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Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp

Site descriptive modelling SDM-Site Laxemar

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July 2009

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Preface

During the period 2002–2007, the Swedish Nuclear Fuel and Waste Management Company (SKB) has conducted site investigations at two different locations in Sweden, Forsmark and Laxemar-Simpevarp. The overall objective of these investigations is the siting a geological repository for spent nuclear fuel.

The present report constitutes a summary and synthesis of the work on surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Important contributions to the present report have been provided by the following individuals:

Emma Bosson (SKB), and Mona Sassner and Lars-Göran Gustafsson (DHI Sverige AB), who carried out the MIKE SHE modelling that is summarised in this report, and provided important feedback to the conceptual description.

Johan Öhman (Golder Associates AB), who carried out most of the work related to handling and presentation of time-series data.

Anders Engqvist (Royal Institute of Technology), who provided input concerning the conceptual description of the coastal basins at Laxemar-Simpevarp.

Ingvar Rhén (SWECO Environment), who provided valuable support on the hydrogeological conceptual description of the area.

Sten Berglund (SKB), who reviewed and provided comments on the report.

Summary

This report provides a description of surface hydrology and near-surface hydrogeology in Laxemar-Simpevarp. The work has been performed for the final site descriptive model of Laxemar-Simpevarp produced in the site investigation stage, SDM-Site Laxemar. The description is based on evaluation of a comprehensive data set and supported by quantitative water flow modelling.

The Laxemar-Simpevarp area (here abbreviated Laxemar) in south-eastern Sweden is located c 350 km south of Stockholm on the coast of the Baltic Sea, close to the Oskarshamn nuclear power plant in the municipality of Oskarshamn. The topography of the area is characterised by relatively distinct valleys, surrounded by higher-altitude areas dominated by exposed or shallow rock. The south-western and central parts of the regional model area are characterised by hummocky moraine and thereby a smaller-scale topography. Almost the whole area is located below 50 m.a.s.l. and the entire area is located below the highest coastline.

As a long-term average, the site-average annual precipitation and specific discharge are estimated to be on the order of 600 mm and 165 mm, respectively. The precipitation demonstrates a near-coastal gradient, with less precipitation on the coast compared to areas further inland. The main lakes in the regional model area are Lake Jämsen (0.24 km^2), Lake Frisksjön (0.13 km^2), Lake Sörå (0.10 km^2), Lake Plittorpsgöl (0.03 km^2), Lake Fjällgöl (0.03 km^2) and Lake Grangöl (no size data). All lakes are located above sea level, which implies that there is no sea-water intrusion to the lakes.

Wetlands cover totally c 3% of the delineated catchment areas. The flow in the streams demonstrates large seasonal variability. Of the monitored streams, there is flow throughout the year in the streams Laxemarån, Kåreviksån downstream from Lake Friskjön and Kärrviksån. The stream Ekerumsån is dry during dry summers, whereas the other monitored small streams are dry during approximately half of the year.

There are many water-handling activities in Laxemar, including SKB (e.g. groundwater inflow to the underground Äspö Hard Rock Laboratory) and the water supply to the nuclear power plant. Further, the regional model area contains more than 200 private wells, and most streams in the area are affected by land improvement and drainage operations.

Sandy-gravelly till is overlying the rock in more or less the whole regional model area, also in most areas with shallow rock. The till has a relatively high hydraulic conductivity ($K \approx 4\cdot10^{-5}$ m·s^{-1}). There are indications that the hydraulic conductivity of the till overlying the rock in the deepest parts of the large valleys is about one order of magnitude higher than that of till in other parts of the area. Permeameter tests on till indicate an anisotropic hydraulic conductivity, with a horisontal conductivity that may be 15–30 times higher than the vertical conductivity.

The hydraulic conductivity of the rock decreases with depth, both within deformation zones and in the rock mass between the deformation zones. The deformation zones are mostly subvertical and typically one order of magnitude more conductive compared to the surrounding rock. Many deformation zones coincide with and outcrop in valleys. Tests on 100-m scale indicate that the rock above c 150 m.b.s.l. (metres below sea level) has a geometric average hydraulic conductivity of c $2\cdot10^{-7}$ m·s^{-1} when considering the entire data set (deformation zones and the rock between them); this value is also applicable to the rock mass between deformation zones.

Groundwater levels in the QD (Quaternary deposits) are shallow. On average, the depth to the groundwater table in the QD is less than c 1 m during 50% of the time. There is hence a close correlation between the ground-surface topography and groundwater levels in the QD, which implies that topography has a strong influence on near-surface patterns of groundwater recharge and discharge. Overall, there seems to be less correlation between point water heads in the upper parts of the rock and ground-surface elevations, as compared to groundwater levels in the QD, even though there is a general trend indicating such a correlation.

Groundwater recharge mainly takes place in high-altitude areas, dominated by exposed/shallow rock. Precipitation and snowmelt are considered to be the dominant sources of groundwater

recharge. Snow accumulation during winter, snowmelt in spring and seasonally variable potential evapotranspiration imply that the actual "source term" for groundwater recharge and surface runoff demonstrates strong seasonal variations. Evaluation of site investigation data shows that even on an annual basis, snowmelt represents an important source term.

The high-altitude areas containing exposed/shallow rock are difficult to parameterise in conceptual models and also to represent properly in quantitative water flow models. Results of quantitative (MIKE SHE) water-flow modelling, conducted as part of SDM-Site Laxemar, indicate that in areas with exposed/shallow rock on the order of 10% of the annual precipitation forms groundwater in the rock.

Groundwater discharge mainly takes place in the low-altitude areas. This is supported by MIKE SHE modelling results, which show that groundwater discharge areas are located to low-lying areas such as stream valleys, Lake Frisksjön and the sea bays near the coast. One can identify two main sub-flow systems for groundwater flow in the discharge areas: One system located to the upper part of the rock and the QD, which overlies a larger-scale flow system primarily associated with deformation zones (of different orientations) in the rock.

Most groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper part (say, 10 m) of the rock. Groundwater flow in the deeper parts of the rock primarily occurs in a system of connected deformation zones, and the associated groundwater discharge takes place at locations where this system connects to zones that outcrop in the valleys. Groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones.

Except for some minor wetlands, the surface waters are located to the low-altitude areas. These surface waters are mainly underlain by glacial and post-glacial sediments. However, some parts of the streams pass through areas where there are no such sediments, which is also the case for some near-shore areas of the lakes. Groundwater-level monitoring in the QD near the shore of Lake Jämsen and below Lake Frisksjön indicates that interaction between lake water and groundwater in the underlying QD is limited to near-shore areas. The local conditions for surface water-groundwater interaction are also influenced by land improvement and drainage operations, which for instance imply that water flows in subsurface pipes along parts of the stream valleys.

Groundwater discharge from the upper rock-QD part of the groundwater flow system to the surface (surface waters) is hence strongly influenced by the geometry and the hydrogeological properties of the QD overlying the till. Moreover, there is also an influence on this process of the hydrogeological properties of the upper rock (including the deformation zones) and the high-conductive QD overlying the rock in the valleys.

The conceptual and quantitative modelling presented in the report conveys the current understanding of the hydrological and hydrogeological driving forces and the overall water-flow patterns, as well as knowledge gaps in terms of properties and detailed process descriptions. For instance, there are some uncertainties associated with the data used for modelling of hydrology and near-surface hydrogeology. Examples of such uncertainties include a non-standard weir design and some natural sections at surface-discharge gauging stations.

There are generally a larger amount of detailed field investigations performed in the central parts of the Laxemar local model area, and also on Hålö, the island of Ävrö and the Simpevarp peninsula. There are hence less detailed underlying descriptions available for other parts of the local model area, for which the descriptions primarily are based on remote sensing studies.

There are relatively few hydrogeological monitoring data from the high-altitude areas in Laxemar that can be used to describe the processes of infiltration and groundwater recharge. This bias also concerns the MIKE SHE modelling, since the hydrogeological and hydrological (surface-water discharges) calibration data set primarily includes data from low-lying areas.

Sammanfattning

Denna rapport ger en beskrivning av ythydrologi och ytnära hydrogeologi i Laxemar-Simpevarp. Arbetet har utförts för den sista platsbeskrivande modellen av Laxemar-Simpevarp som redovisas under platsundersökningsskedet, SDM-Site Laxemar. Beskrivningen baseras på utvärdering av en omfattande datamängd och stöds av kvantitativ vattenflödesmodellering.

Laxemar-Simpevarpområdet (här förkortat Laxemar) i sydöstra Sverige är beläget ca 350 km söder om Stockholm vid Östersjöns kust, nära Oskarshamns kärnkraftverk i Oskarshamns kommun. Områdets topografi karaktäriseras av relativt distinkta dalgångar, som omges av högre belägna områden som domineras av berg i dagen eller ytnära berg. De sydvästra och centrala delarna av det regionala modellområdet karaktäriseras av småkuperad moränterräng och därmed en mer småskalig topografi. I stort sett hela området är beläget lägre än 50 m.ö.h. och hela området är beläget under högsta kustlinjen.

Som ett långtidsmedelvärde och som ett medelvärde för området, kan den årliga nederbörden och specifika avrinningen skattas till i storleksordningen 600 mm respektive 165 mm. Nära kusten finns det en nederbördsgradient, med mindre nederbörd vid kusten jämfört med områden längre inåt land. De största sjöarna i det regionala modellområdet är Jämsen (0.24 km^2), Frisksjön (0.13 km^2), Sörå (0.10 km^2), Plittorpsgöl (0.03 km^2), Fjällgöl (0.03 km^2) och Grangöl (inga data). Samtliga sjöar är belägna ovan havsnivån, vilket innebär att det inte sker någon inträngning av havsvatten till sjöarna.

Våtmarker täcker totalt ungefär 3 % av de avgränsade avrinningsområdena. Flödet i bäckarna uppvisar en stor säsongsvariation. I de bäckar där flödet mätts är det flöde året om i Laxemarån, Kåreviksån nedströms Friskjön och Kärrviksån. Ekerumsån är torr under torra somrar. De övriga små bäckarna i vilka flödet mätts är torra under ungefär halva året.

Vattenhanteringen i Laxemar är omfattande. Vattenhanteringen innefattar bland annat SKB (till exempel inflöde av grundvatten till undermarksanläggningen Äspölaboratoriet) och vattenförsörjningen till kärnkraftverket. I det regionala modellområdet finns det fler än 200 enskilda brunnar, och de flesta bäckarna i området är påverkade av kulturtekniska och andra åtgärder.

Sandig-grusig morän överlagrar berget i stort sett i hela det regionala modellområdet, även i de flesta områden med ytnära berg. Moränen har en relativt hög hydraulisk konduktivitet ($K \approx 4\cdot10^{-5}$ $m\cdot s^{-1}$). Det finns indikationer på att den hydrauliska konduktiviteten i moränen som överlagrar berget i de djupaste delarna av de stora dalgångarna är ungefär en storleksordning högre än i moränen i andra delar av området. Permeametertester på morän indikerar en anisotrop hydraulisk konduktivitet, med en horisontell konduktivitet som kan vara 15–30 gånger högre än den vertikala konduktiviteten.

Bergets hydrauliska konduktivitet minskar med djupet, både i deformationszonerna och i berget mellan deformationszonerna. De flesta deformationszonerna är subvertikala och har i regel en hydraulisk konduktivitet som är en storleksordning högre än det omgivande berget. Många deformationszoner sammanfaller med och har sitt utgående i dalgångar. Tester (på skalan 100 m) indikerar att berget över ca 150 m.u.h. (meter under havet) har en hydraulisk konduktivitet med ett geometriskt medelvärde på ca $2\cdot10^{-7}$ $m\cdot s^{-1}$, om man beaktar hela datamängden (deformationszoner och berget mellan dem); detta värde gäller även berget mellan deformationszonerna.

Grundvattennivån i jordlagren är nära markytans nivå. I medeltal är djupet till grundvattenytan i jordlagren mindre än ca 1 m under 50 % av tiden. Det finns därmed en stark korrelation mellan markytans topografi och grundvattennivån i jordlagren, vilket innebär att topografin har en stark påverkan på mönstret för grundvattnets in- och utströmning vid och nära markytan. Det tycks vara en lägre korrelation mellan grundvattennivån i de övre delarna av berget och markytans topografi, även om det finns en generell trend som indikerar på en sådan korrelation.

Grundvatteninströmning sker huvudsakligen i de högre belägna områdena, som domineras av berg i dagen och ytnära berg. Nederbörd och snösmältning bedöms stå för de största bidragen till grundvattenbildningen. Snöackumulation under vintern, snösmältning under våren och säsongsmässiga variationer av den potentiella evapotranspirationen innebär att grundvattenbildningens och ytavrin-

ningens “källterm” har en stor säsongsmässig variation. Utvärdering av platsundersökningsdata visar att även på årsbasis utgör snösmältningen en viktig sådan källterm.

Det är svårt att ansätta parametrar i konceptuella modeller för de högre belägna områdena med berg i dagen eller ytnära berg. Dessa områden är även svåra att representera korrekt i kvantitativa vattenflödesmodeller. Resultat från kvantitativ (MIKE SHE) vattenflödesmodellering, som utförts som del av SDM-Site Laxemar, indikerar att ca 10 % av den årliga nederbörden bildar grundvatten i berg i områden med berg i dagen eller ytnära berg.

Grundvattenutströmning sker främst i de lägre belägna områdena. Denna tolkning stöds av resultat från MIKE SHE-modelleringen som visar att grundvattenutströmningen sker i lågområden, till exempel dalgångar med bäckar, Frisksjön och havsvikarna nära kusten. Man kan identifiera två huvudsakliga grundvattenflödessystem i utströmningsområdena: Ett system i den övre delen av berget och i jordlagren, vilket överlagrar ett storskaligt system som främst är associerat med deformationszoner (med olika orientering) i berget.

Den dominerande delen av grundvattenflödet mot utströmningsområdena i dalgångarna sker i jordlagren och i den övre delen (säg, 10 m) av berget. Grundvattenflödena i de djupare delarna av berget sker främst i ett system med sammanhängande deformationszoner. Grundvattenutströmningen från detta system sker i områden där systemet hänger samman med zoner som har sitt utgående i dalgångarna. Grundvattenutströmning från djupa delar av berget är därmed mindre sannolik i områden där det inte finns några utgående deformationszoner.

Med undantag för några mindre våtmarker, förekommer ytvattnen i lågområdena. Dessa ytvatten underlagras huvudsakligen av glaciala och postglaciala sediment. Delar av bäckarna passerar dock genom områden där det inte finns sådana sediment, vilket även gäller vissa strandnära områden kring sjöarna. Mätningar av grundvattennivån i jordlagren nära sjön Jämsen och under Frisksjön indikerar att vattenutbytet mellan sjöarna och grundvattnet i de underliggande jordlagren främst sker i strandnära områden. De lokala förutsättningarna för utbyte mellan ytvatten och grundvatten påverkas även av kulturtekniska och andra åtgärder, vilka till exempel innebär att bäckvattnet längs vissa delar av dalgångarna rinner i markförlagda rörledningar.

Grundvattenutströmning från den övre delen av berget och jordlagren till ytsystemet (ytvattnen) är således starkt beroende på geometrin och de hydrogeologiska egenskaperna för de jordlager som överlagrar moränen. Grundvattenutströmningen påverkas även av de hydrogeologiska egenskaperna i den övre delen av berget (inklusive deformationszonerna) och av moränen med hög konduktivitet ovan berget i dalgångarna.

Den konceptuella och kvantitativa modellering som presenteras i denna rapport förmedlar den rådande förståelsen av de hydrologiska och hydrogeologiska drivkrafterna och vattnets generella flödesmönster, liksom brist på kunskap vad gäller egenskaper och detaljerade processbeskrivningar. Det finns till exempel osäkerheter kring vissa data som används för modellering av hydrologi och ytnära hydrogeologi. Exempel på sådana osäkerheter är en icke-standardiserad utformning på mätöverfall och de naturliga sektionerna vid några av vattenföringsstationerna.

Generellt har fler detaljerade undersökningar utförts i de centrala delarna av det lokala modellområdet i Laxemar, och även på Hålö, ön Ävrö och på Simpevarpshalvön. Det finns därmed färre detaljerade beskrivningar som kan användas för övriga delar av det lokala modellområdet. De beskrivningar som finns att tillgå för dessa delar baseras främst på fjärranalys.

För de högre belägna områdena i Laxemar finns det en relativt liten mängd hydrogeologiska mätdata som kan användas för att beskriva processer som infiltration och grundvattenbildning. Denna snedfördelning gäller även MIKE SHE-modelleringen, eftersom de hydrogeologiska och hydrologiska (bäckvattenföring) mätdata som används för modellkalibreringen främst inkluderar data från lågområdena.

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1 Introduction

1.1 Background

During the period 2002–2007, the Swedish Nuclear Fuel and Waste Management Co (SKB) has undertaken multi-disciplinary site investigations at two different locations, Forsmark in mid-eastern Sweden and Laxemar-Simpevarp in the south-eastern part of the country. The overall objective of these investigations is the siting of a geological repository for spent nuclear fuel. The investigations were divided into an initial (ISI) and a complete site investigation (CSI) phase /SKB 2001/. The results from the site investigations are used as a basic input to site descriptive modelling, in turn aiming to provide multi-disciplinary descriptions of current properties and processes at the investigated sites. Specifically, a site descriptive model (abbreviated 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.

This report concerns the Laxemar-Simpevarp area (see Figure 1-1), and is produced as one of the background reports for SDM-Site Laxemar, which is the name of the final SDM version to be produced in the Laxemar-Simpevarp site investigations. The site investigations in the Laxemar-Simpevarp area were conducted in campaigns, separated by so called data freezes (abbreviated DF).

