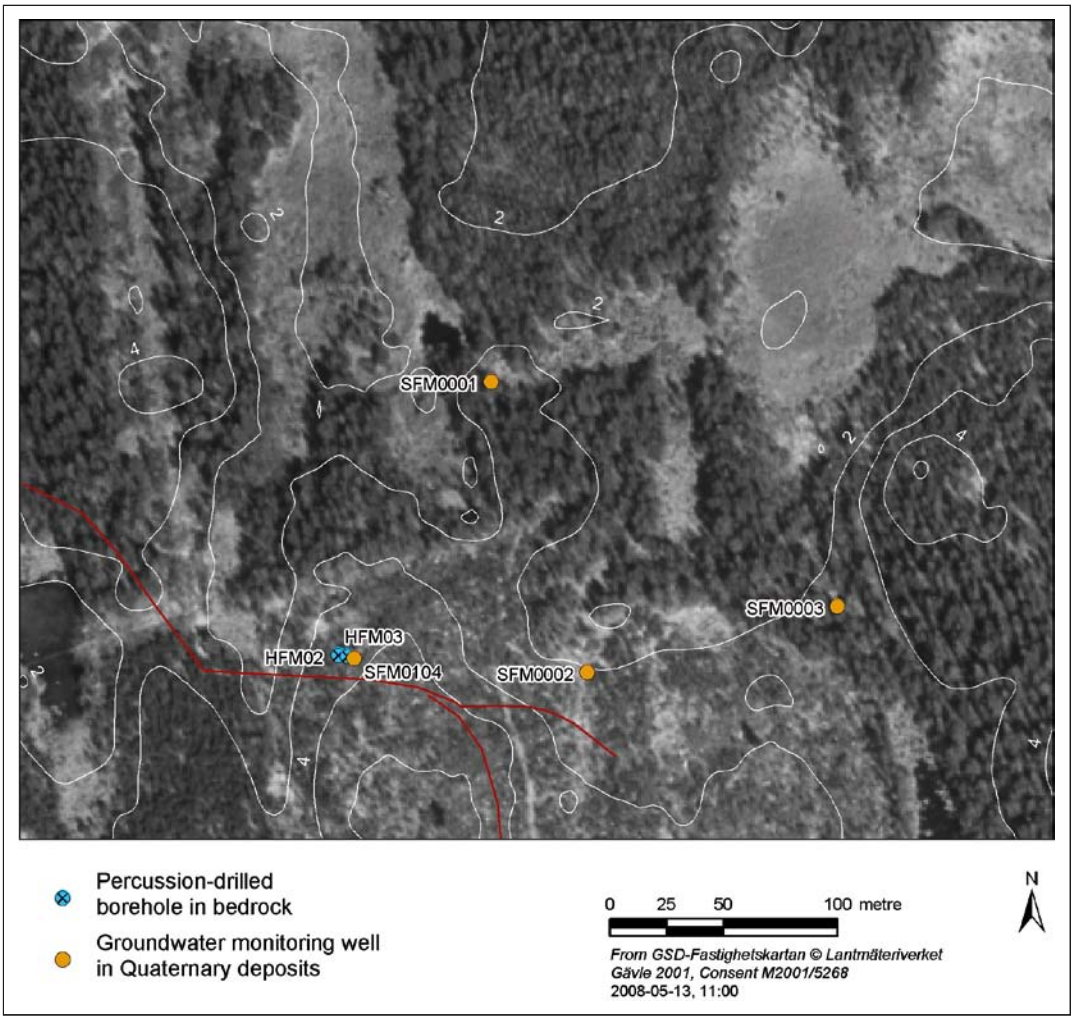


***Figure 3-24.** Groundwater monitoring wells in Quaternary deposits (SFM) and percussion-drilled boreholes in bedrock (HFM) at Drill site 1.*

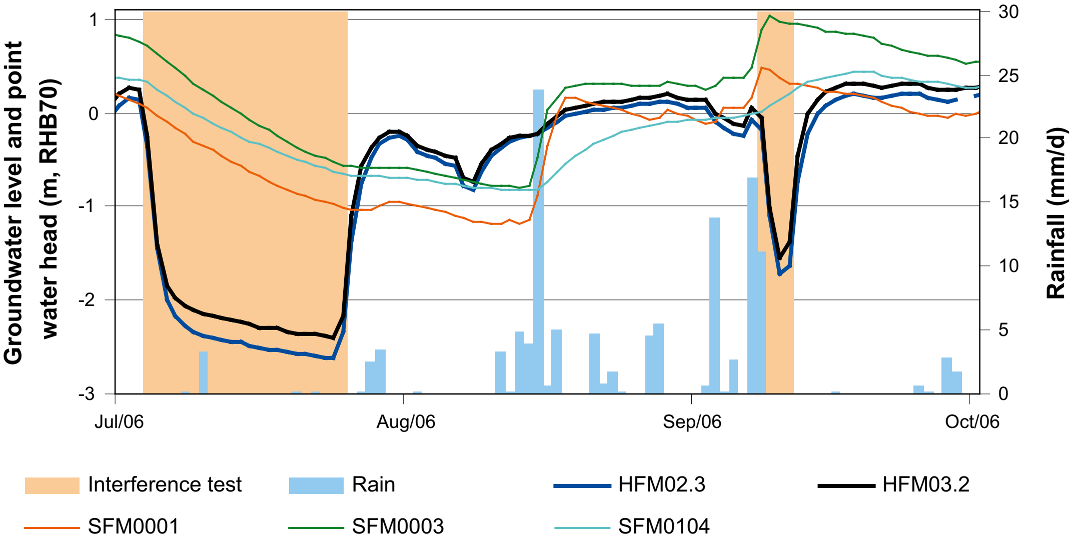


***Figure 3-25.** Close-up of groundwater levels at Drill site 1 during a 4-month period including the July and September 2006 pumping tests in HFM14.*

3.5.2 Drill site 2

In Figures 3-26 and 3-27 groundwater wells close to Drill site 2 are presented. The absolute groundwater levels in QD are also here well above those in bedrock. In difference to the bedrock wells at Drill site 1, no response to the pumping in HFM14 in the summer of 2006 can be seen in the bedrock wells at Drill site 2 (Figure 3-26c). The groundwater time series in the bedrock were highly correlated to the SFM0004, SFM0005 and SFM0009 time series, excluding the three disturbance intervals. Interestingly, there was an observable response in the groundwater of the Quaternary deposits at this site during the disturbances intervals in bedrock groundwater, see /Juston et al. 2007/.

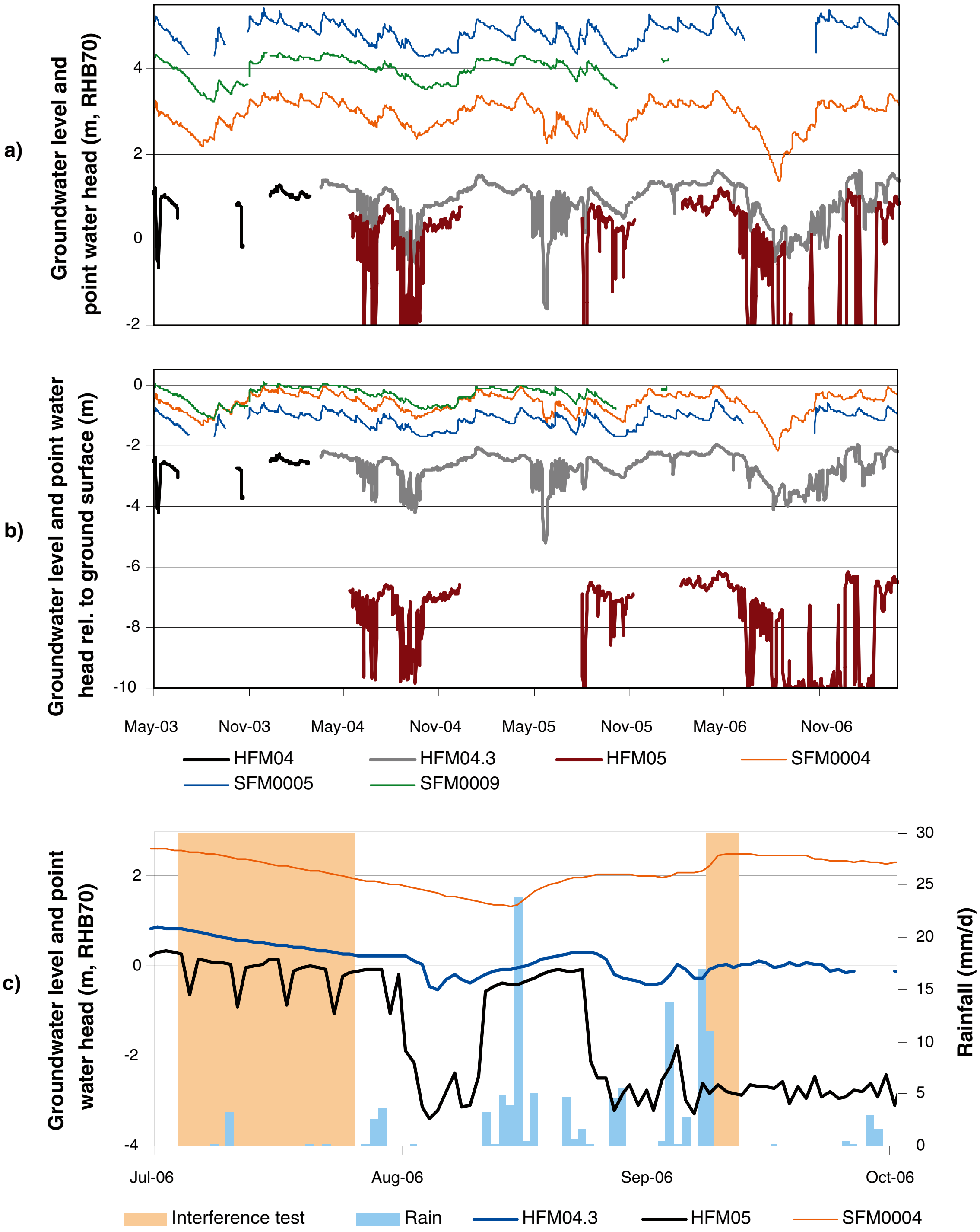


Figure 3-26. Comparison of groundwater levels in Quaternary deposits (SFM) and point water heads in bedrock (HFM, uppermost section) at Drill site 2 in terms of a) metres above sea level, b) depth below ground surface, and c) groundwater levels and point water heads co-plotted with rainfall during July–October 2006 (see Figures 2-32, 2-41 and 3-27 for the locations of the wells).

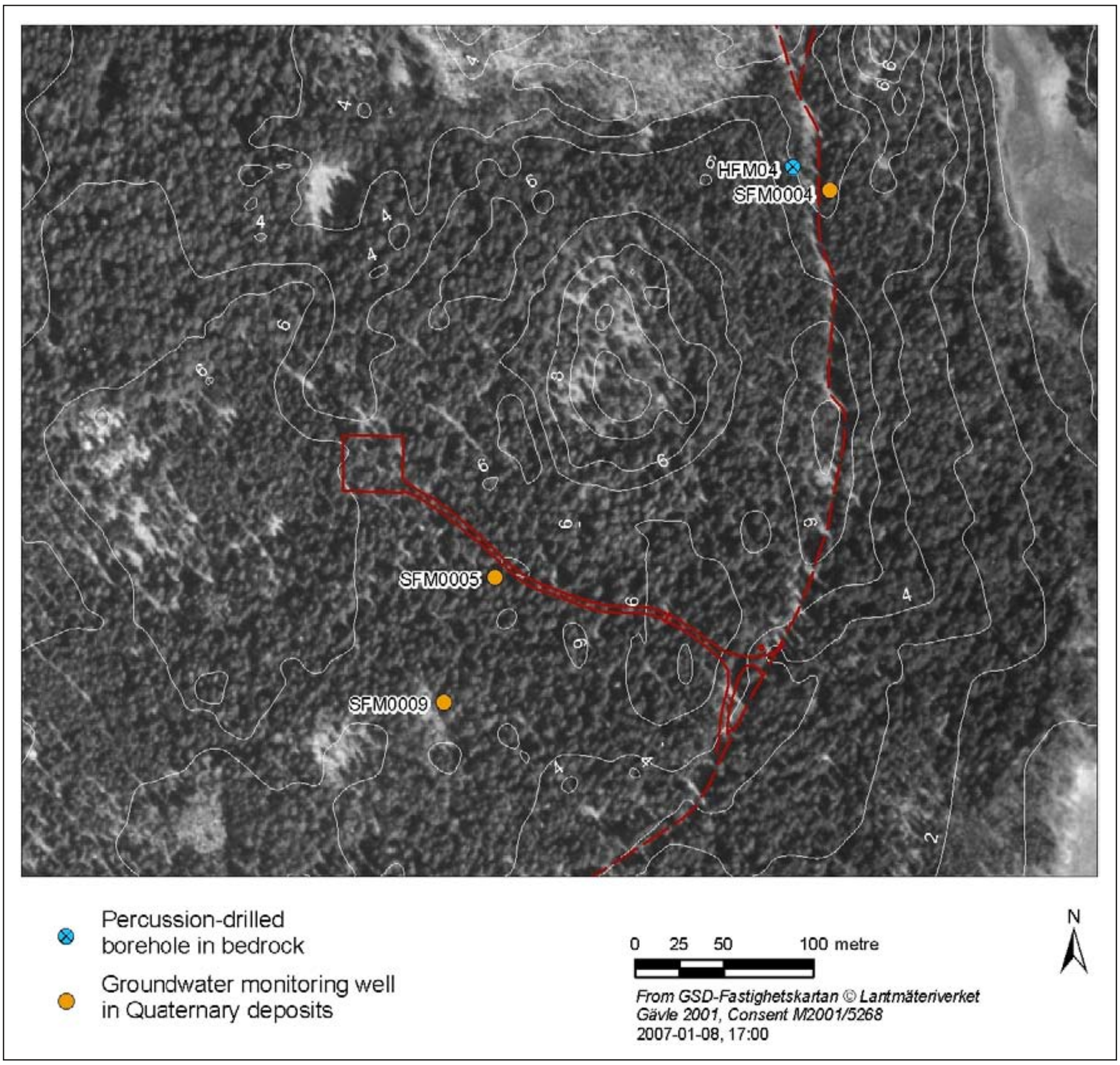


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Figure 3-27. *Groundwater monitoring wells in Quaternary deposits (SFM) and percussion-drilled boreholes in bedrock (HFM) at Drill site 2.*

In Figure 3-28a the groundwater levels of SFM0004 and HFM04 are shown together with the ground and bedrock levels at the wells, and in Figure 3-28b SFM0004 and HFM04.3 are plotted using separate level-axis to illustrate the high correlation between groundwater level variations in Quaternary deposits and bedrock despite the absolute difference of c. 2 m in level.

3.5.3 Drill site 4

As shown in Figure 3-29, the conditions at Drill site 4, located outside the tectonic lens, are quite different from those at the drill sites discussed above. The absolute groundwater levels in the bedrock wells are higher, c. 2.5 m RHB70 and also well above the groundwater levels in QD in the Gällsboträsket depression (SFM0011 and SFM0013, see Figures 2-32, 2-41 and 3-30 for the locations of the wells). Furthermore, the bedrock wells (HFM09 and HFM10) did not show any response to the pumping tests in HFM14 in summer/autumn of 2006.

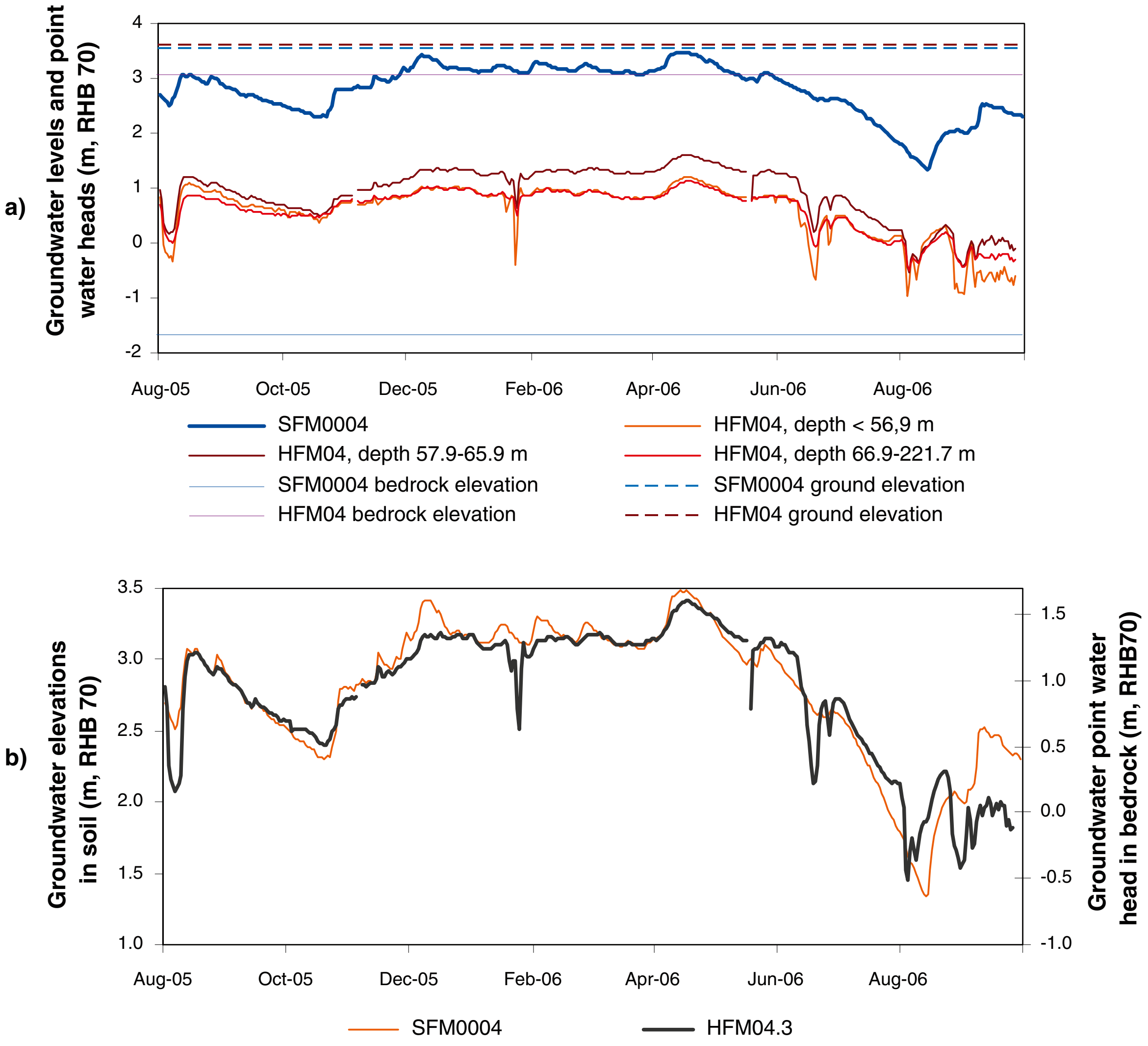

Figure 3-28. *Groundwater levels August 2005 to Sepember 2006 in wells SFM0004 and HFM04.3 and the ground and bedrock levels at the wells indicated (a), and SFM0004 and HFM04.3 (depth < 56.9 m) plotted using separate level-axis to illustrate the high correlation between groundwater levels in Quaternary deposits and bedrock despite the absolute difference of c. 2 m in leve (b).*