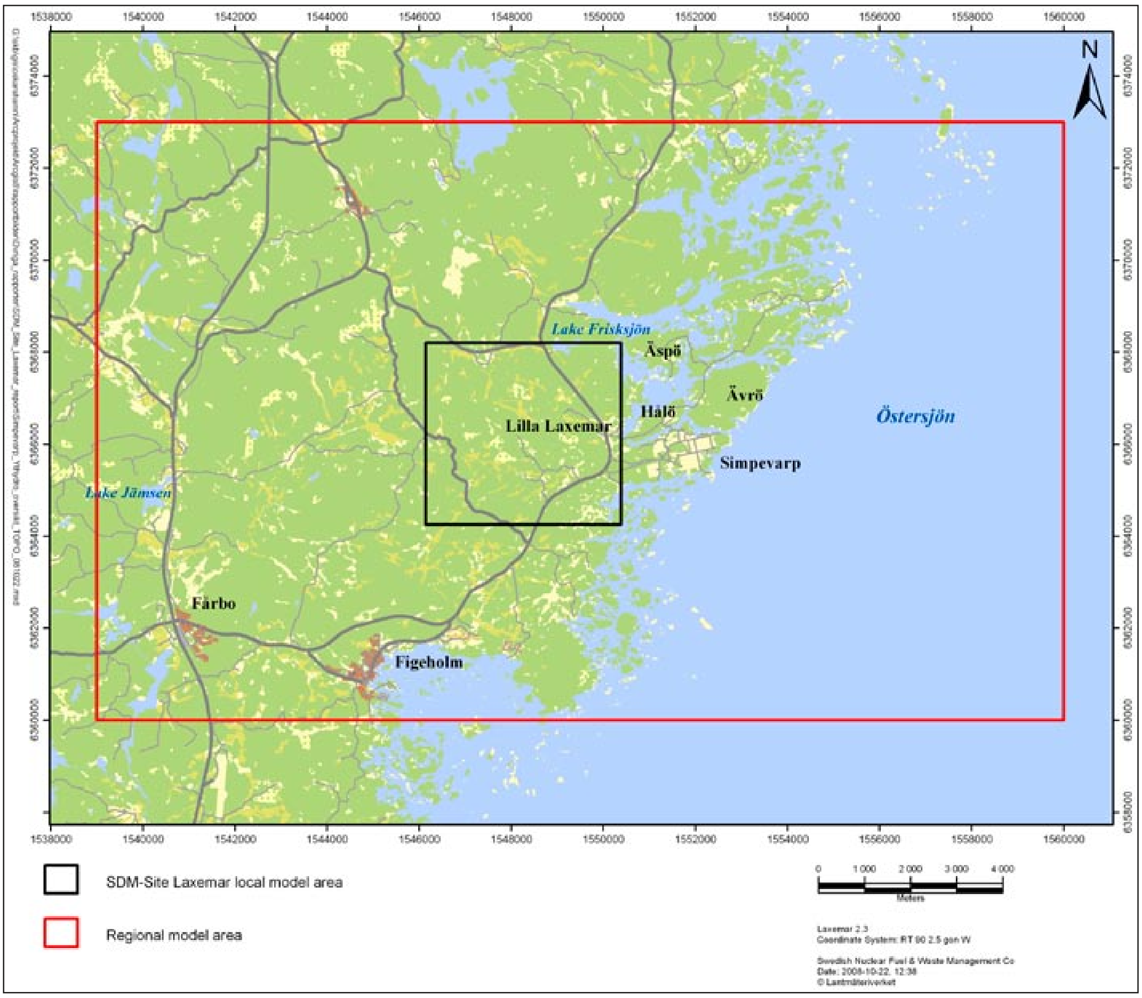

Figure 1-1. *Overview map of the Laxemar-Simpevarp regional model area and the SDM-Site Laxemar local model area.*

The first steps of the site descriptive modelling of the Laxemar-Simpevarp area were taken with SDM versions Simpevarp 1.1 /SKB 2004a/, Simpevarp 1.2 /SKB 2005b, Lindborg (ed.) 2005/ and Laxemar 1.2 /SKB 2006a, Lindborg 2006 (ed.)/, taking into account the data sets present at time of data freezes DF S1.1 (Simpevarp 1.1; July 1, 2003), S1.2 (Apr. 1, 2004), and L1.2 (Laxemar 1.2; Nov. 1, 2004). Specifically, these data freezes contain site data gathered during the initial (ISI) phase, whereas site data pertaining to the complete (CSI) phase are associated to DF L2.1 (Laxemar 2.1; Jun. 30, 2005) and onwards. Specifically, DF L2.1 was followed by the "interim" DF L2.2 (Dec. 31, 2006).

The present report takes into account site investigation data available in SKB's Sicada database at the time for DF L2.3 (Laxemar 2.3; Aug. 31, 2007). It should be noted that for some parameters, the considered time-series data set is not restricted in time to the actual Laxemar 2.3 data freeze. Specifically, for some parameters the report takes into account quality-controlled data available in Sicada up to Dec. 31, 2007 (see /Werner et al. 2008/ for details).

The Laxemar-Simpevarp area in south-eastern Sweden is located c 350 km south of Stockholm on the coast of the Baltic Sea, in the municipality of Oskarshamn in the province of Småland (county of Kalmar). During 2002–2007, site investigations were conducted within a square-shaped area referred to as the Laxemar-Simpevarp regional model area, covering c 273 km^2 (see Figure 1-1). The land parts of the considered area include Laxemar (the mainland), the Simpevarp peninsula, Hålö (connected to the mainland via a narrow land area) and the island of Ävrö. The nuclear power plant and the Central interim storage facility for spent fuel (Clab) are located on the Simpevarp peninsula, whereas the underground Äspö Hard Rock Laboratory (Äspö HRL) is situated below the island of Äspö, north of Hålö.

The site investigations were initially focused to the so-called Simpevarp subarea (including the Simpevarp peninsula, Hålö and the island of Ävrö), and subsequently to the Laxemar subarea on the mainland. Within the SDM-Site context, a smaller square-shaped area is defined within the regional area. This smaller area is referred to as the Laxemar local model area; in principle, this local area is the same as the Laxemar subarea. Obviously, site investigations and descriptive models within different disciplines focus on different areas, depending on the purpose and scope of the investigation or model. For simplicity, this report refer to the area being described as "Laxemar". When necessary, the actual area that the description refers to is specified.

1.2 Physiographic setting

The topography of the Laxemar area (see Figure 1-2) is characterised by relatively distinct valleys, surrounded by higher-altitude areas dominated by exposed or shallow rock. The south-western and central parts of the Laxemar-Simpevarp regional model area are characterised by hummocky moraine and thereby a smaller-scale topography. Almost the whole area is located below 50 m.a.s.l. (metres above sea level) and the entire area is located below the highest coastline.

As a long-term average, the site-average annual precipitation and specific discharge are estimated to be on the order of 600 mm and 165 mm, respectively /Larsson-McCann et al. 2002, Werner et al. 2008/. The precipitation demonstrates a near-coastal gradient, with less precipitation on the coast compared to areas further inland. The main lakes in the regional model area are Lake Jämsen (0.24 km^2), Lake Frisksjön (0.13 km^2), Lake Sörå (0.10 km^2), Lake Plittorpsgöl (0.03 km^2), Lake Fjällgöl (0.03 km^2) and Lake Grangöl (no size data). These relatively small lakes are shallow, with average and maximum depths in the ranges 1–4 m and 2–11 m, respectively. All lakes are located above sea level, which implies that there is no sea-water intrusion to the lakes. Wetlands cover up to c 18% of the delineated catchment areas /Brunberg et al. 2004/. Most streams at the site are affected by land improvement and drainage operations. Of the monitored streams, there is flow throughout the year in the streams Laxemarån, Kåreviksån downstream from Lake Friskjön and Kärrviksån. The stream Ekerumsån is dry during dry summers, whereas the other monitored small streams are dry during approximately half of the year.

Description and parameterisation of different types of Quaternary deposits (here abbreviated "QD") in Laxemar have been performed as part of the SurfaceNet project, whereas description and

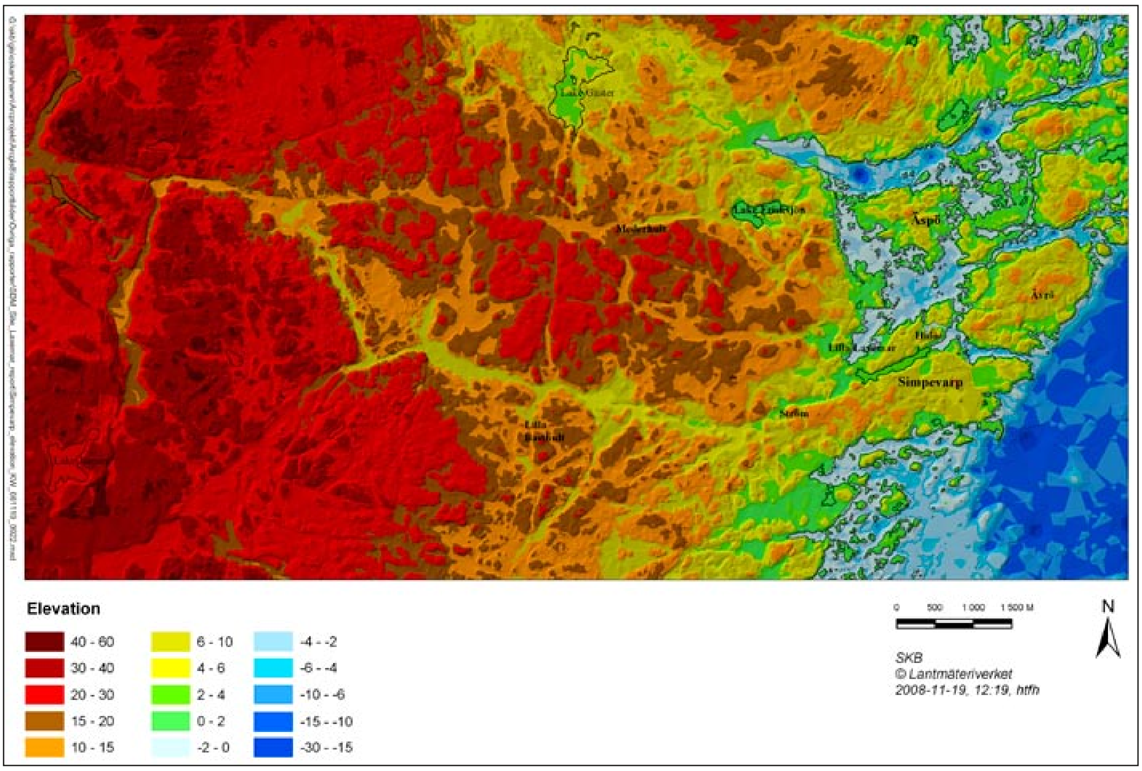

Figure 1-2. *Overview map illustrating the ground-surface topography (m.a.s.l.) in an area roughly corresponding to the Laxemar-Simpevarp regional model area (cf. Figure 1-1), including the bathymetry of lakes and the sea.*

parameterisation of the rock have been performed within the HydroNet project (see further below). As part of the Laxemar site-descriptive modelling of hydrology and near-surface hydrogeology, four hydrogeological type areas have been defined: High-altitude areas, valleys (large and small, i.e. two subtype areas), glaciofluvial deposits, and hummocky moraine areas. These type areas are mainly used as a framework for describing the overall patterns of groundwater recharge and discharge in the Laxemar area; see Chapter 3.

According to the conceptual description of the regolith /Sohlenius and Hedenström 2008/, sandy-gravelly till is overlying the rock in more or less the whole regional model area, also in most areas mapped as exposed/shallow rock (where the thickness of the QD may be up to c 0.5 m). The exceptions are some of the areas with exposed/shallow rock (see Figure 1-3), in which organic soil and a relatively thin vegetation layer is directly overlying the rock. The sandy-gravelly till is characterised by a relatively high hydraulic conductivity K (c $4 \cdot 10^{-5}$ $m \cdot s^{-1}$). Furthermore, there are indications that the hydraulic conductivity of the till overlying the rock in the deepest parts of the large valleys is about one order of magnitude higher than that of till in other parts of the area /Werner et al. 2008/.

Moreover, permeameter tests on till indicate an anisotropic hydraulic conductivity, with an anisotropy ratio (K_h/K_v, where subscripts h and v denote horisontal and vertical, respectively) that may be on the order of 15–30. However, it should be noted that permeameter tests are associated with a smaller tested volume than that of e.g. slug tests providing hydraulic conductivity data. Generic (i.e. not site specific) data are used to support the estimates of the hydrogeological parameters for QD types other than till. According to available groundwater-level data, groundwater levels in the QD are shallow; on average, the depth to the groundwater table in the QD is less than c 1 m during 50% of the time. There is hence a close correlation between the ground-surface topography and groundwater levels in the QD, which implies that topography has a strong influence on near-surface patterns of groundwater recharge and discharge.

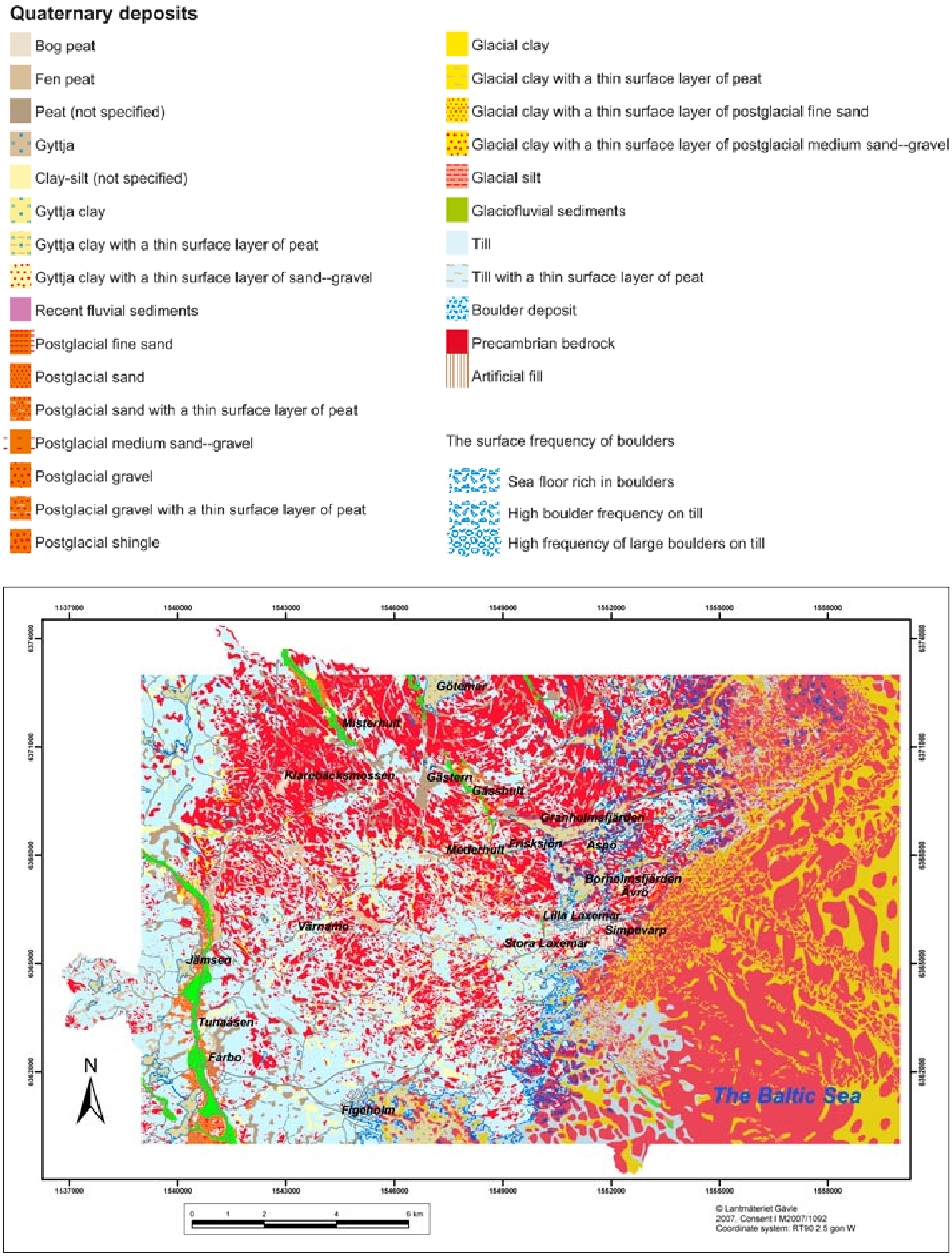

***Figure 1-3.** Map of the QD in the Laxemar-Simpevarp regional model area, including both terrestrial and marine areas /Sohlenius and Hedenström 2008/.*

1.3 Objectives and scope

The general objectives of the site descriptive modelling of the Laxemar area and the specific objectives of the Laxemar SDM-Site modelling are presented in the Laxemar SDM-Site main report /SKB 2009/. The present report is a background report describing meteorology, surface hydrology and near-surface hydrogeology in support of SDM-Site Laxemar. Concerning these disciplines, it may be noted that they were covered by background reports also in the previous Simpevarp 1.2 and Laxemar 1.2 modelling stages /Werner et al. 2005, 2006/. For the SDM-Site model version, data evaluations and quantitative water flow modelling concerning meteorology, surface hydrology and near-surface hydrogeology are reported in /Werner et al. 2008, Bosson et al. 2008b/.

The objectives of this report are to:

- Summarise the Laxemar 2.3 data set on meteorology, hydrology and near-surface hydrogeology (for further details, see /Werner et al. 2008/).
- Summarise the results of quantitative modelling of surface and near-surface water flow at Laxemar (for further details, see /Bosson et al. 2008b/), and discuss the implications of these results for the site-descriptive model.
- Provide an updated conceptual description of meteorology, surface hydrology and near-surface hydrogeology at the Laxemar site (including a discussion of uncertainties), based on the above-mentioned data evaluations and quantitative water-flow modelling.
- Provide an updated site description concerning meteorology, surface hydrology and near-surface hydrogeology as support to related activities, e.g. modelling of groundwater flow in the rock, ecosystems modelling, modelling of mass transport in the surface and near-surface system, safety assessment, repository design, and environmental impact assessment.

1.4 Methodology, terminology and organisation of work

1.4.1 Methodology

The overall methodology of SKB's hydrological and hydrogeological investigations is presented in Figure 1-4. A preliminary conceptual model, mainly based on the data gathered and analysed in the Oskarshamn pre-study /Follin et al. 1998, SKB 2000/, was the starting point for the design of the investigation programme /SKB 2001/. The successive data evaluations and modelling coupled to the data freezes applied in the site investigation methodology, and input from internal and external reviews, have resulted in revisions and additions to the originally proposed site investigation programme /SKB 2005a/.

The data evaluation presented in this report includes meteorological data, surface water levels and discharges, groundwater levels, as well as geometries and properties of the involved hydrological objects and hydrogeological flow domains. As shown in Figure 1-4, these data sets were first evaluated separately and then subject to an integrated analysis. This integrated analysis, supported by data from related site investigation disciplines and generic data, formed the basis for the elaboration of a site-specific conceptual and descriptive model followed by quantitative flow modelling. The procedure has been iterative and repeated for the different model versions.

1.4.2 Terminology

/Rhén et al. 2003/ established the terminology to be used within the site descriptive hydrogeological modelling. The conceptual model should define the framework in which the problem is to be studied, the size of the modelled volume, the boundary conditions, and the equations describing the processes. The (hydrogeological) descriptive model defines, based on a specified conceptual model, geometries of domains and parameters assigned to these domains.