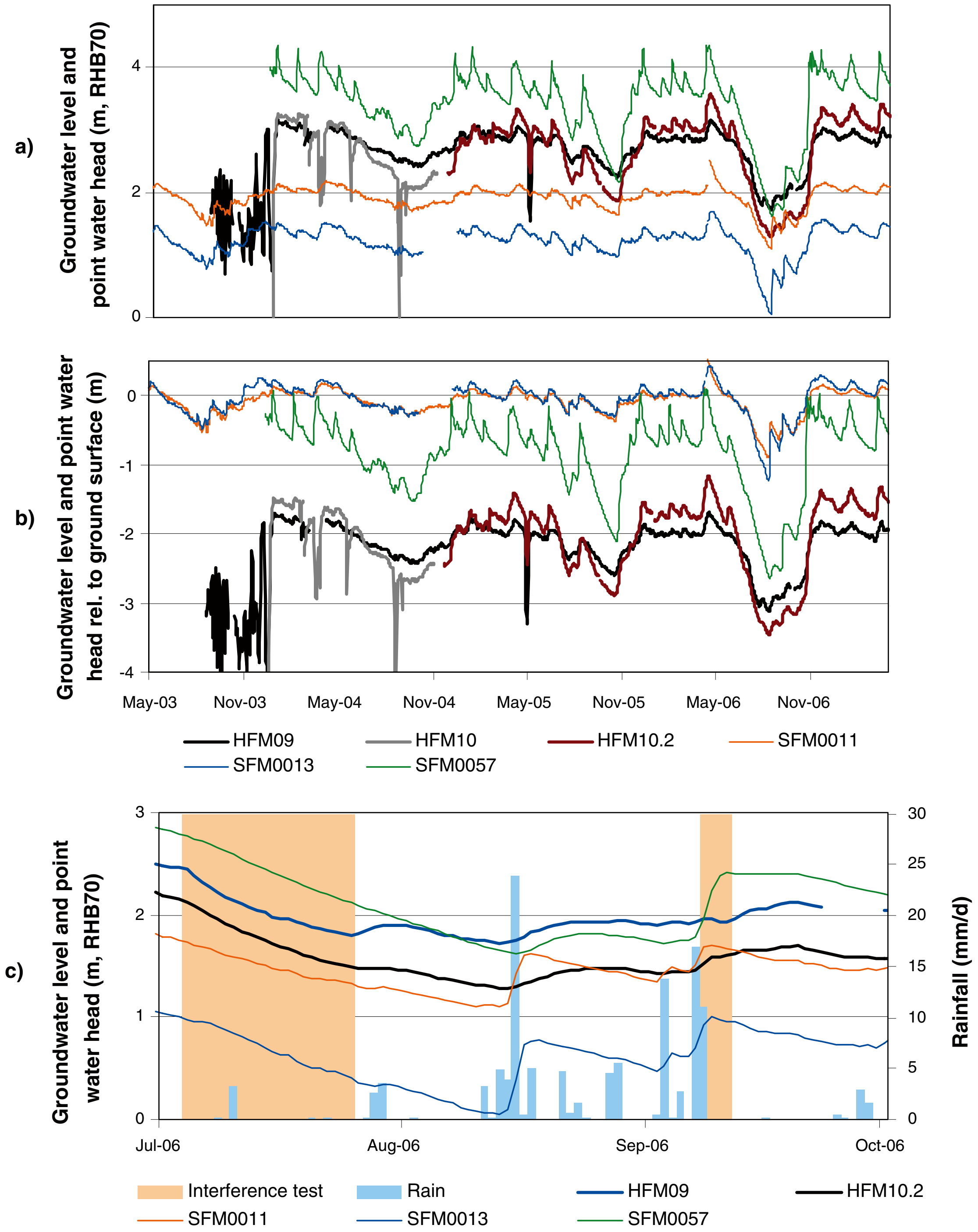

Figure 3-29. *Comparison of Quaternary deposit (SFM) and bedrock (HFM) groundwater level data at Drill site 4 in terms of a) metres above sea level, b) depth below ground, and c) groundwater levels and point water heads co-plotted with rainfall during July-October 2006. Data for the open borehole HFM10 are shown together with the uppermost sections HFM10.2 to prolong the HFM10-time series (see Figures 2-32, 2-41 and 3-30 for location of the wells).*

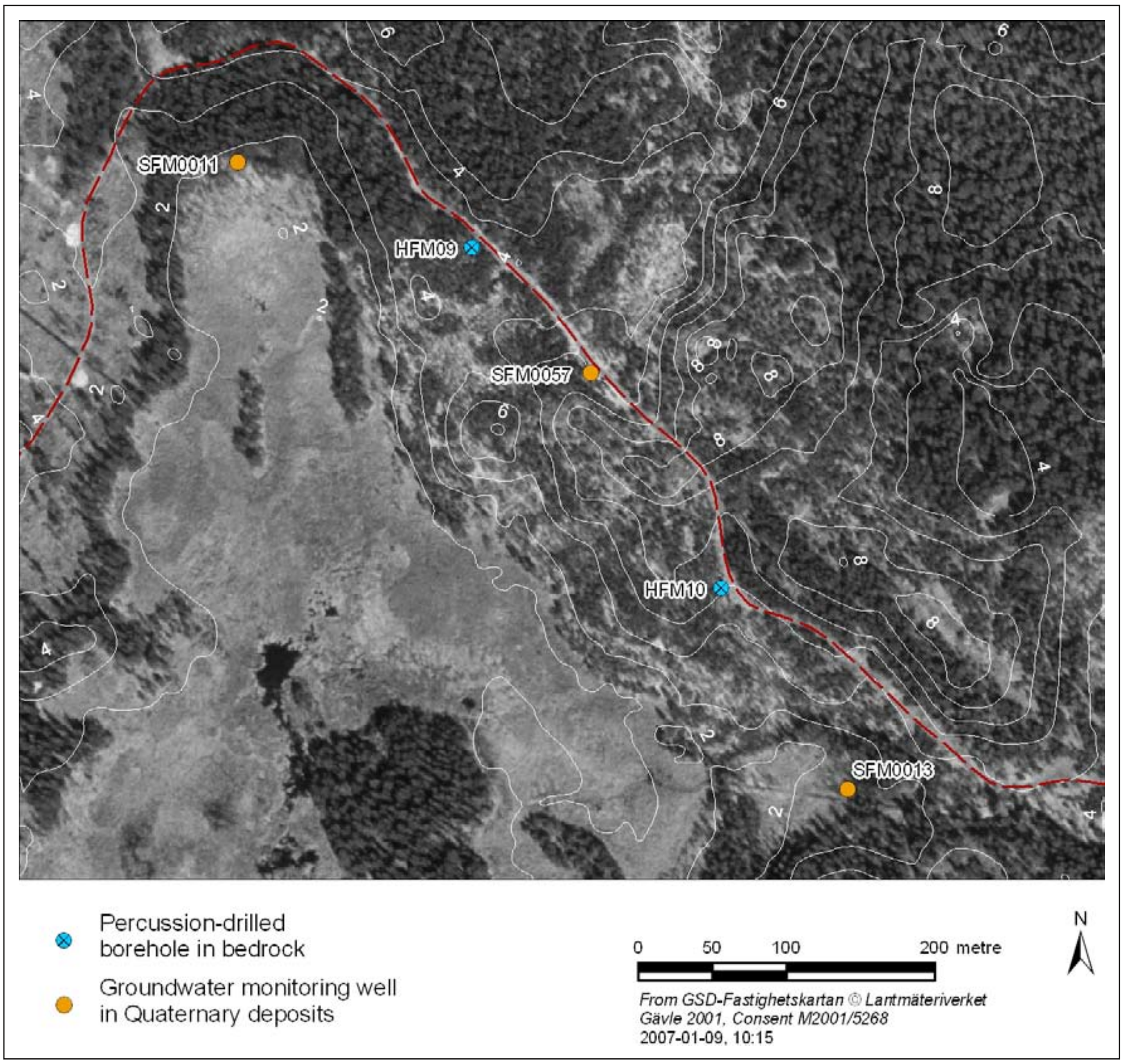

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Figure 3-30. *Groundwater monitoring wells in Quaternary deposits (SFM) and percussion-drilled boreholes in bedrock (HFM) at Drill site 4.*

3.5.4 Drill site 5

Figure 3-31, from Drill site 5, again shows the situation with groundwater levels in QD well above those in bedrock. However, during dry summer conditions the QD-levels may fall below the groundwater levels in bedrock. During summer 2006, the groundwater level in SFM0058 fell below the till/rock interface and the uppermost part of the bedrock profile was here unsaturated. The co-variation of the groundwater levels in QD and bedrock, due to rainfall+snowmelt and evapotranspiration is obvious. However, the hydraulic contact between groundwater in the QD and the bedrock seems to be limited, which is clear from the second pumping test in HFM14 in September 2006 (Figure 3-31c) when the groundwater level in QD (SFM0058) increases due to rainfall despite a drawdown by several meters in the groundwater level in bedrock (HFM15).

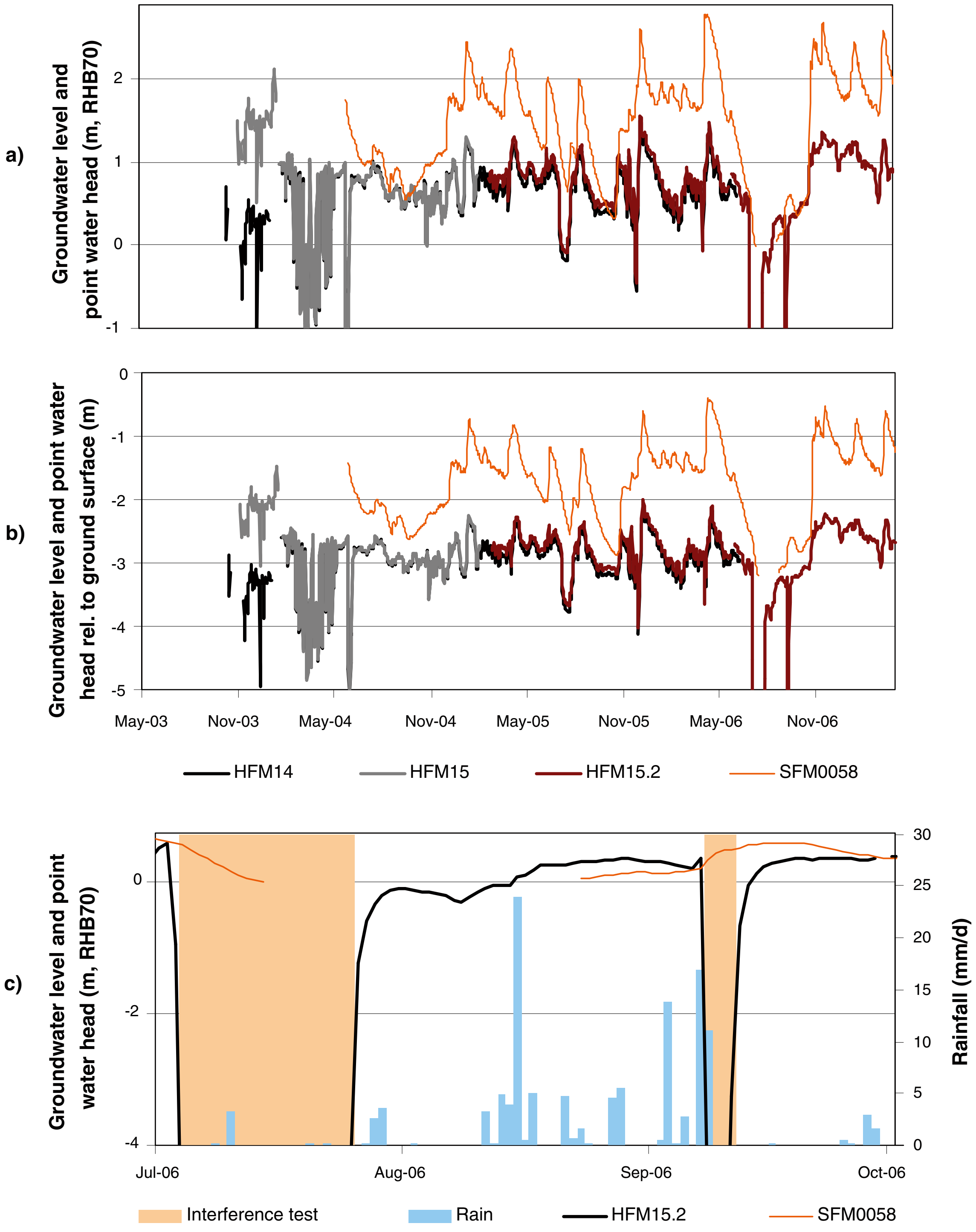

Figure 3-31. *Comparison of groundwater levels in wells in Quaternary deposits (SFM0058) and point water heads in bedrock (HFM14 and 15) at Drill site 5 in terms of a) metres above sea level, b) depth below ground surface, and c) groundwater levels and point water heads co-plotted with rainfall during July-October 2006. HFM14 is an open borehole and HFM15.2 is the uppermost section of the HFM15 well; the head difference between sections is within a few centimetres (see Figures 2-32, 2-41 and 3-32 for the locations of the wells).*

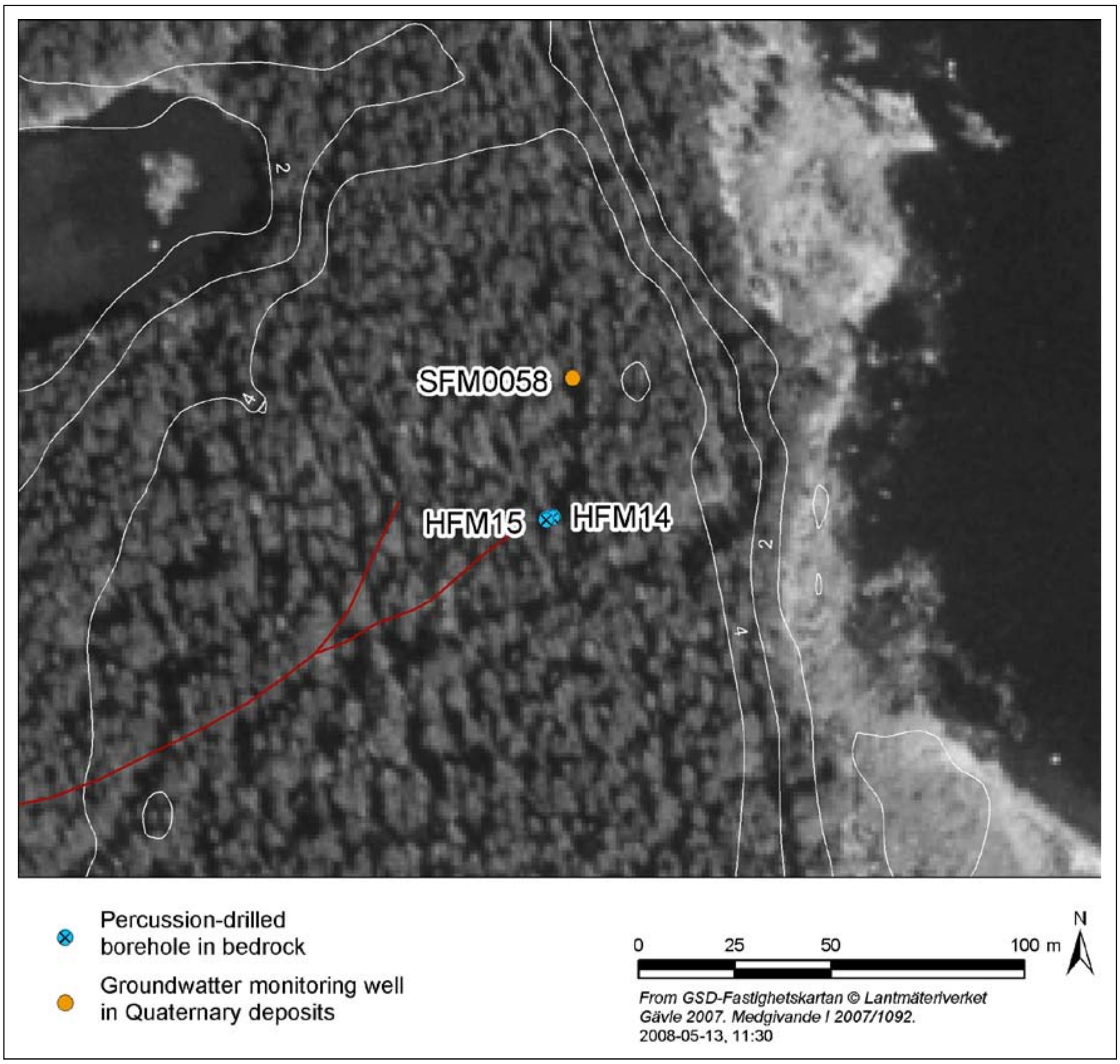

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Figure 3-32. *Groundwater monitoring wells in Quaternary deposits (SFM) and percussion-drilled boreholes in bedrock (HFM) at Drill site 5.*

3.5.5 Drill site 6

A co-variation of groundwater levels in QD and bedrock is also obvious at Drill site 6, see Figure 3-33. As at the other drill sites within the tectonic lens, the groundwater level in QD is well above the groundwater level in bedrock. However, the groundwater level in QD is below the one in bedrock under dry summer conditions. The response in the bedrock well HFM16 to the pumping tests in HFM14 in summer/autumn 2006 is also quite clear. The distance to the pumping well exceeds 800 metres. The drawdown extended below Lake Bolundsfjärden and was approximately one metre in HFM16.