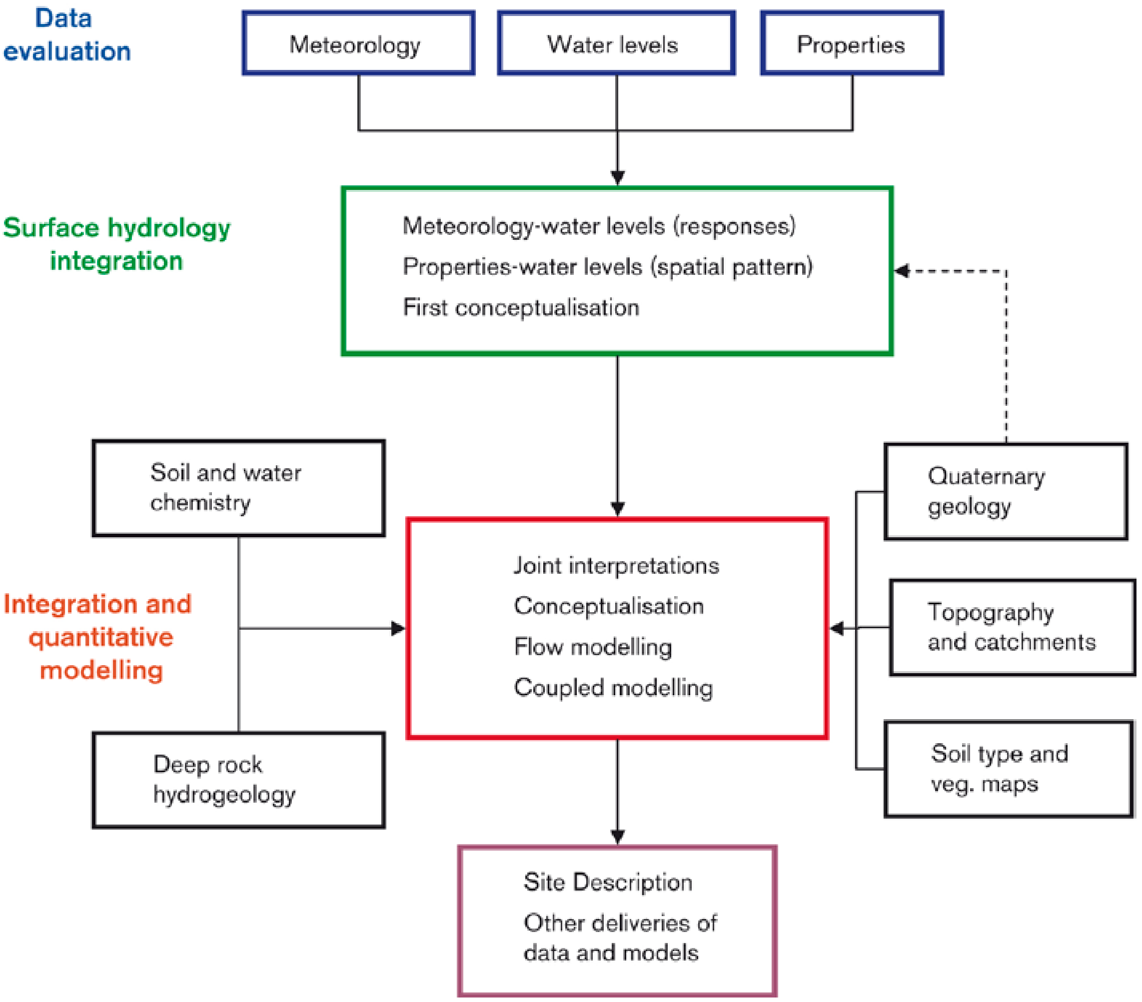

Figure 1-4. *Overall description of the methodology of the hydrological and near-surface hydrogeological modelling work performed within the Laxemar site descriptive modelling /Werner et al. 2006/.*

Since the term "hydrology" often refers to all aspects of the hydrological cycle, i.e. atmospheric, surface and subsurface processes and parameters, it should be noted that the following distinction is made between "hydrology" and "hydrogeology" in the data handling within SKB's site investigation programme:

- Hydrology refers to the surface water system only; hydrological data include surface-water divides and the associated catchment areas and subcatchment areas and water levels and flow rates in streams and lakes.
- Hydrogeology refers to the subsurface system, i.e. the water below the ground surface, including the unsaturated and saturated parts of the subsurface; hydrogeological data include groundwater levels and hydraulic parameters for unsaturated and saturated flow.

Thus, the terminology is clear as far as the input data are concerned; hydrological data are obtained on the ground surface and in surface waters, and hydrogeological data from the subsurface, primarily from drillings and observation wells (sampling for analysis of hydrogeological properties has also been made in pits and trenches).

In the site descriptive modelling, it was found practical to make a distinction between near-surface and deep-rock hydrogeology. The main reason was the high resolution in time and space needed in the description of the surface and near-surface system. Shallow flowpaths dominate the water balance of the area and data from this part are important for the ecosystem modelling. Hence, surface water-groundwater interaction is a main issue of the near-surface hydrogeology.

Obviously, there is an overlap between “near-surface” and “deep-rock” hydrogeological models, since they must incorporate components of each other in order to achieve an appropriate parameterisation and identification of boundary conditions. The present report includes groundwater-level data from percussion-drilled boreholes, i.e. from the upper c 150–200 m of the rock. For a detailed conceptual and descriptive model of the shallow as well as the deep rock, the reader is referred to /Rhén et al. 2008, 2009/.

In the different disciplines of the site investigation several terms are used for the Quaternary deposits as overburden, soil, regolith and hydraulic soil domain (HSD). In this report, the term Quaternary deposits is most commonly used, often abbreviated QD.

In SKB’s systems approach to hydrogeological modelling, three hydraulic domains/flow domains are defined (cf. Section 1.5), (i) hydraulic soil domain (HSD), (ii) hydraulic conductor domain (HCD), and (iii) hydaulic rock mass domain (HRD). For surface water, the flow domains are (i) overland flow, (ii) streams, (iii) lakes, and (iv) the sea. Wetlands are described separately in the report, but are not considered as a separate flow domain.

Groundwater recharge is defined as “Process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation” /UNESCO 1992/. A groundwater recharge area may be defined as an area where water flows from the unsaturated zone to the saturated zone, or from a groundwater flow perspective, as an area where the shallow groundwater flow has a downward flow component. In the same way, a groundwater discharge area may be defined as an area where water leaves the saturated zone, or from a groundwater flow perspective, as an area where the groundwater flow has an upward component /Grip and Rodhe 1985/. The present report adopts a definition of groundwater recharge and discharge areas as areas where groundwater has a downward and upward flow component, respectively. As mentioned above, the groundwater table is very shallow in large parts of the site investigation area, meaning that vegetation water uptake takes place from the groundwater zone, directly or indirectly by inducing capillary rise, especially during periods of dry conditions. Under such conditions these areas, from the definition used, will be characterised as groundwater discharge areas.

The term stream is used throughout this report, even though most streams at the Laxemar site in fact are ditches, constructed or deepened for purposes of land improvement and drainage (see Section 3.3.3).

The term groundwater level is used as a common term for the position of the groundwater table in unconfined aquifers and the potentiometric head in confined aquifers. However, due to depth-dependent groundwater salinity (and thereby density), the groundwater levels measured in some boreholes in the rock should be regarded as so called point water heads. For a correct interpretation of groundwater flow directions, measured point water heads should be re-calculated to so called fresh water heads (for the horisontal flow component) or to environmental water heads (for the vertical flow component) /Lusczynski 1961, Post et al. 2007/. A short summary of the theory of the methodology to transfer point water heads to fresh water and environmental water heads are presented in /Johansson 2008, Werner et al. 2008/.

1.4.3 Organisation of work

The modelling of hydrology and hydrogeology within and related to the surface system has been performed as part of the SurfaceNet project. This project incorporates all site descriptive modelling of the surface system, i.e. both abiotic aspects such as hydrology and hydrogeology, and models of the biotic parts of the system. A project group with representatives for all the surface system modelling disciplines was formed early in the site descriptive modelling process. Most disciplines have had additional modellers associated with the project group.

The interactions with related modelling disciplines, primarily the hydrogeological and hydrogeochemical modelling of the deep rock, have taken place both by informal contacts and discussions and by participation in project meetings with the HydroNet and ChemNet teams. Interactions have also been handled in connection with meetings within the Laxemar site descriptive modelling project (POM). In a similar manner, the integration and interactions within the surface system modelling have been taken care of by means of both informal contacts and SurfaceNet project meetings.

The SurfaceNet modelling for SDM-Site Laxemar is reported in /Söderbäck and Lindborg (eds.) 2009/. Furthermore, the contents of the present report are used in the overall conceptual and descriptive model of the hydrogeology at Laxemar /Rhén et al. 2008, 2009/. The contents of these reports are then summarised in the SDM-Site Laxemar main report /SKB 2009/. The structure of the SDM-Site Laxemar reporting is illustrated in Figure 1-5. In this structure, the surface system (SurfaceNet) report is referred to as a "level II" report, whereas the present report is referred to as a "level III" report (see Figure 1-5).

1.5 Model structure and contents of report

1.5.1 Structure of SKB hydrogeological models

The present report provides a conceptual and descriptive model of the surface hydrological and near-surface hydrogeological system of the Laxemar area. The model describing this system is based on site-specific, regional and generic data, and quantitative water flow modelling. The conceptual model includes the main components

- hydrological objects and hydrogeological flow domains,
- external and internal boundaries,
- infiltration and groundwater recharge,
- sub-flow systems and discharge.

Figure 1-6 illustrates SKB's systems approach to hydrogeological modelling. This modelling approach is described in detail in /Rhén et al. 2003/. The division into three types of hydraulic domains (QD, rock mass, and conductors in rock) constitutes the basis for the quantitative models.

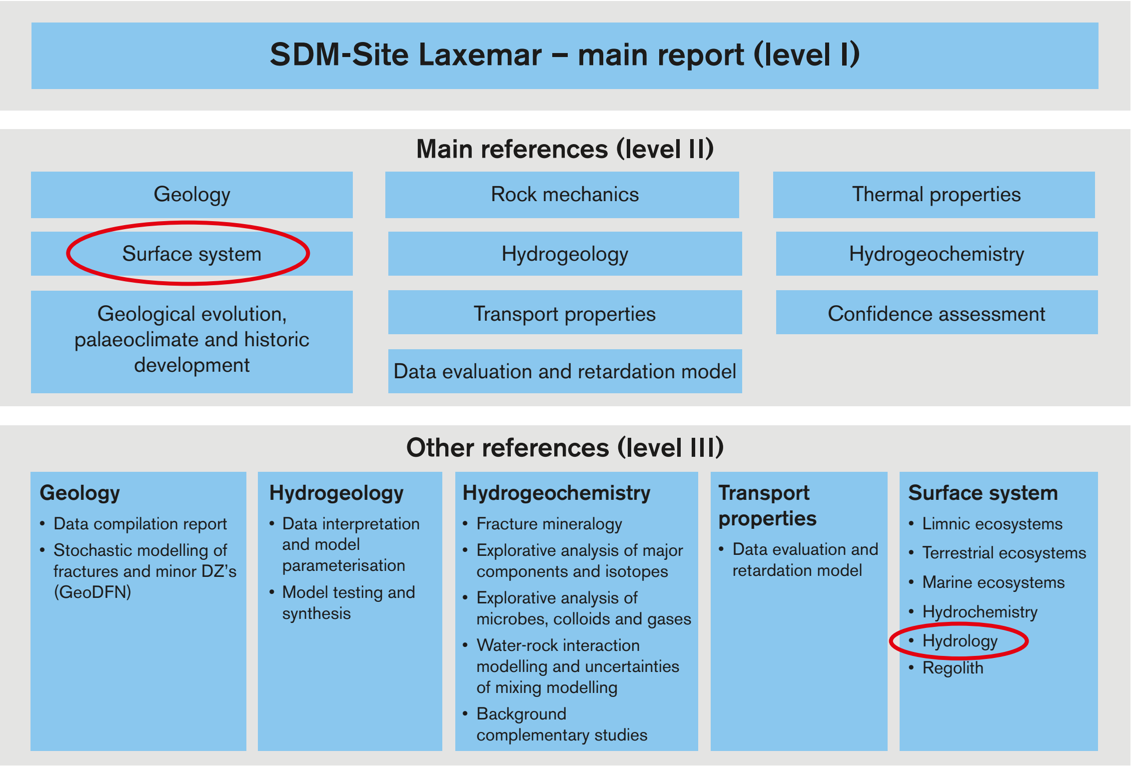

Figure 1-5. *The SDM-Site Laxemar report structure /Söderbäck and Lindborg (eds.) 2009/. The present report is a level III report ("Hydrology") primarily providing input to the "Surface system" level II report, which, in turn, is one of the main references used in the SDM-Site Laxemar main report.*

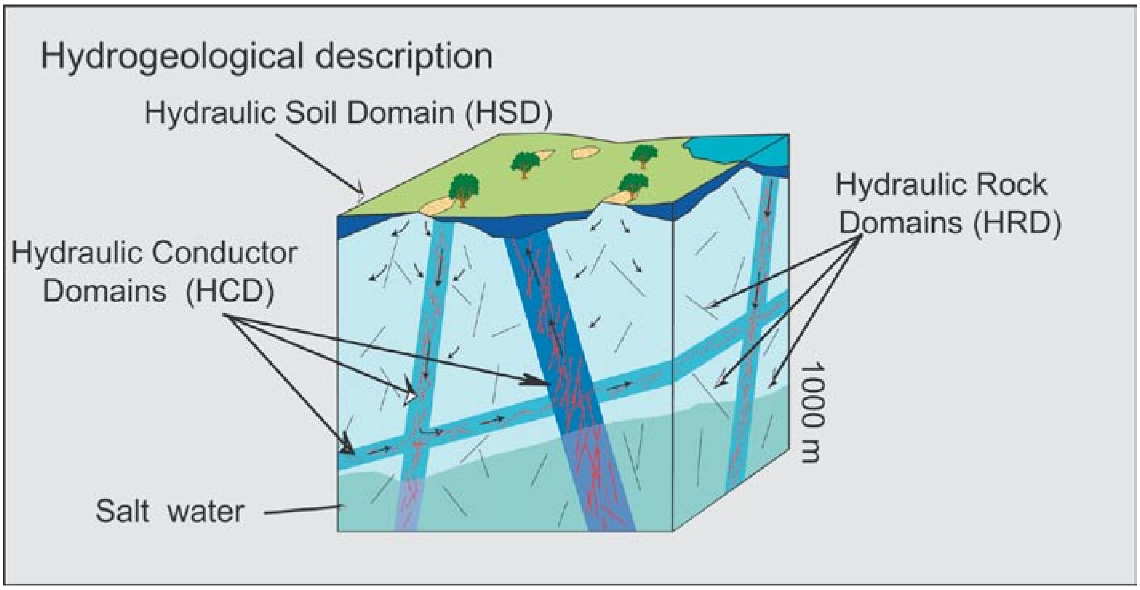

Figure 1-6. Division of the QD and the bedrock into hydraulic domains representing the QD (HSD) and the rock domains (HRD) between fracture zones modelled as conductor domains (HCD) /Rhén et al. 2003/.

From a hydrogeological perspective, the geological data and related interpretations constitute the basis for the geometrical modelling of the different hydraulic domains. Thus, the investigations and documentation of the QD and the rock provide input to the following:

- The distribution of QD (HSD), including genesis, composition, stratification, thickness and total depth.
- The geometry of deterministic fracture zones (HCD) or lineaments, if needed, and the rock in between (HRD).

In the present context, where the HSDs are investigated in detail, a further division is made of the near-surface hydrogeology than shown in Figure 1-6.

A complete conceptual and descriptive model of the hydrology and the hydrogeology at a site involves a description of the integrated (continuous) hydrological-hydrogeological system, i.e. surface waters, groundwater in QD and groundwater in rock. As described above, the focus of the modelling presented here is on the surface and near-surface conditions. The hydrogeological properties of the rock used in the present quantitative modelling are therefore just described very briefly in this report and reference is made to /Rhén et al. 2008, 2009/.

1.5.2 This report and its background reports

The disposition of this report follows the overall disposition of the SDM reports: First, data presentation and evaluation, followed by conceptual, descriptive and quantitative flow modelling, and then the resulting description. The database for the conceptual and descriptive model is mainly the data referred to and presented in Chapter 2. In Chapter 3, the overall conceptual and descriptive model is presented as derived from site-specific field observations, and regional and generic data. The hydrological objects and hydrogeological flow domains and their hydraulic interaction are presented and analysed. Examples are also given of supporting evidence from other disciplines of the site investigation. Furthermore, the uncertainties of the derived conceptual and descriptive model are discussed.

Chapter 4 presents the quantitative water flow modelling. This involves the transfer of the conceptual and descriptive model developed in Chapter 3 to quantitative models, description of water modelling tools, and presentation and interpretation of modelling results. Furthermore, the results of the quantitative modelling are compared with the conceptual and descriptive model based on field observations, and agreements, deviations and uncertainties are discussed. Finally, the resulting site description is presented in Chapter 5, including uncertainties in data, conceptualisation and modelling.

The present report is associated with a set of background reports, in which more detailed descriptions of certain parts of the modelling work are given. Specifically, the available data, the data evaluations and the numerical modelling are detailed in background reports, as follows:

- Presentation and evaluation of meteorological, hydrological and hydrogeological monitoring data: SKB R-08-73 /Werner et al. 2008/.
- Numerical modelling of surface water and groundwater flow: SKB R-08-72 /Bosson et al. 2008b/.

As indicated above, also data and models from other modelling disciplines are used in the work presented herein. In addition to the hydrogeological background reports to SDM-Site Laxemar referred to above, results from backgrounds reports from other surface system disciplines are referred to in the present report /Nyman et al. 2008, Sohlenius and Hedenström 2008, Strömgren and Brydsten 2008, Tröjbom et al. 2008/.

2 Presentation of site investigations and available data

2.1 Previous investigations

The previous SDM version 0 /SKB 2002/, Simpevarp 1.1 /SKB 2004a/, Simpevarp 1.2 /SKB 2005b, Lindborg 2005 (ed.), Werner et al. 2005/ and Laxemar 1.2 /SKB 2006a, Lindborg (ed.) 2006, Werner et al. 2006/ are for simplicity in the following referred to as S0, S1.1, S1.2 and L1.2, respectively. For the dates of the associated data freezes, see Section 1.1. The present site descriptive model is referred to as SDM-Site Laxemar.

S0 was developed before the beginning of the site investigations in the Laxemar-Simpevarp area. It was therefore mainly based on information from the pre site-investigation (feasibility) study /SKB 2000/, selected sources of pre-existing data, and additional data collected and compiled during the preparatory work for the site investigations, especially related to the discipline "Surface ecosystems". S0 was regional in character, as local data were scarce in the official databases. The data inventory established in the S0 modelling work also served as a platform for prioritising analyses for the subsequent S1.1 modelling.