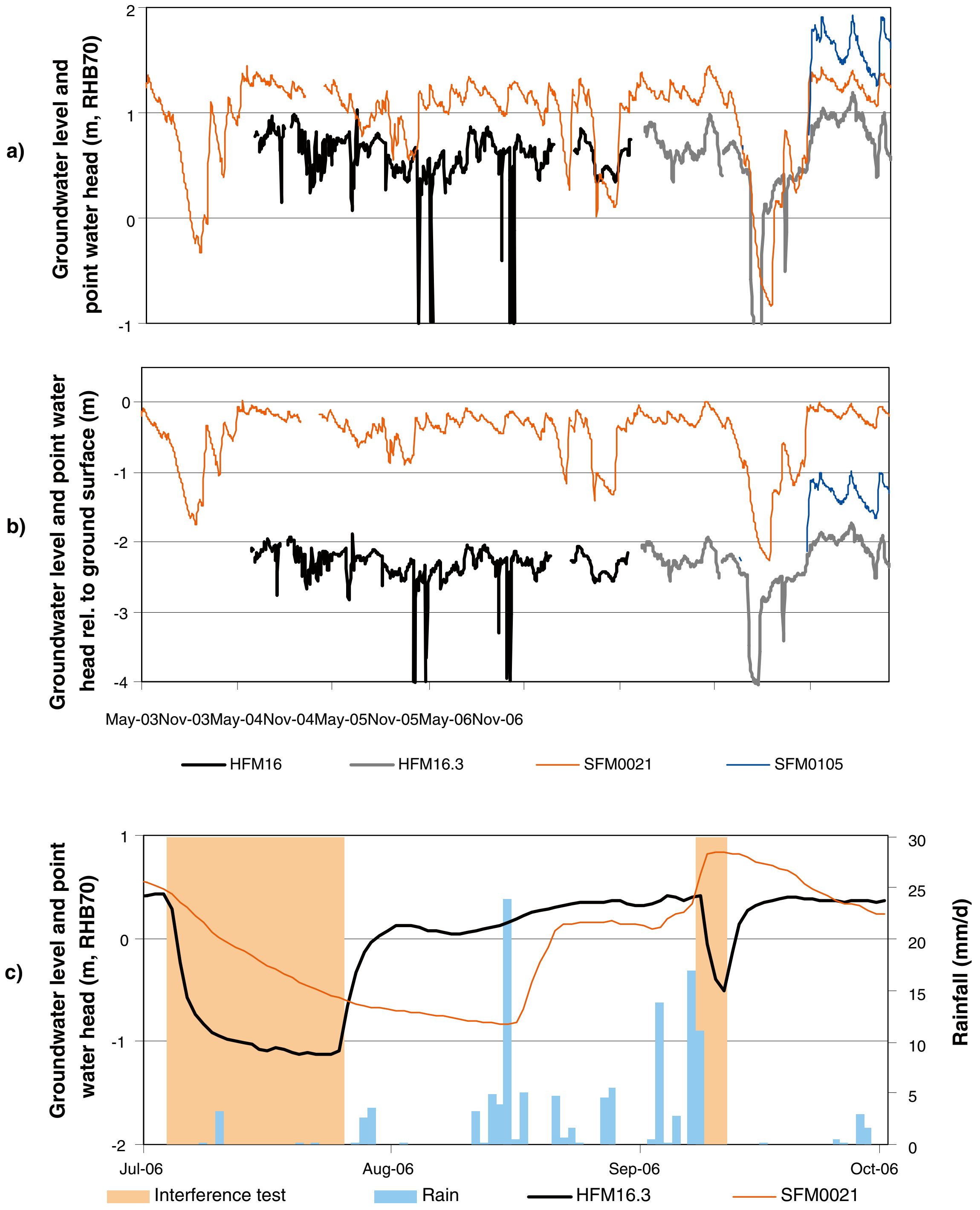

Figure 3-33. *Comparison of Quaternary deposit (SFM) and bedrock (HFM) groundwater level data at Drill site 6 in terms of a) metres above sea level, b) depth below ground,* ***,*** *and c) groundwater levels and point water heads co-plotted with rainfall during July-October 2006 (see Figures 2-32, 2-41 and 3-34 for the locations of the wells). HFM16 is the open borehole while HFM16.3 is the uppermost section after the packer-installation.*

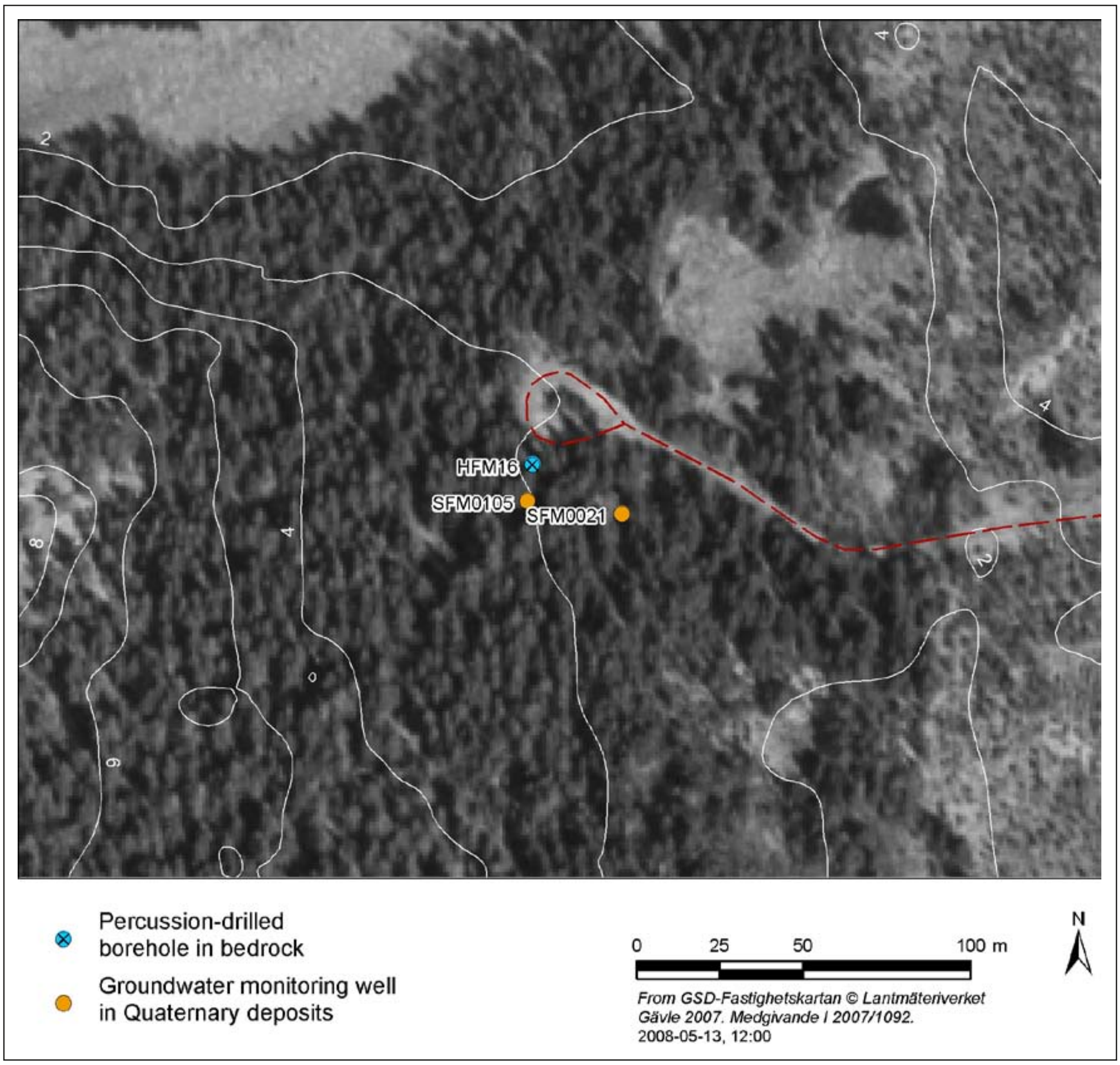

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***Figure 3-34.** Groundwater monitoring wells in Quaternary deposits (SFM) and percussion-drilled boreholes in bedrock (HFM) at Drill site 6.*

3.5.6 Drill site 9

In Figure 3-35 the groundwater levels at Drill site 9 are presented. At this drill site, located close to the boundary of the tectonic lens, one of the wells in Quaternary deposits (SFM0107) shows lower groundwater levels than in one of the bedrock wells (HFM23). However, HFM23 has very low transmissivity and is classified as located at the border of the tectonic lens. This borehole does not seem well-connected to any of the highly transmissive shallow horizontal and sub-horizontal sheet joints/fracture zones, known to exist within the tectonic lens.

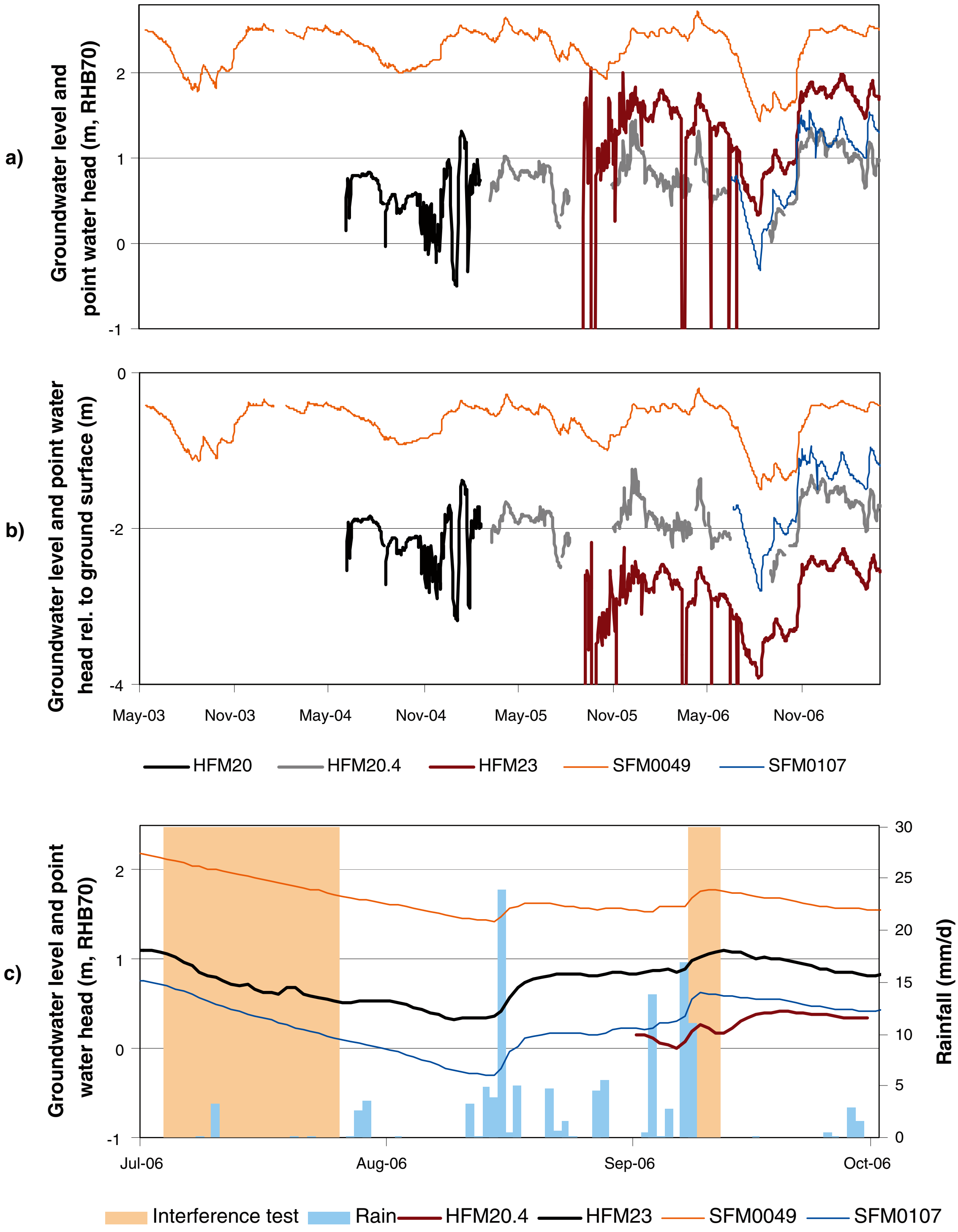

Figure 3-35. *Comparison of Quaternary deposit (SFM) and bedrock (HFM) groundwater level data at Drill site 9 in terms of a) metres above sea level, b) depth below ground, and c) groundwater levels and point water heads co-plotted with rainfall during July-October 2006 (see Figures 2-32 and 2-41 for the locations of the wells).*

3.5.7 Below Lake Bolundsfjärden

Figure 3-36 shows the groundwater levels in a monitoring well in till below the middle of Lake Bolundsfjärden (SFM0023) and a nearby percussion-drilled borehole (HFM32) located on a small island in the lake. Water levels in the sea and in the lake are also shown in the figure. The lake level and the groundwater level in till are considerably higher than the levels in the four sections of HFM32. The HFM-levels shown are point water heads. However, the density differences between the borehole sections are small; only in the deepest section the calculated environmental head is more than 0.1 m higher than the point water head, while the differences between the two head types are insignificant for the other sections.