The investigations that provided the basis for the S1.1 model version in terms of meteorology, surface hydrology, and near-surface hydrogeology included airborne photography, airborne and surface geophysical investigations, and mapping of QD. In addition, a few groundwater monitoring wells were established in the QD. The still very limited amount of site-specific data implied that also S1.1 was mostly based on regional and/or generic meteorological, hydrological and hydrogeological data.

The S1.2 and L1.2 data freezes contained site investigation (local) data from the Simpevarp and Laxemar subareas, including the following meteorological, hydrological and near-surface hydrogeological investigations:

- Establishment of local meteorological stations on the island of Äspö (S1.2) and at Plittorp (L1.2).
- Delineation and description of catchment areas, streams and lakes.
- Manual discharge measurements (mainly S1.2) and establishment of discharge-gauging stations (mainly L1.2) in streams.
- Drillings in the QD, and installations and slug tests of groundwater monitoring wells.
- Manual (S1.2) and automatic (L1.2) groundwater-level measurements in groundwater monitoring wells.

2.2 Overview of meteorological, hydrological and hydrogeological investigations in the Laxemar area

The meteorological, hydrological and near-surface hydrogeological investigations for SDM-Site Laxemar comprise the major components listed below (cf. Section 2.1).

Time-series data, including the following:

- Meteorological data from two stations (Äspö and Plittorp) and observation points for winter parameters (snow depth at one location, ice freeze/breakup at four locations, and ground frost at four locations).
- 9 surface-water discharge gauging stations in 7 streams.
- 4 surface-water level gauging stations in lakes and 3 stations in bays of the Baltic Sea. It should be noted that the water-level gauging station in the downstream end of Lake Frisksjön is also a discharge-gauging station, measuring the stream discharge from the lake.
- Groundwater-level monitoring in 62 groundwater monitoring wells, with their screens installed in the QD or across the QD/rock interface.

- 37 sections for monitoring of point water heads in percussion boreholes in rock.
- 132 sections for monitoring of point water heads in core boreholes in rock.

Near-surface hydrogeological properties data, including the following:

- Particle-size distribution curves (PSD) and permeameter test data on QD samples.
- Slug tests, single-hole tests, interference (pumping) tests, and tracer dilution tests in groundwater monitoring wells.
- Interference and tracer tests between percussion boreholes in rock and groundwater monitoring wells.

In addition to the investigations listed above, the modelling in the present report is based on data from SKB's Sicada and GIS databases concerning the following:

- Topographical and other geometrical properties.
- Surface-based geological investigations of QD and soil type mapping.
- Composition and stratigraphy data from boreholes, pits and trenches in QD.
- The hydrogeological properties of the rock.
- Chemistry of QD, groundwater and surface water.

Five types of time-series data are used in this report: (1) Meteorological data, (2) data on surface-water levels measured in lakes and bays of the Baltic Sea, (3) surface-water discharges measured in streams, (4) groundwater levels measured in groundwater monitoring wells installed in the QD, and (5) point water heads measured in percussion and core boreholes in rock. For a subset of the boreholes in rock, an attempt has also been made to transform the measured point water heads into environmental water heads /Werner et al. 2008/.

Figure 2-1 provides an overview of the data availability during the period from Jan. 1, 2003 to Dec. 31, 2007, considering data from SKB's site investigations in Laxemar. The figure shows the number of meteorological and hydrological (discharge and water level) stations, groundwater monitoring wells, and monitored borehole sections providing data each day during the considered period. "Short-term variations" in the number of available data are due to malfunction of equipments and specific tests in some wells /Werner et al. 2008/.

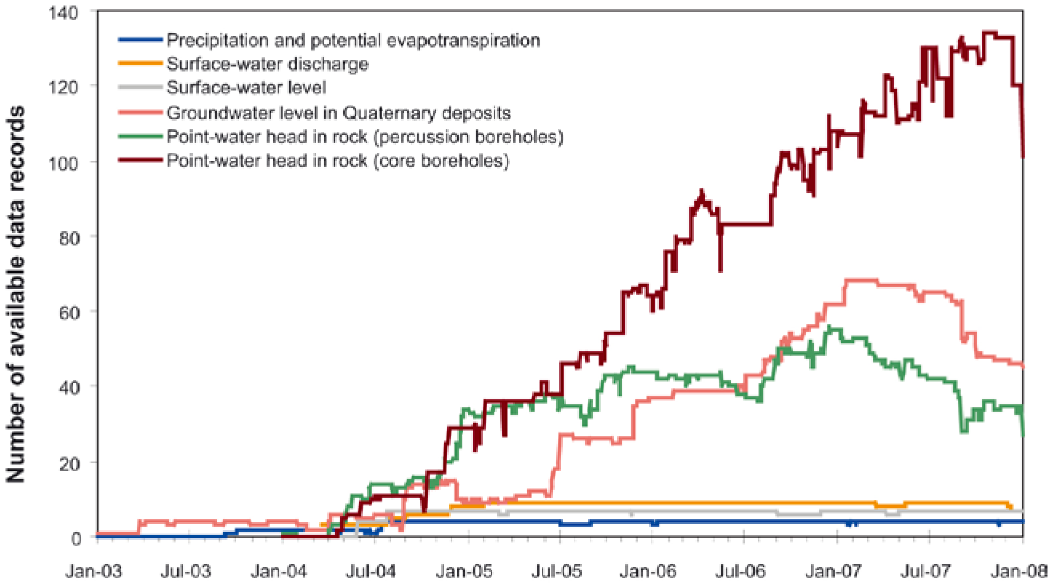

***Figure 2-1.** Time-series plot illustrating the data availability during the period 2003–2007, in terms of the number of meteorological and hydrological (discharge and water level) stations, groundwater monitoring wells, and monitored borehole sections providing data each day during the considered period.*

All time-series data presented and analysed in this report are obtained from Sicada deliveries #Sicada_07_370 (delivery date Oct. 16, 2007), #Sicada_07_386 (delivery date Oct. 19, 2007), and #Sicada_08_024 (part deliveries on Feb. 22 and Mar. 3, 2008). These data deliveries contain all of the considered time series available from the site investigations in the Laxemar area up to Dec. 31, 2007. Table 2-1 provides references to site investigation reports and other sources that present meteorological, hydrological and hydrogeological data for the SDM-Site Laxemar modelling. Table 2-2 lists the corresponding information with respect to other disciplines and types of investigations. The site investigation data are available in SKB's Sicada and GIS databases.

Table 2-1. Available meteorological, hydrological and near-surface hydrogeological data and their handling in the SDM-Site Laxemar modelling.

Available site data Data specification	Ref.	Usage in SDM-Site analysis/modelling	Cf. Section
Meteorological data			
Regional data			
Meteorological data from surrounding stations prior to and during the site investigations	/Lindell et al. 2000/, /Larsson-McCann et al. 2002/, /Lärke et al. 2005ab/, /Sjögren et al. 2007ab/, Sicada	Basis for general description and quantitative modelling of surface water and groundwater flow Comparison with local meteorological data for extension of time series	1.2 2.2.1 3.5.1 Ch. 4–5
Site Investigation data			
Meteorological data from the stations on Äspö (Sep. 2003–Aug. 2007) and in Plittorp (Jul. 2004–Aug. 2007)[1]	/Lärke et al. 2005ab/, /Sjögren et al. 2007ab/, Sicada	Basis for site-specific description of the meteorological conditions, and conceptual, descriptive and quantitative modelling of surface water and groundwater flow Comparison with regional meteorological data for extension of time series	1.2 2.2.1 3.5.1 Ch. 4–5
Winter parameters (snow depth, ground frost and ice cover)	/Lärke et al. 2005b/, /Sjögren et al. 2007ab/, Sicada	Validation of snow routine in quantitative modelling	2.2.1 3.5.1 Ch. 4–5
Hydrological data			
Regional data			
Regional discharge data prior to and during the site investigations	/Lindell et al. 2000/, /Larsson-McCann et al. 2002/, Sicada	Specific discharge in initial conceptual, descriptive and quantitative modelling	1.2 2.1
Site Investigation data			
Investigation of potential locations for hydrological stations	/Lärke and Hillgren 2003/	Size of catchment areas for manual and automatic surface-water discharge measurements	
Geometrical data on catchment areas, lakes and streams	/Brunberg et al. 2004/, SKB GIS	Delineation and characterisation of catchment areas, lakes and streams Input to quantitative water flow modelling	1.2 2.2.2 3.3.1–3 Ch. 4–5
Monitoring of surface-water discharges in streams	/Ericsson and Engdahl 2004ab, 2005/, /Morosini and Lindell 2004/, /Lärke et al. 2005ab/, /Sjögren et al. 2007ab/, Sicada	Data for site-specific description and water balance, conceptual and descriptive modeling, and for calibration of quantitative water flow models	1.2 2.2.2 3.3.3 3.5.2–3 Ch. 4–5
Monitoring of surface-water levels in lakes and the sea	/Lärke et al. 2005ab/; /Sjögren et al. 2007ab/, Sicada	Surface water-groundwater level relations, conceptual and descriptive modelling, and calibration of quantitative water flow models	1.2 2.2.2 3.3.2 3.3.5 3.5.3 Ch. 4–5

Available site data Data specification	Ref.	Usage in SDM-Site analysis/modelling	Cf. Section
Field checks of streams and land improvement and drainage operations	/Svensson 2005/, /Bosson and Berglund 2005/	Delineation and characterisation of streams	1.2 2.2.2 3.3.1–3 Ch. 4–5
Oceanographical data			
Regional oceanographical data	/Larsson-Mc Cann et al. 2002/, /Lindell et al. 2000/	Characterisation and quantitative water-exchange modelling of coastal basins	3.3.5
Hydrogeological data			
Hydrogeological inventory in the Oskarshamn area, inventory of private wells	/Nyborg et al. 2004/, /Morosini and Hultgren 2003/	General description of hydrogeology, water handling and land improvement and drainage operations	2.2.4
Monitoring of groundwater levels in the QD and the rock	/Nyberg et al. 2005/, /Nyberg and Wass 2005, 2007, 2008/	Conceptual and descriptive modelling, calibration of quantitative models	1.2 2.2.3 3.4–5 Ch. 4–5
Hydraulic conductivity of QD	/Bergman et al. 2005/, /Johansson and Adestam 2004cd/, /Johansson and Göransson 2006/, /Johansson et al. 2007/, /Morosini et al. 2007b/, /Nilsson 2004/, Rudmark et al. 2005/, Sohlenius et al. 2006a/, /Svensson and Zetterlund 2006/	Basis for assigning hydraulic conductivity of QD in conceptual and quantitative models	1.2 2.2.3 3.4–5 Ch. 4–5
Hydraulic conductivity and storage-properties data from single-hole and interference tests in groundwater monitoring wells	/Gokall-Norman and Ludvigson 2007/	Conceptual and descriptive modelling, calibration of quantitative models	1.2 2.2.3 3.4–5 Ch. 4–5
Hydraulic interference and tracer tests in percussion boreholes and groundwater monitoring wells	/Morosini and Wass 2007/, /Morosini et al. 2007a/, /Svensson et al. 2008/	Conceptual and descriptive modelling	1.2 2.2.3 3.4–5 Ch. 4–5
Groundwater flow velocities from tracer dilution tests in groundwater monitoring wells	/Askling 2007/	Conceptual and descriptive modelling	1.2 2.2.3 3.4–5 Ch. 4–5

[1] Data up to Dec. 31, 2007 are used in the site descriptive modelling.

Table 2-2. Input data from other disciplines and their handling in the SDM-Site Laxemar modelling.

Available site data, data specification	Ref.	Usage in SDM-Site analysis/modelling	Cf. section
Geometrical and topographical data			
Digital Elevation Model (DEM), geometrical model of depth and stratigraphy of regolith, surveying of streams	/Brydsten 2004/, /Brydsten and Strömgren 2005, 2008/, /Nyman 2005/, /Nyman et al. 2008/, Strömgren et al. 2006/, SKB GIS	Conceptual, descriptive, and quantitative modelling	1.2 Ch. 3–5
Surface-based geological data			
Soil-type map	/Lundin et al. 2004, 2005/, SKB GIS	General description of QD	1.2 3.4.2
QD map	/Rudmark 2004/, /Ingvarsson et al. 2004/, /Elhammer and Sandkvist 2005/, /Bergman et al. 2005/, /Rudmark et al. 2005/, /Sohlenius and Hedenström 2008/, /Bergman and Sohlenius 2007/, SKB GIS	Basis for the conceptual hydrogeological model of QD and quantitative modelling	1.2 Ch. 3–5
Ground-based and airborne geophysical investigations	/Lindqvist 2004abc, 2005, 2006/, /Thunehed and Triumf 2005, 2006/, /Thunehed and Pitkänen 2003/, /Triumf et al. 2003/, /Thunehed 2006/	Conceptual, descriptive, and quantitative modelling	1.2 Ch. 3–5
Investigation of lake sediments, peat lands and wetlands	/Nilsson 2004/, /Sohlenius et al. 2006b/	Characterisation of QD at bottom of lakes, wetlands, and peat areas	1.2 2.2.3 3.2–3 Ch. 4–5
Characterisation of streams, including vegetation, bottom substrate and technical encroachments	/Carlsson et al. 2005/	Characterisation of surface water-groundwater interaction	1.2 3.3 3.5.3 Ch. 4–5
Geological data from boreholes and pits			
Stratigraphical data of QD	/Ask 2003, 2004/, /Ask et al. 2005/, /Johansson and Adestam 2004ab/, /Sohlenius etal.2006a/,/Johansson et al. 2007/, /Morosini et al. 2007b/, /Bergman et al. 2005/	Basis for the conceptual hydrogeological model of QD and for quantitative modeling	1.2 3.4–5 Ch. 4–5
Hydrogeological properties of the rock	/Rhén et al. 2008, 2009/	Conceptual, descriptive, and quantitative modelling	3.4–5 Ch. 4–5
Groundwater levels in the rock	Sicada	Conceptual, descriptive, and quantitative modelling	3.4–5 Ch. 4–5
Vegetation data			
Vegetation map	/Boresjö Bronge and Wester 2003/, /Andersson 2004/, /Löfgren (ed.) 2008/, SKB GIS	Conceptual, descriptive, and quantitative modelling	1.2 3.2.4 3.3.1 Ch. 4–5

Available site data, data specification	Ref.	Usage in SDM-Site analysis/modelling	Cf. section
Water chemistry data			
Chemical data from surface water and shallow groundwater	/Ericsson and Engdahl 2006; 2007/, /SKB 2004b; 2006b/, /Tröjbom and Söderbäck 2006, 2008/, /Laaksoharju and Gurban 2007/	Interpretation of water flow systems	3.2.6 3.5.4

2.2.1 Meteorological data

Figure 2-2 shows the locations of SKB's two meteorological stations in the Laxemar area, as well as the SMHI stations from which data were obtained and used in this study. The enlarged view in Figure 2-3 shows a detailed map of the SKB meteorological and winter stations; the latter were used for observation of snow depth, ground frost and ice freeze/breakup.

At the SKB (Äspö and Plittorp) stations, meteorological data are stored every half hour. Precipitation (P) is stored in form of the accumulated precipitation during 30 minutes, whereas air temperature, global radiation, air pressure, and relative humidity data are stored as 30-minutes (arithmetic) averages of one-second readings. Specifically, wind speed and wind direction data are stored as the latest 10-minutes (arithmetic) average for the current half hour; e.g. for the 10.00 AM data, the stored data is the 10-minutes average for the period 09.51–10.00 AM.

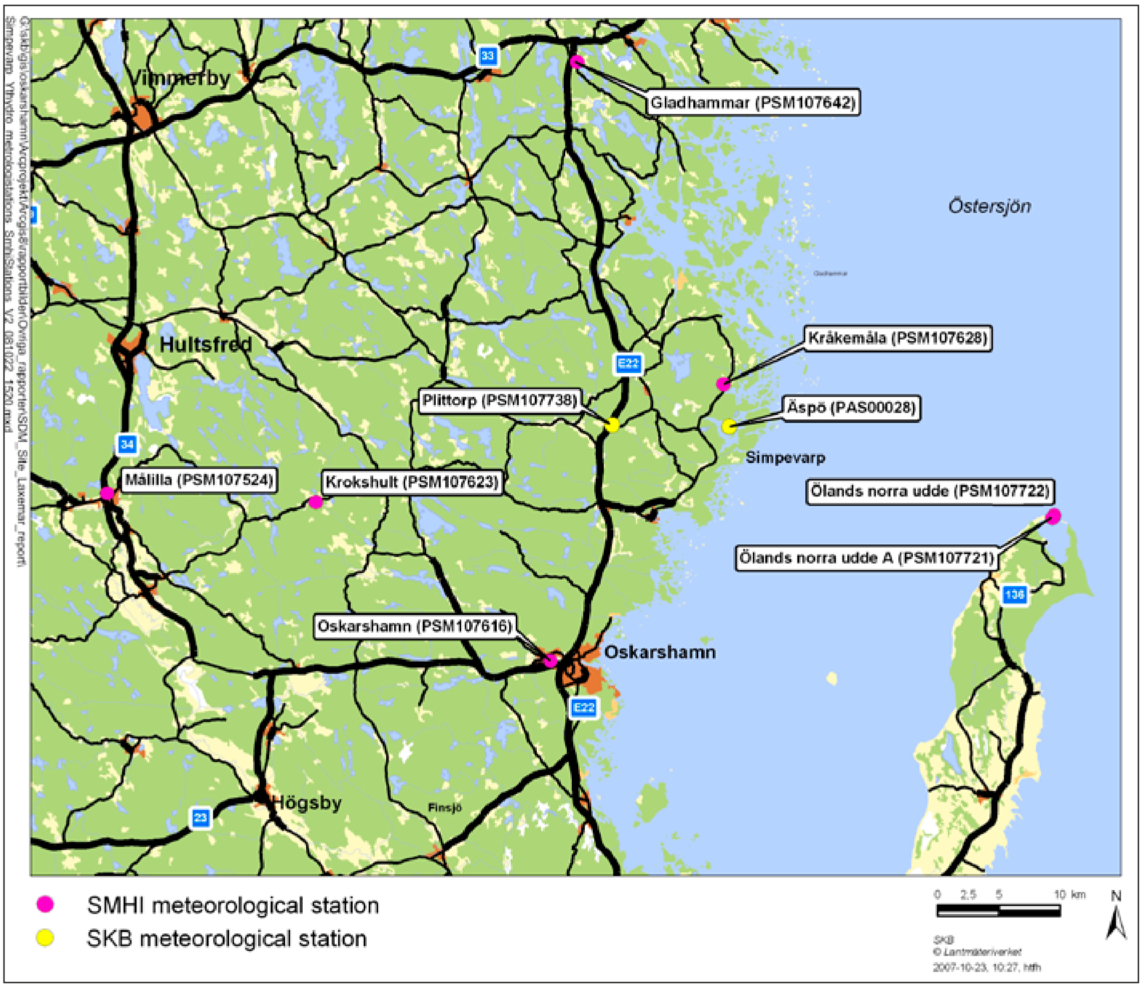

Figure 2-2. Overview map of the local SKB meteorological stations and the closest SMHI stations.

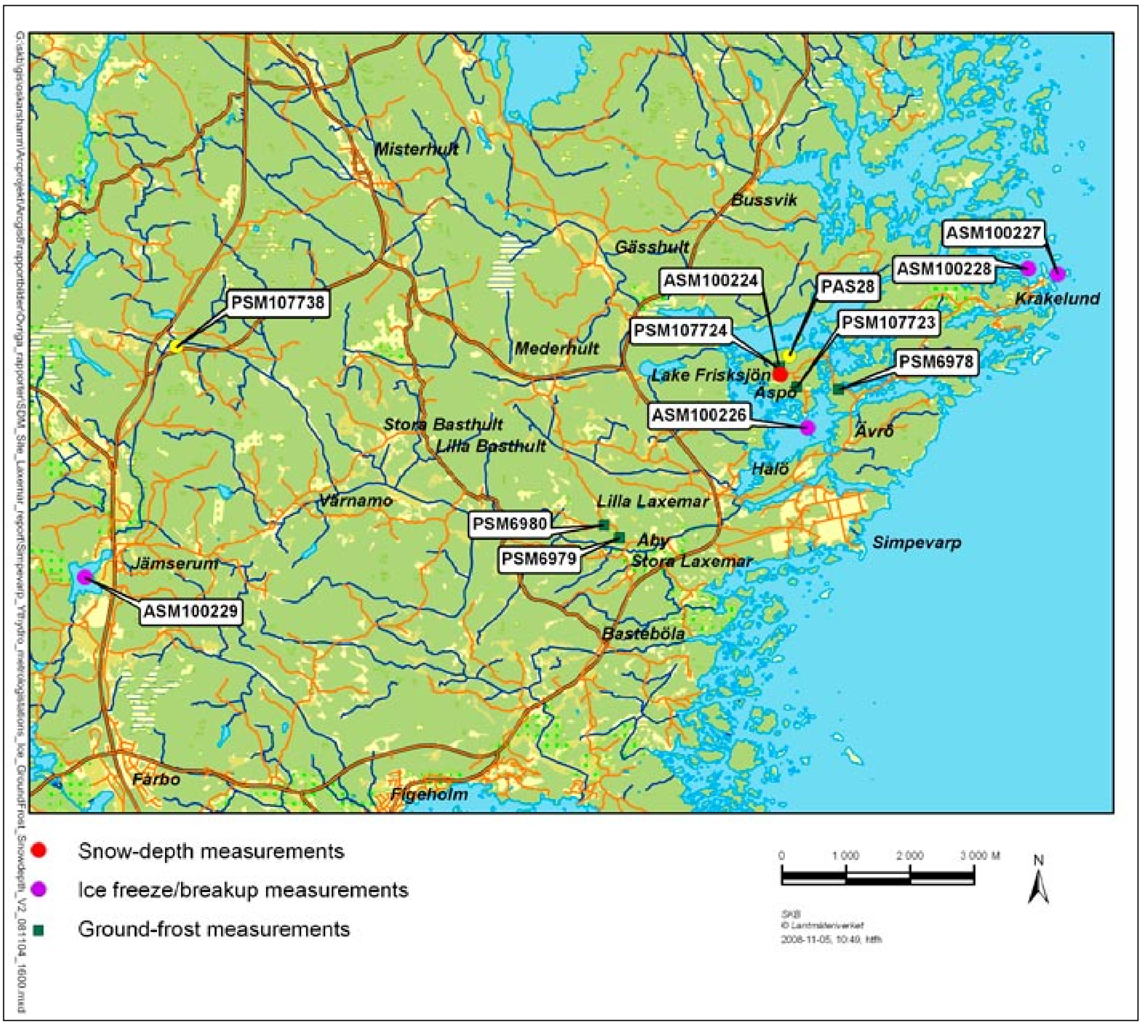

Figure 2-3. Detailed map of the local SKB meteorological stations (yellow symbols; cf. Figure 2-2) and winter stations (snow depth, ground frost and ice freeze/breakup). Note that the ID number of some stations is abbreviated by removing the initial zeros. For instance, station PAS000028 on Äspö is denoted PAS28.

Concerning the SMHI data available in the Sicada data base, the temporal resolution of the data differs between parameters and data periods. In addition to the monitoring at the two SKB meteorological stations, a set of meteorological winter parameters (snow depth, ground frost penetration depth and ice freeze/breakup) have been measured and observed. These measurements/observations started during the winter season 2002/2003, and data are available up to the winter season 2006/2007. The locations of the monitoring points are shown in Figure 2-3.

2.2.2 Hydrological data

In Laxemar, surface-water level monitoring was in May and August, 2004, respectively, initiated in four lakes (Lake Jämsen, Plittorpsgöl, Friskjön and Sörå), as well as in three bays of the Baltic Sea. Figure 2-4 shows the locations of the level-gauging stations. Water-level data are stored every full hour.

Stream discharges, surface-water temperatures and electrical conductivity have been monitored at 9 discharge-gauging stations in 7 streams: Vadvikebäcken, Gloebäcken and Skölkebäcken on the island of Ävrö (measurements initiated in April 2004), Kåreviksån up- and downstream from Lake Frisksjön (initiated in July and November 2004), 2 locations in Laxemarån (initiated in September and November 2004), Ekerumsån (initiated in February 2005) and Kärrviksån (measurements initiated in July 2004). The locations of the gauging stations are shown in Figure 2-5. Discharge data are stored every full hour. Note that station PSM000348 is located at the outlet from Lake Frisksjön,

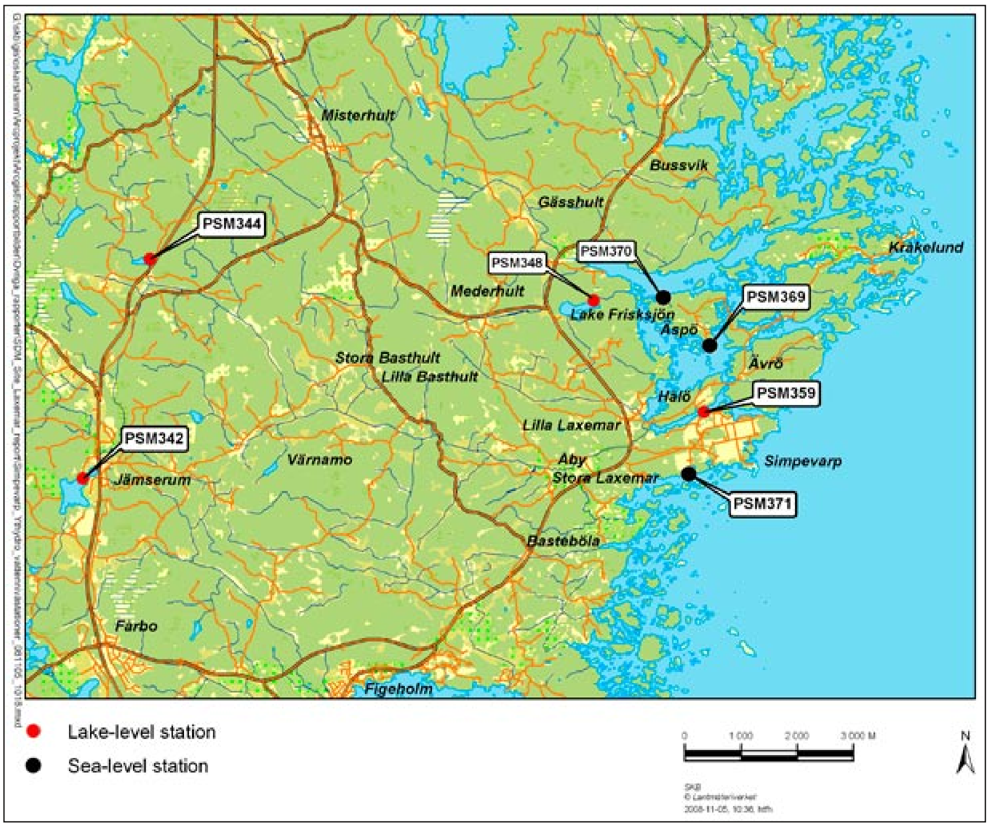

Figure 2-4. Overview map showing the locations of surface-water level gauges in the Laxemar area. Note that the ID numbers of the stations are abbreviated by removing the initial zeros. For instance, station PSM000342 in Lake Jämsen is denoted PSM342.

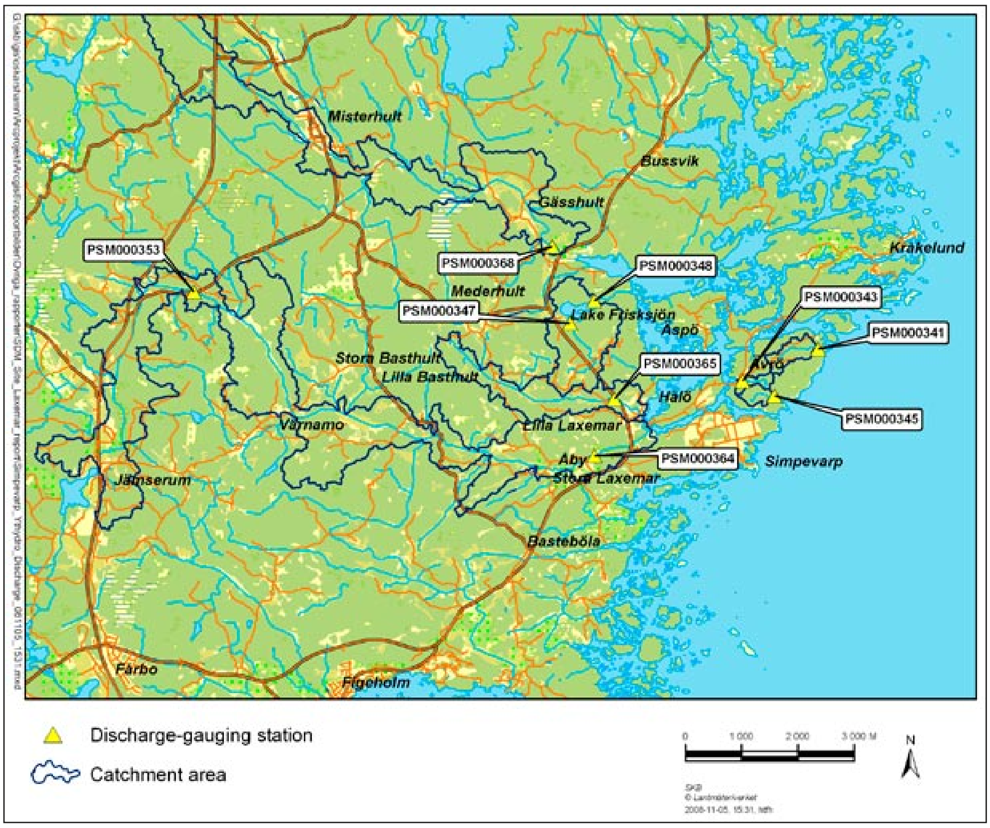

Figure 2-5. Overview map of discharge-gauging stations and their associated catchment areas, as determined from the DEM.

and therefore also measures the water-level of the lake. Five of the stations are designed as V-notch weirs, whereas the other four are so called natural critical sections. The latter group includes station PSM000364 in Laxemarån, which is designed as a composite rectangular weir; this station is treated as a natural section when calculating the stream discharge.

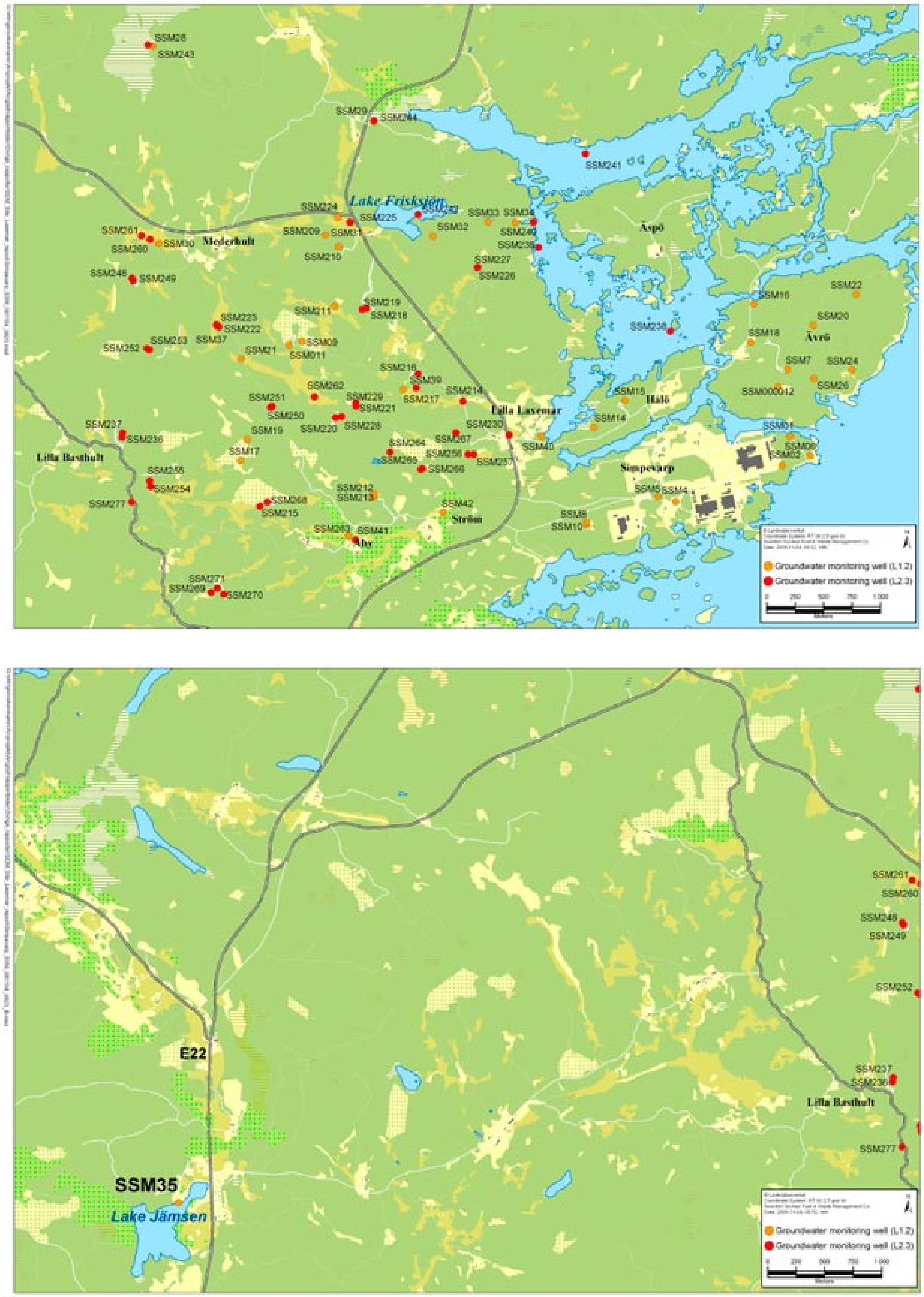

Figure 2-6. Overview maps showing the locations of groundwater monitoring wells in QD. Groundwater monitoring well SSM000035 (bottom map) is installed at the shore of Lake Jämsen, west of the area shown in the upper map. Note that the ID numbers of the wells are abbreviated in the map by removing the initial zeros. For instance, well SSM000035 at Lake Jämsen is denoted SSM35.

2.2.3 Hydrogeological data

This section summarises the hydrogeological monitoring data available in the Laxemar 2.3 data set. Hydrogeological properties data are summarised in Section 3.4. During the period 2002–2007, totally 92 groundwater monitoring wells have been installed as part of the site investigations in Laxemar-Simpevarp (see Figure 2-6), of which data are available from totally 76 wells. Groundwater levels have been monitored in up to 68 wells at the same time (during the period January–March, 2007). 62 wells were monitored at the time of DF L2.3 (August 31, 2007) and 45 wells on Dec. 31, 2007.

The available data periods are illustrated in Figure 2-7, which for each well also shows data days that were removed as a result of screening of disturbed groundwater-level data (see /Werner et al. 2008/). On

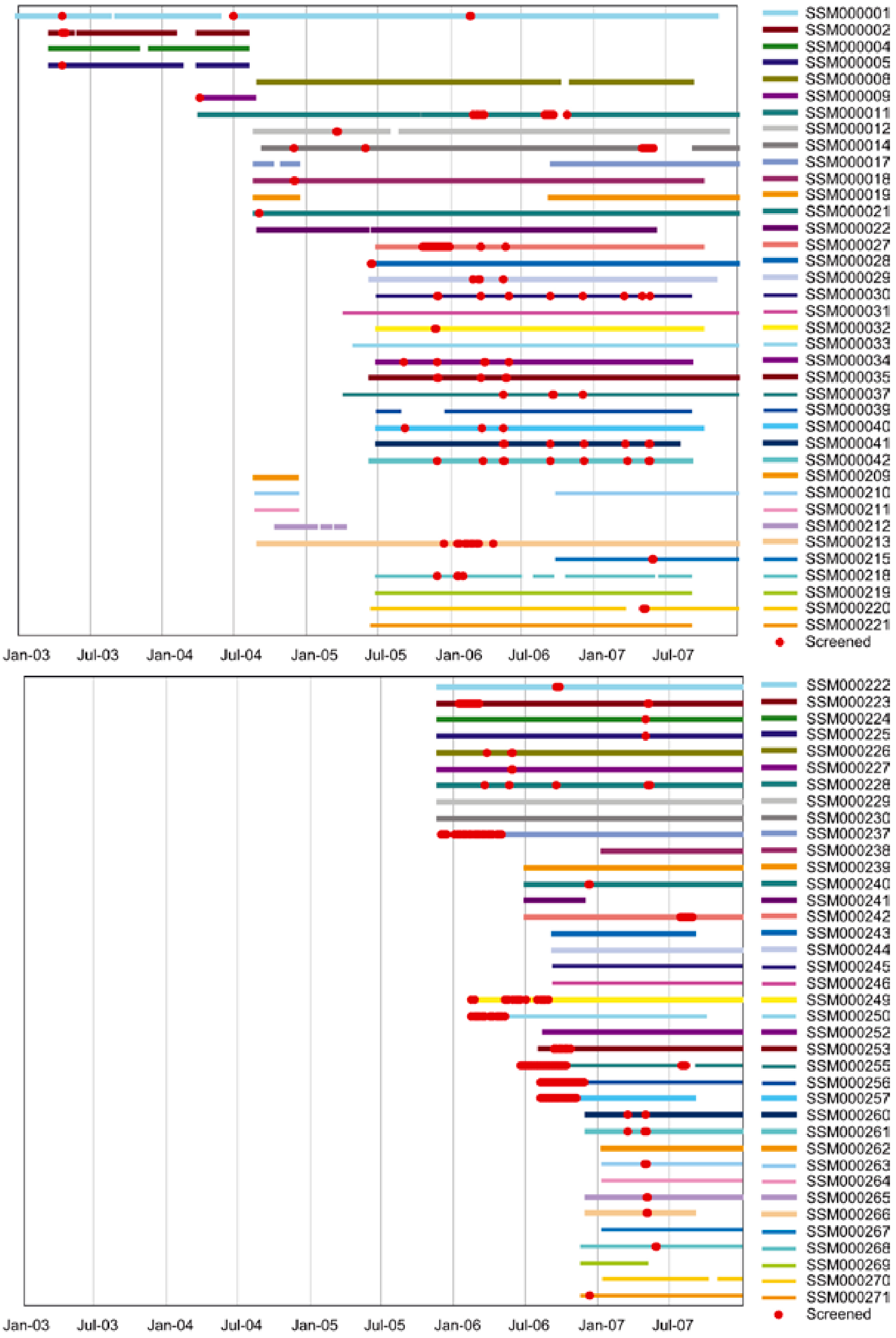

***Figure 2-7.** Overview of available groundwater-level time series from groundwater monitoring wells. Red dots indicate screened data days, i.e. days for which data are removed.*

average, 11 data days per well were removed as a result of the data screening. No data days were removed for 29 wells, whereas the maximum number of removed data days was 127 (well SSM000255). It should be noted that no detailed screening was performed for the post-data freeze period (i.e. after August 31, 2007). This implies that data for the period September 1–December 31, 2007 are kept intact. The risk of disturbed groundwater levels is assumed to be small after the data freeze, due to fewer activities at the site. As can be seen in Figure 2-7, the data periods for many wells are interrupted by periods of missing data. In most cases, this is due to instrument problems (Lars Andersson, SKB, pers. comm. 2007).