The heads are lowest in the two deepest sections. The difference between these two sections is small but after re-calculation to environmental head the second deepest section has the lowest head, i.e. the horizontal and sub-horizontal fractures in this section act as drains for water coming from above as well as from below. The results indicate a downward flow gradient from the lake and QD to the bedrock. In Figure 3-37 the levels are shown during two pumping tests in HFM14 (see Figure 2-41 for well locations). The responses were strongest in the two deepest well sections, but are also obvious in the upper two sections and interestingly also in the till well (SFM0023). The response in SFM0023 is best seen at the start of the July pumping test. The very large drawdown in SFM0023 following the initial phase is coupled to water sampling and not to the pumping test.

Figure 3-38 shows the point water heads in percussion-drilled boreholes surrounding Lake Bolundfjärden plotted with the sea water level and the accumulated rainfall+snowmelt-potential evapotranspiration. The point water head in HFM33, located close to SFR, is also included in the figure. The borehole section with the lowest point water head in each borehole is shown (see Figure 2-41 for the locations of the boreholes); the differences between point water heads and environmental water heads are insignificant.

HFM32 has the lowest point water head. Only HFM33 and HFM38 have occasionally point water heads at the same level or below. The head variations are mainly controlled by the annual precipitation-evapotranspiration cycle, represented by R+S-PET in the figure, and the sea water level. The sea water level has a stronger influence on HFM33 and HFM38 than on HFM32. The groundwater level in HFM32 is below the sea level during the summer and autumn of 2006.

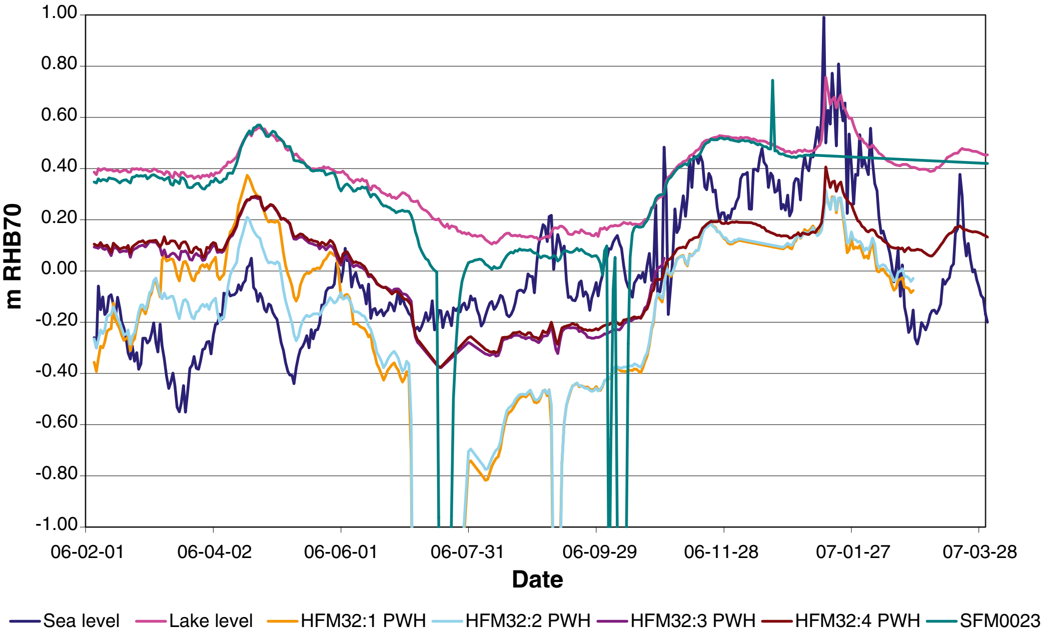

Figure 3-36. *Water levels in the Baltic Sea and Lake Bolundsfjärden plotted together with groundwater levels in till below the lake (SFM0023) and in sections in the bedrock borehole HFM32 (elevations in m RHB70: HFM32:1: –198.75 to –96.27; HFM32:2: –95.27 to –30.95; HFM32:3: –29.95 to 24.97; HFM32:4: –23.97 to 0.97).*

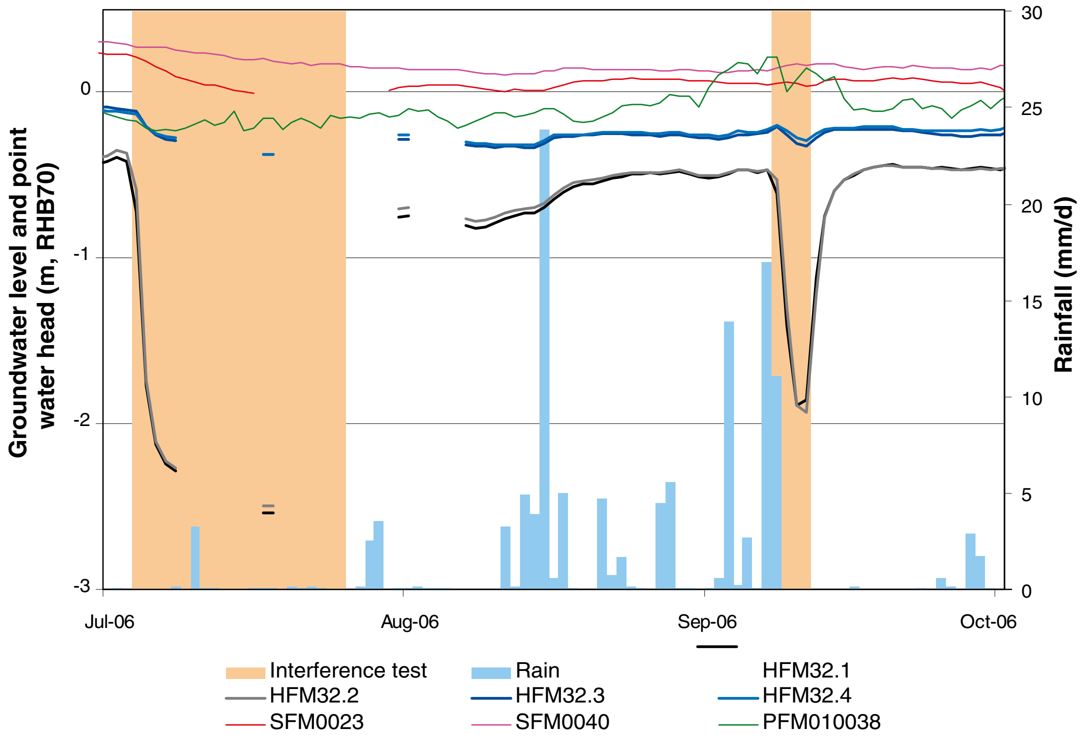

Figure 3-37. Water levels in the Baltic Sea (PFM010038) and in Lake Bolundsfjärden (SFM0041), and groundwater levels in till below the lake (SFM0023) and at different depth intervals in the bedrock (HFM32:1-4). Rainfall and duration of pumping tests in HFM14 are also shown (see Figure 3-36 for the levels of the borehole sections of HFM32).

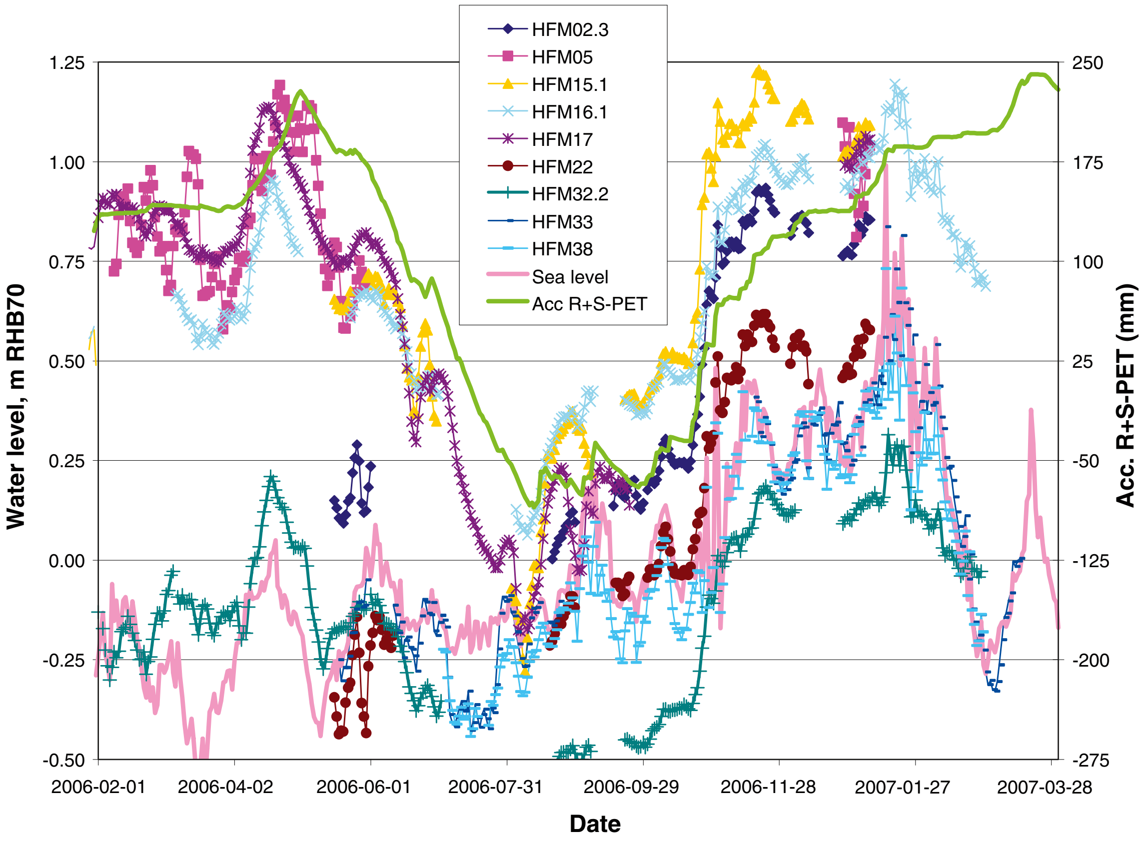

Figure 3-38. Point water heads in wells surrounding Lake Bolundsfjärden plotted with the sea level and accumulated values of rainfall (R) plus snowmelt (S) minus potential evapotranspiration (PET).

Two possible, perhaps superimposed, phenomena could explain this: (i) the groundwater level in the bedrock is indirectly influenced by evapotranspiration extracting water from the groundwater zone in the QD thereby inducing an upward flow from the bedrock, and/or (ii) the borehole is influenced by the pumping at SFR (approximately 6 L/s).

An influence from evapotranspiration requires that the groundwater level in the bedrock is above the QD/rock interface, which is the case in the low-lying areas surrounding Lake Bolundsfjärden, so that no unsaturated zone exists in the bedrock. An influence from the pumping at SFR requires a good hydraulic contact all the way to SFR. From a pumping test in HFM33, immediately west of SFR, it is known that quick and strong responses were observed in e.g. HFM02 (c. 0.3 m) and HFM15 (c. 0.1 m) located c. 1.5 km inland from the pumping well. The pumping rate in HFM33 was approximately 3.8 L/s /Gokall-Norman and Ludvigson 2008, Follin et al. 2008/. Pumping tests in HFM14 have also shown quick and strong responses in other quite distant HFM-wells (c. 1 km away, such as HFM16 and HFM38), confirming the high transmissivity and low storativity of the upper bedrock.

3.6 Relationships between surface discharge and groundwater levels in the Quaternary deposits

Well-defined relationships were identified between specific discharge magnitudes and the dynamic groundwater storage in upstream catchment areas /Juston et al. 2007/ and a conceptual groundwater storage-surface discharge model was developed. In Figure 3-39 time series of the average groundwater level in relation to ground surface (from the wells SFM0010, SFM0011, SFM0013, SFM0014, SFM0017, SFM0019, SFM0030, SFM0057) and discharge for the catchment area of discharge gauging station PFM005764 are shown. The dynamics of the average groundwater level is directly reflected in the surface discharge.

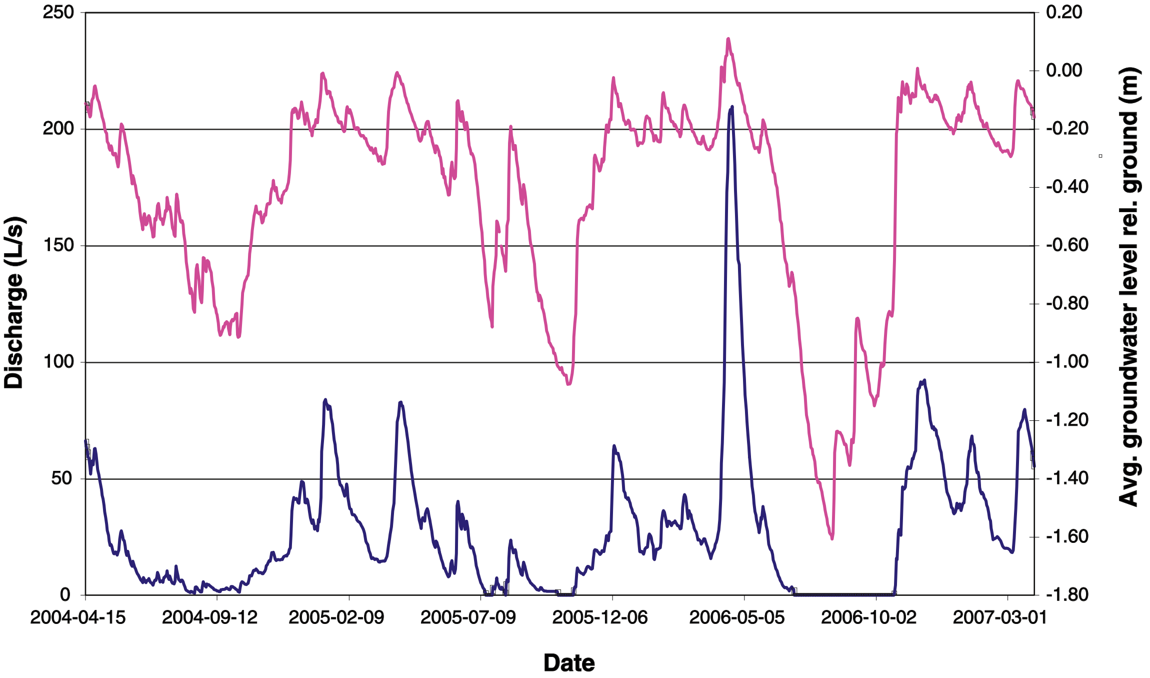

Figure 3-39. Average groundwater level and surface discharge for the catchment area of discharge gauging station PFM005764 (see Figures 2-32 and 2-51 for the locations of the groundwater observation wells and the surface discharge gauging station).

3.7 Water balance estimates for the PFM005764 basin

If the full three-year period of April 15, 2004 until April 14, 2007, is considered the corrected mean precipitation was 546 mm/year while the mean specific discharge of the largest catchment of 5.6 km^2 was 154 mm/year. From a comparison of groundwater and surface water levels at the start and end of the period it can be concluded that the these storages were a little smaller at the end of the period but only corresponding to a difference of c. –5 mm/year.

The mean precipitation was 13 mm/year lower than the 30-year normal precipitation estimated by SMHI, /Johansson 2008, Appendix 1/. Since approximately 2/3 of the precipitation goes to evapotranspiration, the precipitation deficit should correspond to a discharge deficit of approximately 5 mm/year. These estimates of storage changes and precipitation deficit indicate that the measured three-year mean discharge should be close the long-term average discharge. A rough estimate of the long-term overall water balance of the area is then: P (precipitation) = 560 mm/year, ET (evapotranspiration) = 400–410 mm/year, and Q (runoff) = 150–160 mm/year.

4 Conclusions and discussion

4.1 Observations in time series data

4.1.1 Meteorological data

Two meteorological stations were established in the site investigation area in May 2003. The main results from measurements at these stations and comparisons with SMHI stations in surrounding areas are:

- The corrected mean annual precipitation of the two stations for the full four-year period of June 2003–May 2007 was 563 mm. The lowest and highest recorded annual precipitation for the available three full calendar-years 2004–2006 were 504 and 578 mm, respectively (average 537 mm/year).
- The measurements at the two stations showed good agreement with less than 5% difference in precipitation over the period of available measurements.
- Data indicated that of the nearby SMHI stations, the station at Östhammar had precipitation values most similar to those of the two SKB stations. There is a strong precipitation gradient from east to west, with an annual corrected precipitation at Örskär north-east of Forsmark that is approximately 200 mm lower than at Lövsta west of the investigated area.
- Based on data from nearby SMHI stations, SMHI has calculated a 30-year average annual precipitation of 559 mm for Forsmark, meaning that the four-year average for the period June 2003–May 2007 at Forsmark was very close to the long-term average.
- Potential evapotranspiration was calculated from measured data at Högmasten. The calculations were based on the Penman equation applied according to /Eriksson 1981/. For the full four-year period of June 2003–May 2007, the mean annual potential evapotranspiration was 526 mm. The lowest and highest annual potential evapotranspiration for the three available full calendar-years 2004–2006 were 494 and 522 mm, respectively (average 509 mm/year).
- The collected time series at the meteorological stations in the site investigation area can be used to establish correlations with nearby SMHI stations. Establishment of such correlations is important to enable use of SMHI's long-term time series for analysis and modelling. The uncertainties in these correlations will decrease with continued monitoring of meteorological parameters at Forsmark
- Snow depth and snow water content measurements were performed at three sites in the investigation area, two in forest land and one in open land. Generally, there was a snow cover at the site from the end of November/beginning of December to the end of March. During the period of measurements, 2002/03 to 2006/07, there was a snow cover during 105 and 80 days/year in forest land and open land, respectively. The maximum snow depth in forest was 48 cm and in open land 25 cm, and the corresponding values for snow water content were 144 mm and 65 mm for the forest and open land sites, respectively.

4.1.2 Surface water level data

Surface water levels were recorded in six lakes and at two locations in the Baltic Sea. The main results and observations from evaluations of the results are as follows:

- The highest recorded half-hour value of the sea level, 1.40 m RHB70, was during the "Per" storm (January 2007), which can be compared with 0.94 m during the "Gudrun" storm (January 2005); the corresponding maximum daily averages were 0.99 and 0.75 m, respectively. For comparison, it can be noted that the mean sea water level during the whole monitoring period was –0.04 m and the minimum recorded half-hour value –0.68 m (minimum daily average: –0.55 m).

- During periods of high sea water levels, sea water intruded Lake Norra Bassängen, Lake Bolundsfjärden and Lake Lillfjärden and during the extreme events in January 2005 and 2007 also Lake Fiskarfjärden. The level of Lake Lillfjärden seemed to be mainly determined by the sea level, while the levels of Lake Norra Bassängen and Lake Bolundsfjärden were determined by the lake thresholds and the inflow from inland, except for some periods with very high sea levels.
- Salinity profiles from Lake Bolundsfjärden after the sea water intrusions indicated a strong stratification when the lake had an ice cover, while a complete mixing appeared when the there was no ice cover. This mixing of the shallow water body (c. 2.5 m as maximum depth) is most probably mainly wind driven.