In the present context, joint evaluations of groundwater levels in the QD and point water heads and environmental water heads in the rock are used for interpretation of interactions between groundwater in the QD and groundwater in rock /Werner et al. 2008/. For more information on rock hydrogeology in Laxemar, the reader is referred to /Rhén et al. 2008, 2009/. The site investigations in Laxemar include point water head data from 44 percussion boreholes (comprising 77 borehole sections) and 37 core boreholes (comprising 180 borehole sections). As of Aug. 31, 2007, point water heads in rock were monitored in 37 percussion borehole sections and 132 core borehole sections; as of Dec. 31, 2007, the corresponding numbers were 35 and 120. Figure 2-8 shows the locations of the boreholes.

Figure 2-9 and 2-10 give an overview of the available point water head time series, divided into percussion boreholes (Figure 2-9) and core boreholes (Figure 2-10). As indicated in these figures, most boreholes are divided into sections by means of packers. These sections are numbered from the borehole bottom and upwards. For instance, HAV06.1 and HAV06.2 denote the lower and upper section, respectively, in percussion borehole HAV06. Note that open boreholes without packers (e.g. HLX02) contain a single section, denoted by the extension .1 (e.g. HLX02.1). For each borehole section in Figures 2-9 and 2-10, the red dots show data days that were removed during the data screening. Note that that for the core boreholes, Figure 2-10 only includes the upper sections, due to the large total number of borehole sections.

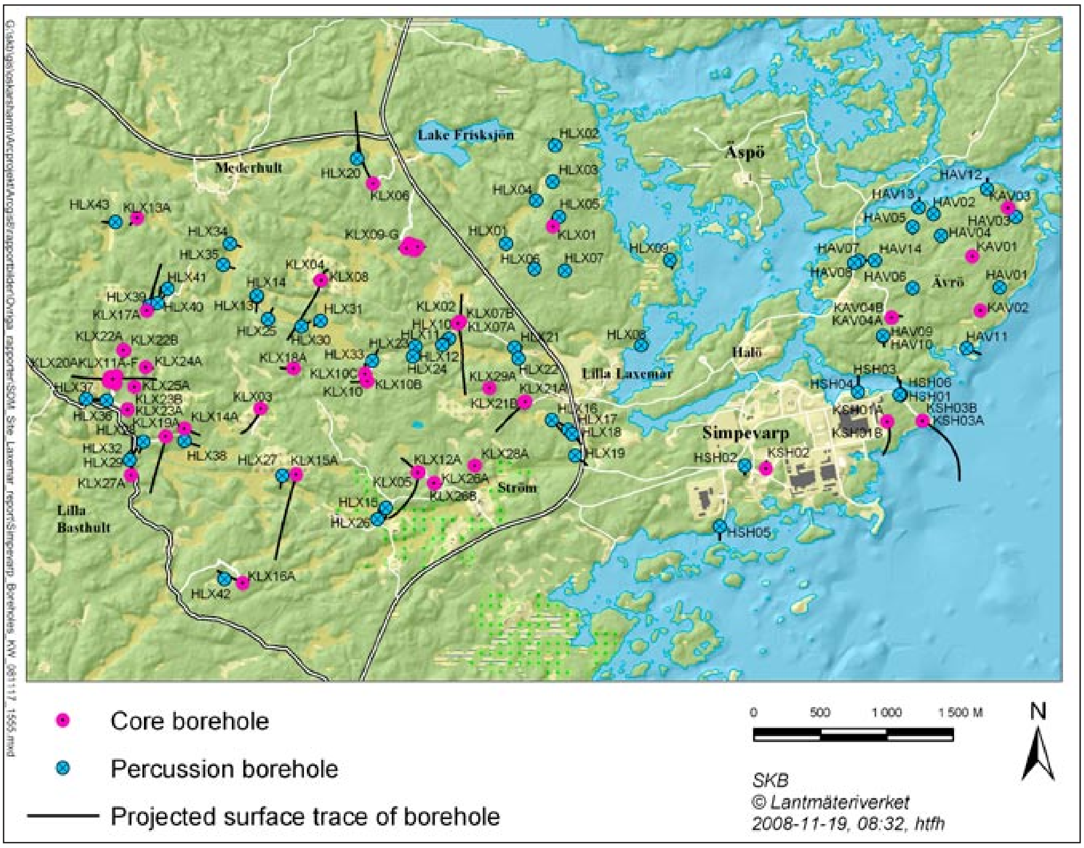

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Figure 2-8. Overview map showing the locations of percussion and core boreholes in Laxemar, among which point water head data are available from 44 percussion boreholes and 37 core boreholes in the Laxemar 2.3 data set.

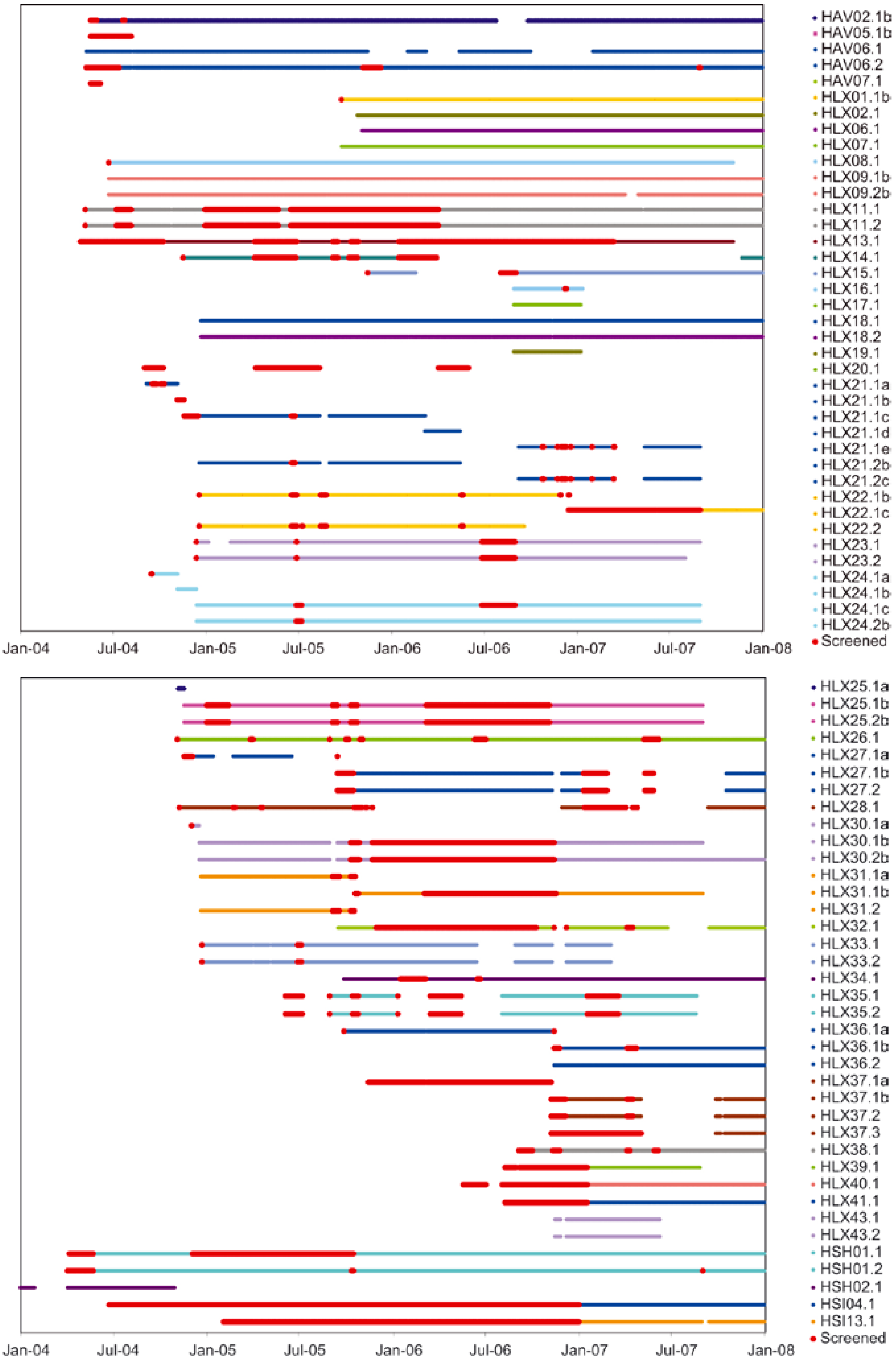


Figure 2-9. *Overview of available point water head time series from percussion boreholes. Red dots indicate screened data days, i.e. days for which data are removed.*

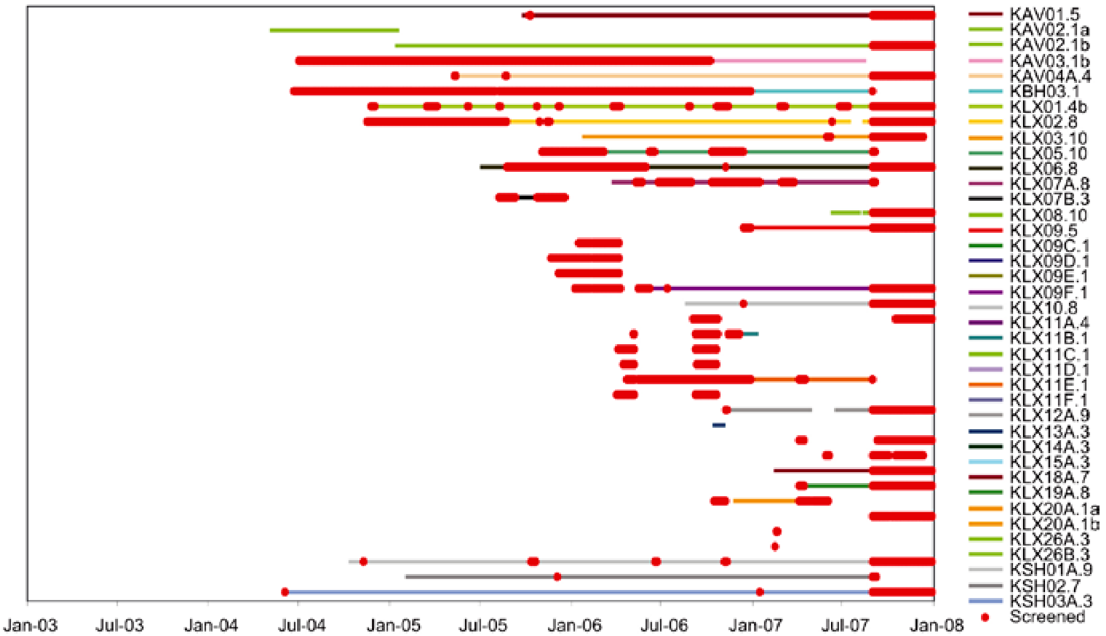


Figure 2-10. *Overview of available point water head time series from core boreholes. Red dots indicate screened data days, i.e. days for which data are removed. Note that only the upper borehole sections are included in the figure, and that all post-data freeze data (i.e. Sep. 1, 2007 and onwards) are screened, since no actual detailed screening analysis was performed for the period Sep. 1–Dec. 31.*

On average, 170 data days per percussion borehole/borehole section were removed during the screening, varying between 0 days in 8 borehole sections and a maximum of 1,043 data days for HSI04. For the core boreholes, the corresponding numbers are 158 data days (average), 0 data days (minimum; 4 borehole sections), and 1,172 data days (maximum; the whole point water head data set was removed for KSH01A.1). It should again be noted that for the percussion boreholes, no detailed screening was performed for the post-data freeze period (i.e. after Aug. 31, 2007). This implies that data for the period Sep. 1–Dec. 31, 2007 are kept intact. The risk of disturbed groundwater levels is assumed to be small after the data freeze, due to fewer activities at the site. For the core boreholes, all data were screened (i.e. removed) for the period Sep. 1–Dec. 31, 2007 (see Figure 2-10).

2.2.4 Water handling not associated to the site investigations

Activities involving artificial water handling (pumping, drainage, "forced" discharge and recharge, and so forth) are relevant for the overall understanding of the water system in the region where Laxemar is located. In particular, SKB, and also OKG (owner and operator of the nuclear power plant on the Simpevarp peninsula) represent most of the water-handling activities in the Laxemar area. Therefore, this section summarises some previous and present water-handling activities in the Laxemar area and its surroundings, including a brief summary of some relevant information and data from the associated investigations. Note that land improvement and drainage operations are summarised in the section on streams and other surface-drainage systems (Section 3.3.3).

Private wells

/Morosini and Hultgren 2003/ describe private wells in the Laxemar-Simpevarp regional model area. They identified more than 200 such wells within the regional model area, and checked most of them in the field. For further details, see /Morosini and Hultgren 2003, Werner et al. 2005, 2006/.

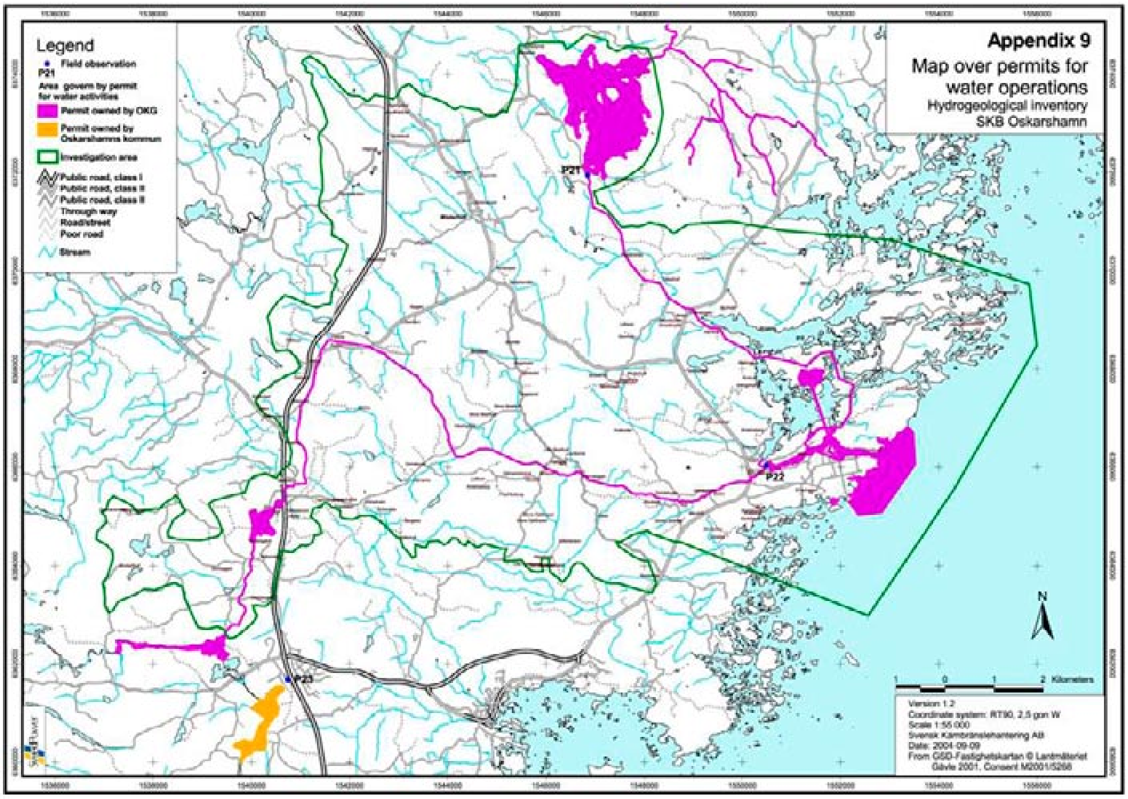


Figure 2-11. *Overview map of water-supply operations in and around the Laxemar area /Nyborg et al. 2004/. The orange area indicates the location of the Fårbo water supply. The lilac areas indicate water-supply operations by OKG and Figeholms Bruk (see sections below).*

The Fårbo public water supply

The Fårbo public water supply (see Figure 2-11) is located to the Tuna esker, providing water to the communities of Fårbo and Figeholm. The groundwater yield of the Tuna esker is considered to be good /Pousette et al. 1981/. Concerning the Fårbo water supply, a water-operations permit was given on Jul. 5, 1954 (case AD 41/1953) to pump groundwater (100,000 $m^3 \cdot y^{-1}$, or a maximum of 400 $m^3 \cdot d^{-1}$ or c 5 $L \cdot s^{-1}$) from the Tuna esker in an area immediately north of Lake Fårbosjön.

In order to satisfy the increasing water demand, a permit was given on Apr. 26, 1968 (case AD 29/1966, permit A 26/1968) to pump and infiltrate up to 310,000 $m^3 \cdot y^{-1}$ or a maximum of 1,700 $m^3 \cdot d^{-1}$) from Lake Fårbosjön, and to increase the groundwater discharge at the Fårbo water supply to 410,000 $m^3 \cdot y^{-1}$, or a maximum of 1,700 $m^3 \cdot d^{-1}$. The County Administrative Board of Kalmar (Länsstyrelsen i Kalmar Län) decided upon a water protection area for the water supply on Jun. 16, 1971 (dnr II G-16-67, now invalidated) and later on Oct. 17, 2003 (08FS 2003:73). The first water-supply well at Fårbo was installed in 1954 (it was replaced in 1966), whereas a second well was installed in 1979.

During the period 1995–1999, on average 600 $m^3 \cdot d^{-1}$ was pumped from the two wells /VBB VIAK 2001/. Starting in 1994, an increased chloride concentration was observed in the pumped water, increasing from normally 25–40 $mg \cdot L^{-1}$ to 60–80 $mg \cdot L^{-1}$ /VBB VIAK 1994, 1995/. Based on the subsequent investigations, it was concluded that the cause of the increasing chloride concentration likely was salt de-icing of the nearby highway E22. This finding led to some protective measures at the site.

According to /VBB VIAK 2001/, the Tuna esker is approximately 20 m deep in its central parts, whereas the depth is a few metres along the edges. The QD of the esker consist of glaciofluvial deposits (sand and gravel), whereas no fine-grained QD have been found /VBB VIAK 2001/. The regional-scale flow along the esker is found to be from north to south, with groundwater divides north and south of Fårbo. Along its edges, the esker is drained towards Lake Fårbosjön and the wetland Stora Ficksjön. It can be noted that in connection to the detailed QD mapping, a spring with a yield of about 1 L·s^{-1} was observed at the foot of the esker, c 5 km north of the Fårbo village /Rudmark et al. 2005/. /VBB VIAK 2001/ summarises the results of groundwater-level measurements in a number of groundwater monitoring wells in the central part of esker. Groundwater levels were c 25 m.a.s.l. or 5–14 m below the ground surface. In this context, it can also be noted that there is a gravel pit located to the Tuna esker.

SKB's water operations

SKB's water operations can be summarised as follows:

- The Clab facility (central interim storage facility for spent nuclear fuel; see Figure 2-12) is located in the vicinity of the nuclear power plant on the Simpevarp peninsula. Clab was ready for operation in 1985. In Clab, Sweden's spent nuclear fuel is stored in pools, placed in rock caverns. A water-operations permit, associated with an extension of Clab, was given on Sep. 8, 1998 (case VA 62/97). There is a monitoring programme associated to the Clab water-operations permit, involving e.g. monitoring of groundwater levels in boreholes and private wells.
- Äspö HRL (Hard Rock Laboratory; see Figure 2-12) is SKB's underground laboratory, located below the island of Äspö. Among other activities, the laboratory is used to test different techniques and methods for the construction and operation of a geological repository for spent nuclear fuel. According to the water-operations permit from Sep. 11, 1990 (case VA 5/1989, permit DVA 42/1990), the groundwater inflow to the underground facility was projected to be

Figure 2-12. Overview map showing the locations of the water-handling activities summarised in this section.

c 25 $L \cdot s^{-1}$. The pumped groundwater is discharged to the bay Hamnefjärden at the cooling-water outlet from the O-I and O-II reactors at Simpevarp. The inflow of groundwater to the Äspö HRL has decreased since 1994, and is currently less than 20 $L \cdot s^{-1}$ /Hartley et al. 2007/. There is a monitoring programme associated to the Äspö HRL water-operations permit, involving e.g. monitoring of groundwater levels and groundwater chemistry in boreholes and private wells.

- Percussion borehole HLX22 (see Figure 2-12) is used as a water-supply well for 14 households in the village of Lilla Laxemar. The water-operations permit of Aug. 8, 2003 (case M 1132-06) states that a maximum of 7,300 $m^3 \cdot y^{-1}$ (or a maximum of 20.8 $L \cdot min^{-1}$) may be pumped from the borehole, whereas the current (since Jan. 2007) pumping rate is approximately 3.3 $m^3 \cdot d^{-1}$ or 1,200 $m^3 \cdot y^{-1}$ /Ask et al. 2007/. This well is planned to be replaced by a surface-water supply (likely Lake Götemar) in the case Laxemar is chosen as site for the geological repository.

Water operations associated to the nuclear power plant (OKG) and the factory at Figeholms Bruk

This section summarises previous and present pumping of drinking-, process- and cooling water at the nuclear power plant, operated by OKG (Kenneth Gustafsson, OKG, pers. comm. 2005). Up to 1983 (in fact, minor pumping took place up to 1987), water was pumped from Lake Trästen (situated west of the Laxemar subarea, upstream of Lake Fårbosjön) into Lake Jämsen, which discharges to the north into the stream Laxemarån (see Figure 2-12). Drinking- and process water for OKG was during this period pumped from Ström at Laxemarån to Lake Sörå. The purpose of the pumping from Lake Trästen to Lake Jämsen was to compensate for the pumping from Laxemarån.

Since 1983, drinking- and process water for OKG is pumped from Lake Götemar (situated north of the Laxemar subarea; see Figure 2-12) in a pipeline to a water supply plant operated by OKG. At present, approximately 150,000–200,000 m^3 of water is pumped each year. Lake Sörå (see Figure 2-12) is used as reserve water supply for drinking- and process water for OKG. Occasionally, on the order of a few days each year or every second year, water is pumped from Laxemarån to Lake Sörå, in order to maintain the available water storage in the lake.

The following description summarises the historical development of the water supplies to OKG (and Figeholms Bruk; see below). In order to arrange a water-supply to the nuclear power plant planned at that time, the company Atomkraftverk AB was in a water-operations permit dated Aug. 21, 1964 (case D 41/1963, permit A 46/1964) allowed to construct a surface-water reservoir by embankment of the sea bay Söråviken. Moreover, according to the permit it was allowed to pump up to 20 $L \cdot s^{-1}$ from the stream Laxemarån, in the vicinity of its outlet into the bay Söråviken, whereas the maximum allowed pumping from Söråviken (hence being transformed to the Lake Sörå storage pond) was set to 50,000 $m^3 \cdot y^{-1}$.

In a water operations permit (partial verdict) dated Dec. 8, 1971 (case AD 42/1970, permit A 68/1971), the maximum allowed pumping from Laxemarån to the Sörå pond was increased to 70 $L \cdot s^{-1}$. The underlying reason for this was an increased water demand associated to the operation of the second nuclear reactor at Simpevarp (O-II). The pumping and subsequent cooling-water discharge were regulated in case AD 10/1969 (permit A 64/1969) dated Dec. 3, 1969, according to which OKG obtained a permit to pump 55 $m^3 \cdot s^{-1}$ of cooling water to the O-I and O-II reactors. The Dec. 8, 1971 permit did not set any limit of the pumping from the Sörå pond. Moreover, permit was given to pump up to 50 $L \cdot s^{-1}$ from Lake Trästen to Lake Jämsen. According to a previous partial verdict from May 13, 1966 (case AD 51/1965, among other things concerning pumping of 25 $m^3 \cdot s^{-1}$ of cooling water to the O-I reactor at Simpevarp), the maximum pumping from Laxemarån was set to 30 $L \cdot s^{-1}$. Moreover, the maximum allowed pumping from the Sörå pond was set to 150,000 $m^3 \cdot y^{-1}$.

According to the above-mentioned permit A 68/1971, the stream discharge in Laxemarån was to be monitored at Åbyberg (located upstream from Ström; see Figure 2-12); pumping from Lake Trästen to Lake Jämsen was not to be allowed if the stream discharge was above 0.25 $m^3 \cdot s^{-1}$ at Åbyberg. Moreover, the discharge in the stream Virån was to be monitored at Sulegångekvarn, located upstream from Lake Trästen (see Figure 2-12). Such monitoring was also to be performed in Virån between Lake Trästen and the downstream Lake Fårbosjön (at Fårbokvarn; see Figure 2-12), in particular if the stream discharge was less than 0.3 $m^3 \cdot s^{-1}$ at Sulegångekvarn. Moreover, the discharge in Virån (Kvarnbacken, downstream from Lake Hummeln; see Figure 2-12) as well as the lake-water level in Lake Trästen were also to be monitored.

In a supplementary application dated May 4, 1972, the OKG company applied for an unrestricted permit to pump water from Laxemarån at Ström (c 1.4 km upstream from the outlet to the sea, and 1.2 km upstream from the at that time operated pumping station) to the Sörå pond. The pumping station was moved to Ström due to the risk for salt-water intrusion into Laxemarån during periods with high sea-water levels, and the associated costs for water treatment at the nuclear power plant. A permit to move the pumping station was given on Sep. 15, 1972 (case AD 42/1970, permit DVA 70/1972). The permit did not change the pumping allowed from Laxemarån to the Sörå pond (70 $L \cdot s^{-1}$). However, the allowed pumping was increased to 120 $L \cdot s^{-1}$ in a later verdict (May, 10, 1974; case AD 42/1970, permit DVA 35/1974).

In a water-operations permit dated Sep. 19, 1973 (case AD 42/1970, permit DVA 15/1973), OKG was required to restore the original stretch of the stream Laxemarån between Ström and the Sörå pond. The reason was that Laxemarån had changed its stretch to a new one, along the trench for the pipe that led water from the stream to the Sörå pond.

In a mutual case (AD 42/1970, permit DVA 19/1976) the factory at Figeholms Bruk and OKG on May 31, 1976 obtained permits to pump water from Lake Trästen to the stream Sörån (30 $L \cdot s^{-1}$) and also to use Sörån as a water supply by pumping 20 $L \cdot s^{-1}$ (AB Figeholms Bruk). Moreover, OKG obtained a permit (the previous permit was temporary) to pump 50 $L \cdot s^{-1}$ from Lake Trästen to Lake Jämsen. The permit regulates the maximum and minimum lake-water levels in Lake Trästen, as well as monitoring and record-keeping of pumping, water levels and discharges at Sulegångekvarn and Fårbokvarn (Sörån, Lake Trästen and Virån), Kvarnbacken (Virån downstream Lake Hummeln) and Ström (Laxemarån); see overview map in Figure 2-12.

Verdicts dated May 10, 1974 and May 31, 1976 regulated water sampling in private wells along Laxemarån and in the Sörå pond. This sampling was later on terminated, according to a verdict from Oct. 25, 1978 (case AD 42/1970, permit DVA 44/1978).

On Apr. 2, 1982, OKG obtained a permit (case VA 34/1981, permit DVA 12/1982, and subsequent permits DVA 97/1984 from Oct. 26, 1984 and DVA 37/1991 from July 3, 1991) to use Lake Götemar as a water supply (23 $L \cdot s^{-1}$, maximum 35 $L \cdot s^{-1}$). According to these verdicts, OKG is required to monitor and regulate the water level of the lake. The pumping from Lake Trästen to Lake Jämsen was discontinued according to a permit of Dec. 9, 1987 (case VA 10/1987, permit DVA 52/1987), whereas the pumping station at Ström and the Sörå pond were kept as a reserve water-supply system.

On Sep. 18, 1980 (case VA 50/1973, permit DVA 52/1980) and Jul. 8, 1983 (same case, permit DVA 38/1983 and 39/1983), OKG got a final permit to pump 55 $m^3 \cdot s^{-1}$ cooling water from the sea to the O-I and O-II reactors, and 50 $m^3 \cdot s^{-1}$ to the O-III reactor, and also to discharge the cooling water back to the sea. Details concerning e.g. fishing protection were regulated in subsequent verdicts (permit DVA 31/1991 from Jun. 14, 1991).

The pumping- and hydrological monitoring data associated to the above water-handling activities are available in a paper log-book at OKG. As part of the present site descriptive modelling work, the available data have been transferred into digital files so that the data set can be more easily accessed and used for analyses and interpretations. It should be noted that these data are associated to the mentioned water-operation permits (e.g. monitoring in relation to set maximum and minimum water levels and discharges). The following paragraphs provide some exemplifying analyses of the data set.

Data related to the pumping from Lake Trästen (data period Dec. 1972–Mar. 1994): The pumping (operated by OKG) to Lake Jämsen took place during the period Dec. 1972–Jul. 1982 (minor pumping occurred up to Dec. 1987). During the period 1973–1982, the annual average pumping rate varied between 5.6 and 21.8 $L \cdot s^{-1}$, with an overall average of 12.9 $L \cdot s^{-1}$. The overall average pumping (Figeholms Bruk AB) rate from Lake Trästen to the stream Sörån was 10.9 $L \cdot s^{-1}$ during the period 1974–1982 (there are no pumping data for the period 1983–1988), and 3.9 $L \cdot s^{-1}$ for the period 1989–1994.

Data related to the pumping from Lake Götemar to the nuclear power plant (data period Feb. 1983–Nov. 2004): The monthly pumped volume varies between 10,626 and 44,060 m^3, with an average of 21,700 m^3 (corresponding to 260,400 m^3 per year). Considering a period with complete annual data (1984–2003), the annual pumped volume varies between 165,336 m^3 (2000) and 417,860 m^3 (1983), with an annual average of 257,660 m^3. Considering the last available data period (Jan. 2000–Nov. 2004), the pumped volume was on average 17,390 m^3 per month, corresponding to 208,680 m^3 per year.

Data related to the pumping from Laxemarån at Ström to Lake Sörå (data period Jun. 1973–Mar. 2003): Considering a period with complete annual data (1983–2002), relevant for the present water need at the power plant, the annual pumped volume was 79,703 m^3, and 95,653 m^3 (including and not including, respectively, periods with unclear data). During this period, pumping took place during 85 of totally 243 months. During the last available data period (Jan. 2000–Mar. 2003), pumping occurred during only 4 months: Jan. 2000 (51,234 m^3), Oct.–Nov. 2002 (63,226 m^3) and Mar. 2003 (19,165 m^3).

Data from the lake-level gauging station at Lake Trästen (data period Dec. 1972–Sep. 2005; two gauges were in operation during year 1973): There are many unclear registrations in the paper logbook. However, a general impression is that the lake-level amplitude is rather small; the maximum minus the minimum lake-water level is on the order of 1.5 m during the period 1972–2005.

Data from the discharge-gauging stations at Fårbokvarn (data period Dec. 1972–Jan. 1998) and Sulegångekvarn (data period Dec. 1972–Jun. 1989): The Sulegångekvarn and Fårbokvarn stations are located to the stream Virån; Sulegångekvarn (estimated catchment area size 394 km^2) upstream of Lake Trästen (along the Lake Hummeln "branch"), and Fårbokvarn (estimated catchment area 401 km^2) downstream of Lake Trästen and upstream of Lake Fårbosjön. Due to the conditions in the water-operations permit (see the historical summary above), many discharge-data registrations (62.5% and 57.8%, respectively) from these two stations only inform that the discharge is above or below a certain value. Moreover, there appears to have been a number of weir changes during the available data period, and the discharge data from Fårbokvarn are disturbed due the pumping from Lake Trästen (located upstream of Fårbokvarn).

Data from the discharge-gauging station at Kvarnbacken (data period Dec. 1972–Oct. 1982): The Kvarnbacken station (estimated catchment area size 154 km^2) is located in the Lake Hummeln branch of the stream Virån, downstream from both Lake Hummeln and Lake Fårbosjön. Only 25.2% of the data registrations informs that the discharge is above or below a certain value, and this station can be considered to provide undisturbed, long-term discharge data. For the whole period with available full-year data (1973–1982), the average specific discharge is 4.9 $L \cdot s^{-1} \cdot km^{-2}$, and 5.9 $L \cdot s^{-1} \cdot km^{-2}$ if data are neglected from two years with few registrations (1973 and 1976).

Data from the discharge-gauging station at Åbyberg (data periods Nov. 1972–Nov. 1975 and Dec. 1977): The Åbyberg station (estimated catchment area size 38 km^2) is located to the stream Laxemarån, upstream of Ström. The discharge data are disturbed, because OKG during the period 1972–1982 pumped water from Lake Trästen to Lake Jämsen, upstream of Åbyberg. Only 10.1% of the data registrations informs that the discharge is above or below a certain value. For the period with full-year data (1973–1975) and subtracting the contribution from Lake Trästen, the average specific discharge is 4.1 $L \cdot s^{-1} \cdot km^{-2}$.

Data from the discharge-gauging station at Ström (data period Jan. 1975–Jun. 2004): The Ström station (estimated catchment area size 40 km^2) is located to the stream Laxemarån, downstream from Åbyberg. The discharge data are disturbed, since OKG during the period 1972–1982 pumped water from Lake Trästen to Lake Jämsen, upstream of Åbyberg. 27.8% of the data registrations informs that the discharge is above or below a certain value, and there appears to have been a number of weir changes during the available data period. Considering the whole available data period and subtracting the contribution from Lake Trästen, the specific discharge is unreasonably high (10 $L \cdot s^{-1} \cdot km^{-2}$) compared to the upstream Åbyberg station (see above), which indicates that there is some error in the Ström discharge dataset.

3 Conceptual and descriptive model of surface and near-surface water flow at the Laxemar site I: Field observations

3.1 Components of the conceptual model

As mentioned in Section 1.5.1, the description of the hydrological-hydrogeological conceptual model of the Laxemar area contains the following main components:

- Hydrological objects and hydrogeological flow domains (Sections 3.3 and 3.4): Descriptions of properties and characteristics of the objects and flow domains that conceptually are thought to be of importance for water flow in the Laxemar area.
- Boundary conditions (Section 3.5.1): Description of the upper (top) boundary, the boundary between terrestrial areas and the sea, and internal boundaries within the considered area (or domain).
- Infiltration and groundwater recharge (Section 3.5.2): Description of processes that are thought to be active in "source" areas, mainly in the high-altitude areas characterised by exposed or shallow rock, for which hydrogeological properties and flow processes need to be described.
- Sub-flow systems and discharge (Section 3.5.3): The processes of groundwater discharge and formation of surface-water flow are conceptually thought to be active in "recipient" areas, mainly in valleys and other low-altitude areas. These areas are characterised by relatively thick QD and deformation zones in the rock, for which hydrogeological properties and flow processes need to be described.
- Water-flow processes in areas/domains between "source" and "recipient areas", and the hydrogeological properties associated to these areas/domains (sections 3.5.2–3).

3.2 Supporting data and models from other disciplines

The following sections summarise data and models from other disciplines, which support the conceptual model of surface hydrology and near-surface hydrogeology in Laxemar.

3.2.1 Digital elevation model (DEM)

Digital elevation models (DEMs) have been developed by SKB for the Laxemar area, including both the ground-surface topography and the bathymetry of lakes and offshore areas. The first SKB DEM had a grid resolution of 10 m and is classified due to national security reasons /Brydsten and Strömgren 2005/. A non-classified lower-resolution DEM (20 m; see Figure 1-2 in Section 1.2) was subsequently developed /Strömgren and Brydsten 2008/, taking into account additional elevation data in the data interpolation. Obviously, a DEM has many applications in the description of the near-surface/surface system. In this context, the DEM has been used as an input both to the conceptual modelling (e.g. to support interpretations of groundwater levels and point water heads in different parts of the area), as well as a direct input to quantitative water-flow modelling (the upper boundary of the model domain).