4.1.3 Groundwater level data in Quaternary deposits

Groundwater levels were recorded automatically in 51 wells in Quaternary deposits in the site investigation area. Of these wells 42 were located on land, while nine were placed in till below the bottom of lakes and the Baltic Sea. The main results and associated observations from these measurements are summarised in the following.

- The measured groundwater levels in Quaternary deposits are actually density-dependent point water heads, but due to short water columns and mostly low salinity, corrections to fresh water heads or environmental water heads were negligible and were not considered.
- Groundwater levels in Quaternary deposits were in general very shallow. 80% of all recorded groundwater levels in the 42 wells on land were between 0.0 and 2.2 m below ground surface.
- Groundwater levels in Quaternary deposits were strongly coupled to the ground level. However, as anticipated a convex local topography resulted in somewhat deeper average groundwater levels than in areas with concave topography. A classification of the well locations from a recharge-discharge area perspective showed in general very shallow average groundwater levels in discharge areas, while the average depths to groundwater varied substantially in recharge areas.
- In individual wells, the temporal variation in groundwater level was less than 1.0 m in approximately 40% of the wells and less than 1.5 m in approximately 60% of the wells.
- Groundwater level time series in many of the wells in Quaternary deposits were strongly correlated with correlation coefficients $R^2 > 0.9$ and similar range of variations.

4.1.4 Point water heads in bedrock

Point water heads (measured groundwater levels) from 36 percussion-drilled boreholes in the site investigation area were analysed. The results of measurements and data evaluations can be summarised as follows:

- In most percussion-drilled boreholes in bedrock there is a variation in groundwater salinity, and thereby in density, with depth. The groundwater levels recorded are therefore regarded as point water heads. No general transformation was made in the report of the actually measured point water heads to fresh water heads or environmental water heads to account for the influence of water density on horizontal and vertical flow gradients, respectively. However, results from such transformations indicated that in nine sections in the percussion-drilled boreholes there were differences of more than 0.1 m between measured point water heads and environmental water heads.
- Due to all ongoing activities in the site investigation area, mainly drilling and pumping, it was difficult to find long enough periods with undisturbed point water heads in the percussion-drilled boreholes for analyses of natural conditions. However, periods of undisturbed conditions of various lengths were identified and used in the analysis.
- 23 of the 36 bedrock wells had mean natural point water heads above the local bedrock surface.
- Contrary to the wells in Quaternary deposits, there was no evident correlation to the elevation of the local ground surface.

- All but two well sections in the percussion-drilled boreholes exhibited average point water heads above 0.0 m RHB70. The two outliers were sections in boreholes close to the existing underground SFR-repository where pumping by c. 6 L/s takes place for drainage purposes.
- All but two of the monitored bedrock well sections within the tectonic lens, constituting the candidate area, had mean natural point water heads below 1.5 m RHB 70. The two outliers had very low transmissivities. The small natural gradients within the tectonic lens indicate high transmissivities in the horizontal and sub-horizontal fracture zones known to exist in the uppermost c. 150 m of the lens.
- The analysis of responses in other bedrock wells to single distinct disturbances of groundwater levels in three bedrock wells indicated good hydraulic contacts over large distances in the upper rock within the tectonic lens. These responses confirmed the high transmissivities in the uppermost c. 150 m indicated by the small natural gradients.

4.1.5 Surface discharge

Surface discharge was measured at four automatic gauging stations. The upstream catchment areas varied in size from 2.3 to 5.6 km^2. The station of the largest catchment area had been in operation since April 2004 and the other three since December the same year. The following main results were obtained:

- The discharge from the largest catchment area varied between 0 and 212 L/s (0–38.0 $L/s/km^2$) during the period of available measurements (April 2004–March 2007). The average specific discharge for this period was 4.87 $L/s/km^2$ (154 mm/year).
- During the two full calendar-years with available measurements at all four stations, 2005 and 2006, the ranges in specific discharges at these stations were 126–142 mm/year (2005) and 167–193 mm/year (2006). The largest catchment had the highest specific discharge both years.
- The available time series are too short to enable firm conclusions regarding the spatial and temporal variations in discharge.

4.2 Relationships between datasets

An important part of the presentation and analysis of time series data were to investigate relationships between different types of data. This work included direct comparisons based on co-plotting of different time series, as well as development of relatively simple models relating different datasets. The conclusions of these studies are summarised below.

- A model for snow accumulation and snowmelt was calibrated against measured snow water content and used to derive a rainfall+snowmelt (R+S) time series. A good fit were obtained for the snow model. Daily values from this time series minus daily potential evapotranspiration (R+S-PET) were used for interpretation of hydrological relationships.
- In a study of ordinary correlations between selected datasets, R^2-values for monthly average groundwater levels in Quaternary deposits to average R+S-PET of the prior two months were typically 0.6–0.8. R^2-values in the same range were obtained when monthly change in groundwater level was correlated to R+S-PET for the same month.
- In contrast, the correlations between R+S-PET and point water heads in bedrock, according to the ordinary correlations analysis, were weak and inconsistent. However, a principal component analysis of the bedrock point water heads indicated that approximately 80% of the total variance was coupled to the seasonal variation of R+S-PET.
- Diurnal variations of groundwater levels in Quaternary deposits, often 2–3 cm, were observed in several wells in areas with shallow groundwater during dry summer conditions. These variations were an indication of direct and/or indirect root water uptake and illustrated the strong connection between transpiration, and water in the unsaturated zone and the groundwater zone.

- The correlation between groundwater levels in Quaternary deposits and the sea level were typically very low, with exception of the two wells located in a glaciofluvial deposit close to the sea. Different time periods for averaging and displacement in time were tested.
- Concerning the correlation between the point water heads in bedrock and the sea level, the ordinary correlation study indicated a typically weak and inconsistent correlation. However, a PLS-model (Partial Least Squares) was applied to further explore the correlations between point water heads and sea level, air pressure, and a simulated groundwater level based on R+S-PET and a tank storage. From the PLS-analysis at least one section in each of the bedrock boreholes HFM33-35, was classified as probably influenced by sea level changes, and HFM02-04, HFM14-15, HFM18, HFM20, HFM22, HFM30, HFM32, and HFM38 as possibly influenced.
- A comparison of lake water levels and groundwater levels in Quaternary deposits in the vicinity of or below the lakes showed that groundwater levels for most of the time were higher than the lake water levels. This means that the lakes and their riparian zones act as discharge areas for shallow groundwater, the actual discharge determined by the hydraulic contact between groundwater and surface water. However, during dry summer conditions the groundwater levels in the riparian zones and for some lakes also below the lake, decreased well below the lake water levels, implying that the lakes constituted potential groundwater recharge sources during these periods. This phenomenon confirmed the important influence of root water uptake on shallow groundwater indicated by the diurnal fluctuations discussed above, and was also an indication of a limited hydraulic contact between the lakes and the groundwater.
- Where groundwater levels in Quaternary deposits and point water heads in bedrock were observed in wells in close proximity, mostly at core drill sites, the groundwater levels in Quaternary deposits were 1–2 m higher, with Drill site 4 as an exception. Transformation of point water heads to environmental heads indicated that the difference in groundwater levels in Quaternary deposits and point water heads in rock could not be explained by water density differences; they indicated a downward flow gradient from the Quaternary deposits to the bedrock. However, the lack of response in groundwater levels in Quaternary deposits to pumpings in nearby bedrock wells indicated a limited hydraulic contact between groundwater in Quaternary deposits and bedrock, at least in the vicinity of the pumping wells.
- At Drill site 4, located outside the tectonic lens, the two monitoring wells in Quaternary deposits with lower groundwater levels than bedrock point water heads were situated in typical groundwater discharge areas for shallow groundwater and with ground elevations 3–4 m lower than at the percussion-drilled boreholes.
- At some of the sites within the tectonic lens where wells in Quaternary deposits and bedrock are in close proximity, the groundwater levels in the Quaternary deposits decreased below the groundwater levels in the bedrock during dry summer conditions, creating possibilities for an upward groundwater flow from the bedrock to the Quaternary deposits.
- The drainage of the SFR-repository (c. 6 L/s), together with a high horizontal transmissivity of the upper bedrock, is a possible explanation for the generally low groundwater levels in the upper bedrock within the tectonic lens.
- Based on a water balance calculation for the full three-year period of April 15 2004–April 14 2007 (including measurements of precipitation and discharge, and estimates of storage changes from measured lake and groundwater levels), and comparison of the precipitation for this period and the long-term average precipitation, a long-term overall water balance was roughly estimated to: P (precipitation) = 560 mm/year, ET (evapotranspiration) = 400–410 mm/year, and Q (runoff) = 150–160 mm/year.

4.3 Reliability of results

The installation of the monitoring equipment for the site investigation has been an on-going process from the first installations in late 2002. The performed measurements are considered to give a good basis for the description of the site conditions during the period of measurements and to constitute a firm basis for the development of a conceptual model of the hydrological and near-surface hydrogeological conditions. The conclusions regarding the representativity of the present period for long-term average conditions and variations can be summarised as follows:

- Almost four years of meteorological data were available for the analysis. These time series can be used to establish relationships with nearby SMHI stations with much longer time series as a basis for long-term hydrological and hydrogeological modelling. The uncertainties in the correlations will decrease with the continued monitoring at Forsmark.
- The sea and lake level time series are considered to give a good indication of the average conditions and the variations to be expected.
- The groundwater level time series from Quaternary deposits and the upper bedrock are considered to give a good indication of existing average conditions and of the variations to be expected. The possible influence of the SFR drainage on the groundwater levels in bedrock, especially within the tectonic lens, needs to be further investigated.
- The available time series of surface discharge give a good estimate of the average specific discharge in the area, but they are too short to enable firm conclusions on spatial and temporal variations of the discharge to be drawn.
- Existing time series are considered to form a good basis for estimation of the average long-term water balance. However, longer time series of precipitation and surface discharge are needed for better estimates of the spatial and temporal variation of the water balance.

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