3.2.2 Geological map of Quaternary deposits

Based on extensive field investigations, a detailed map of the QD in both terrestrial and offshore areas (less detailed for the latter) of the Laxemar-Simpevarp regional model area is presented by /Rudmark 2004, Rudmark et al. 2005, Sohlenius and Hedenström 2008/; the map is reproduced in Figure 1-3 in Section 1.2. The QD map has been used as a support for identification of hydrogeological type areas and to assign hydrogeological properties data to different parts of the model volume consisting of QD. It should be noted that the corresponding soil map /Lundin et al. 2004, 2005/ was not used in the present work.

3.2.3 The regolith depth and stratigraphy model (RDM)

A model of the depth and the stratigraphy of the regolith (here abbreviated RDM) has been developed for the Laxemar-Simpevarp regional model area /Nyman et al. 2008/. In this context, the RDM has been used as an input both to conceptual and quantitative water-flow modelling. Due to its importance in the modelling work, the main characteristics of the RDM are briefly summarised below.

The RDM (illustrated further in Section 3.4.1) is a 3D representation of the regolith (or QD), including both the total regolith thickness as well as the individual thicknesses of totally 6 layers. The model is based on the 20-m DEM, the detailed QD map, and a large amount of geological and geophysical observation data (as available in the Laxemar 2.2 data freeze; December 31, 2006). The 6 layers of the RDM are denoted Z1–Z6, where Z1 represents the upper layer. Except for this upper Z1 layer, the lower boundary of all layers are produced by so-called kriging. In order to enable the construction of the RDM, /Nyman et al. 2008/ divided the area into 3 type areas (denoted I–III) and 9 domains, and developed specific "rules" for assigning layer thicknesses in different parts of the area. The 6 RDM layers (see cross section in Figure 3-1) can be characterised as follows /Nyman et al. 2008, Sohlenius and Hedenström 2008/:

Layer Z1 represents a thin surface(-affected) layer. It is present both on land, below lakes and below the sea. The only exception is areas with peat on the surface; in those areas, layer Z2 is the upper layer. In the RDM, the layer thickness is set to 0.10 m in areas with exposed/shallow rock (i.e. rock outcrops on the QD map), and to 0.60 m in other areas. If the total QD depth is less than 0.60 m, Z1 is the only layer (i.e. there are no Z2–Z6 layers). In the terrestrial areas, layer Z1 is assumed to be affected by soil-forming processes.

Layer Z2 represents (fen or bog) peat. This layer is only present in land areas where the QD map shows peat. Hence, layer Z2 is not present below lakes and the sea. The peat areas are further divided into "shallow" and "deep" peat areas. In the shallow peat areas, layer Z2 is directly underlain by layer Z6 (till; see below), which implies that there are no Z3–Z5 layers in those areas. In deep peat areas, Z2 is underlain by layers Z3–Z6. The thickness of Z2 is set equal to the calculated average thickness of peat in the area (0.85 m).

Layer Z3 represents postglacial clay, clay gyttja/gyttja clay, gyttja or recent fluvial sediments. The Z3 layer is only present in areas where clay gyttja is shown on the QD map, and where layer Z2 is present (i.e. in the "deep" peat areas). Layer Z3 is always underlain by layers Z4–Z6.

Layer Z4 represents postglacial sand/gravel, glaciofluvial sediments or artificial fill, and is hence only present in areas where these types of QD or peat (underlain by postglacial clay in layer Z3 and postglacial sand/gravel in layer Z3) are shown on the QD map. Note that glaciofluvial sediments and artificial fill rest directly on the rock (which is located below layer Z6), which means that there are no Z5 or Z6 layers in those areas. In areas with postglacial sand/gravel in layer Z4, this layer is underlain by glacial clay (layer Z5) and till (layer Z6).

Layer Z5 represents glacial clay. The Z5 layer is present where the QD map shows post-glacial sand/gravel, glacial clay or peat (in the "deep" peat areas).

Layer Z6 represents (glacial) till, which is directly underlain by rock. Layer Z6 has zero thickness is exposed/shallow rock areas (i.e. areas with a total QD depth less than 0.60 m), and in areas where layer Z4 directly overlies the rock. The lower level of layer Z6 can hence be considered as a "digital elevation model" of the rock surface.

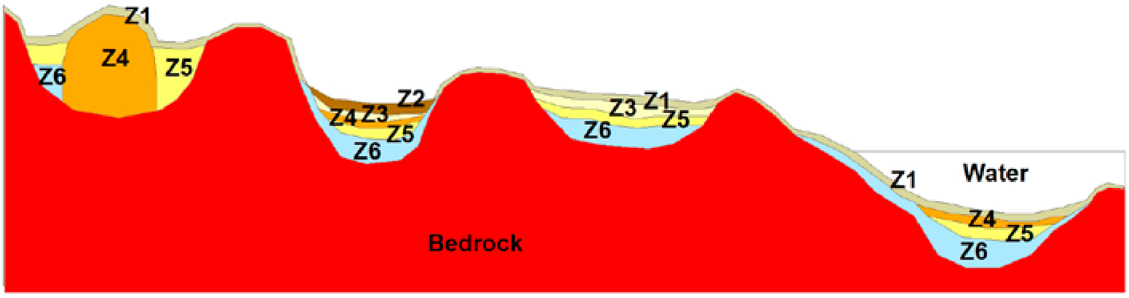


Figure 3-1. *Cross section illustrating the basic principles of the Laxemar RDM /Nyman et al. 2008/.*

3.2.4 Vegatation map

The vegetation map /Andersson 2004, Boresjö Bronge and Wester 2003/ has mainly been used as an input to the quantitative modelling of evapotranspiration processes using the MIKE SHE modelling tool /Bosson et al. 2008b/.

3.2.5 Conceptual geological and hydrogeological modelling of the rock

The conceptual geological and hydrogeological models of the rock in Laxemar are presented in /La Pointe et al. 2008, Rhén et al. 2008, 2009, Wahlgren et al. 2008/. These conceptual models are obviously important components of the overall description of the site-specific hydrological and hydrogeological system, in particular the geological and hydrogeological properties of the upper parts of the rock and their interactions with the overlying QD. Due to their importance for the present work, this section introduces the methods and some key concepts and terms used for developing the conceptual geological and hydrogeological models of the rock in Laxemar. The conceptual hydrogeological models of QD and rock in Laxemar are described in more detail in Section 3.4.1, whereas an overview of the hydrogeological properties of the near-surface rock is presented in Section 3.4.3.

The rock within the Laxemar-Simpevarp regional model area (or rather, volume) is dominated by a rock type denoted Ävrö granite, whereas large parts of the SDM-Site Laxemar local model area (volume) also contain the rock types Quartz monzodiorite and Ävrö quartz monzodiorite, with abundant diorite/gabbro. The 3D deformation zone (DZ) model /Wahlgren et al. 2008/ contains 209 DZ within the regional model area. Figure 3-2 illustrates the defined rock domains, along with the 70 DZ identified within the SDM-Site Laxemar local model area.

As described in detail in /Rhén et al. 2003, 2008/, the hydrogeological modelling of the rock includes the identification and hydrogeological parameterisation of deterministically defined deformation zones (HCD) and the less fractured rock between these zones (HRD). In this context, a deformation zone is a general term defining an essentially 2D structure, along which there is a concentration of brittle, ductile or combined brittle and ductile deformation. The basis for the identification of these two domains is the geological deformation zones (DZ) and a so called Geo-DFN (DFN = Discrete Fracture Network). The latter is a stochastic representation of the fractured rock outside the DZ, which is hydrogeologically parameterised in terms of a so called Hydro-DFN.

The parameterisation of the HCD and the HRD (i.e. the Hydro-DFN; see /Rhén et al. 2008/) constitutes a platform for constructing regional-scale ECPM (equivalent continuum porous medium) numerical groundwater flow models. Within the SDM-Site Laxemar modelling, CONNECTFLOW has been the main tool for modelling of groundwater flow in the rock /Rhén et al. 2009/. Detailed analyses of the spatial distribution of fractures and their hydrogeological properties motivated so called fracture domains to be defined (see Figure 3-3). In a subsequent step, these fracture domains were slightly modified geometrically to define HRD (Figure 3-4) that were used within the hydrogeological modelling of the rock.

A number of north-south trending subvertical dolerite dykes (Figure 3-5) have been observed in some core and percussion boreholes in the SDM-Site Laxemar local model area. As part of the hydrogeological modelling of the rock, three of these dykes are taken into account deterministically. These are thought to have a very low transversal hydraulic conductivity, whereas the longitudinal hydraulic conductivity may be substantially higher. These structures may therefore partially act as barriers for groundwater flow in the rock.

3.2.6 Hydrochemical data and modelling

The hydrochemistry of surface water, groundwater in the QD and groundwater in the rock in the Laxemar area is analysed and modelled by /Tröjbom and Söderbäck 2006, Tröjbom et al. 2008/. In the present context, hydrochemical data interpretations are used as a supplementary support for the conceptual modeling. Specifically, as presented in Section 3.5.4, the hydrochemical data and modelling are used to address aspects such as infiltration and groundwater recharge, sub-flow systems and groundwater discharge, and interactions between lake water and groundwater in the underlying QD.

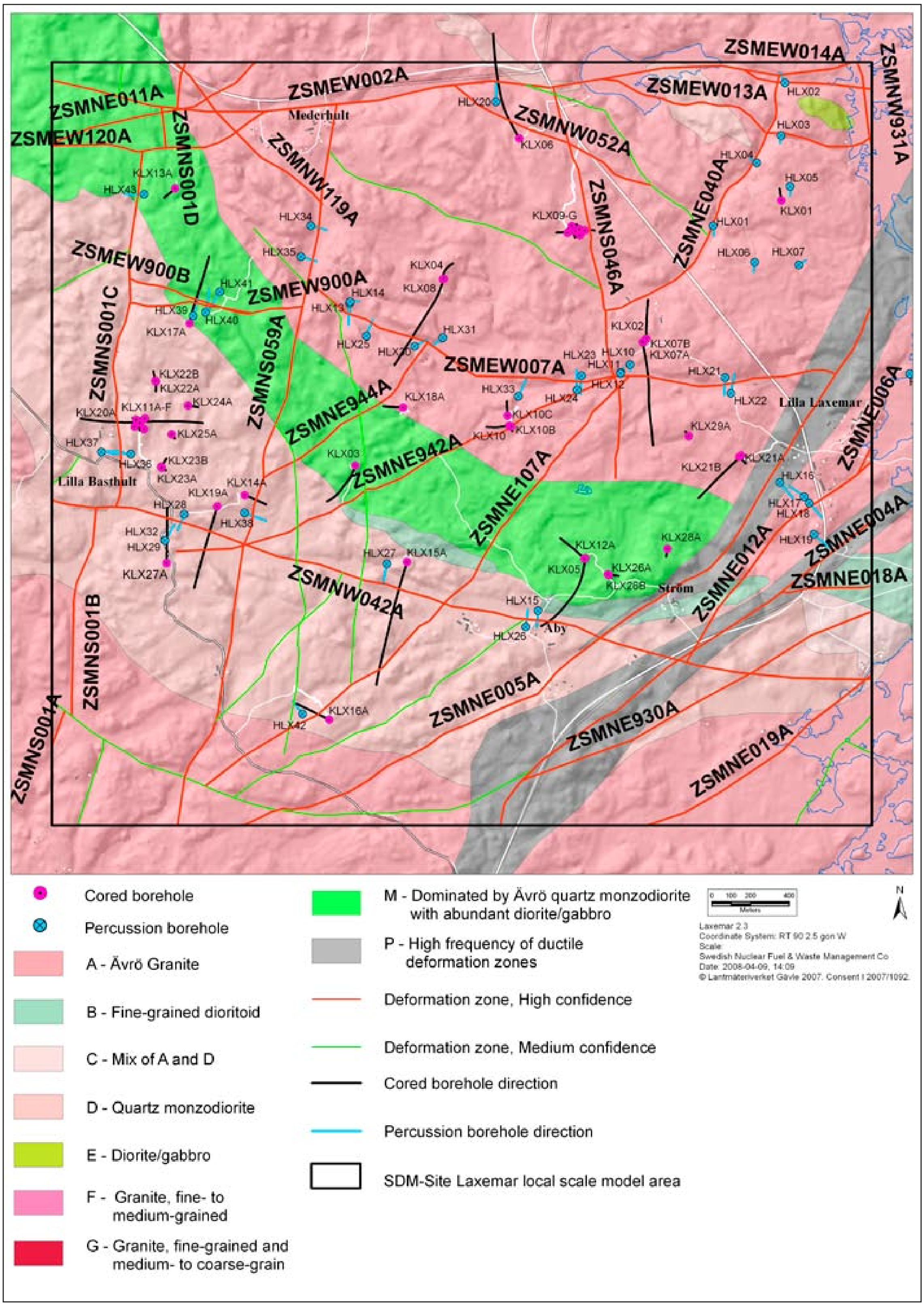


Figure 3-2. *Rock domains (coloured areas) and deterministic deformation zones (lines) within the SDM-Site Laxemar local model area /Wahlgren et al. 2008/.*

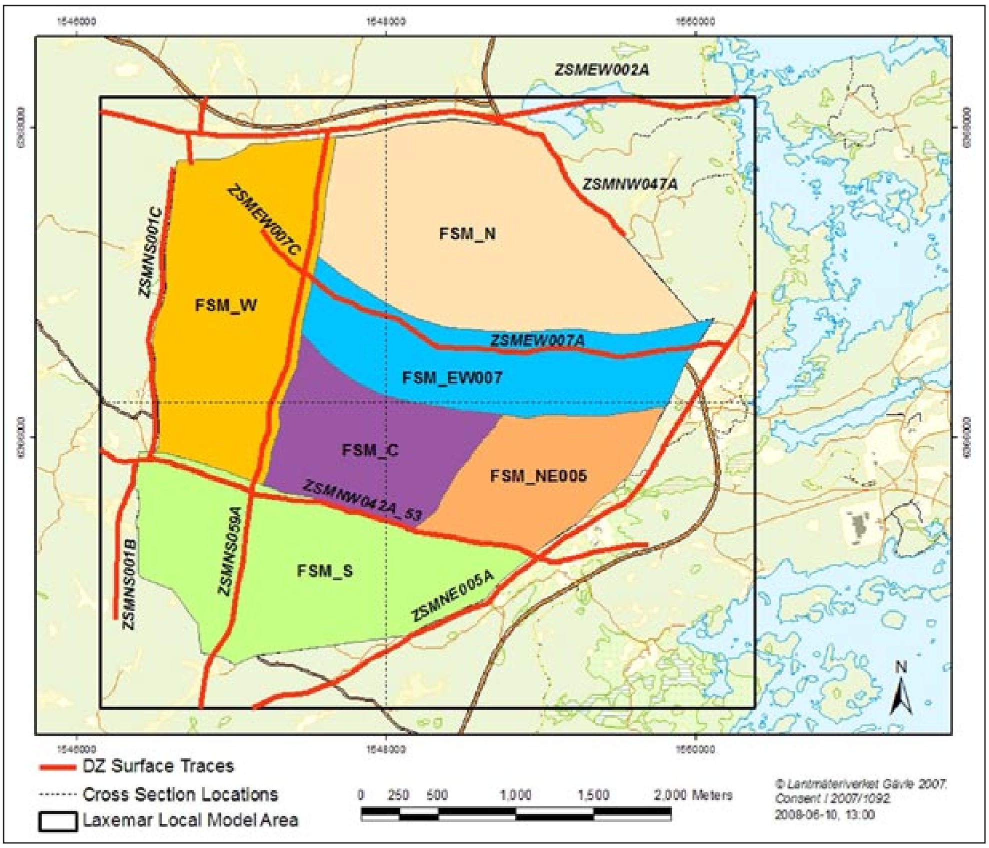


Figure 3-3. *Surface projections of fracture domains (coloured areas) and bounding deformation zones in Laxemar. The black box represents the limits of the SDM-Site Laxemar local model area /La Pointe et al. 2008/.*

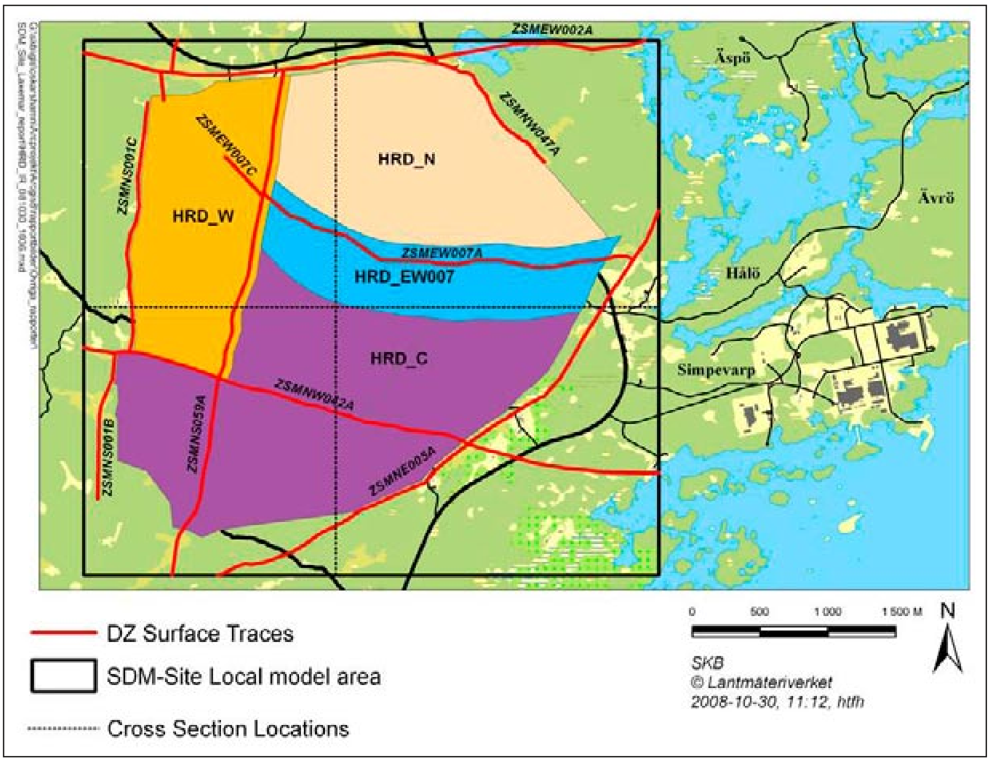


Figure 3-4. *Surface projections of hydraulic rock domains (HRD), based on the underlying division into fracture domains, cf. Figure 3-3 /Rhén et al. 2008/.*

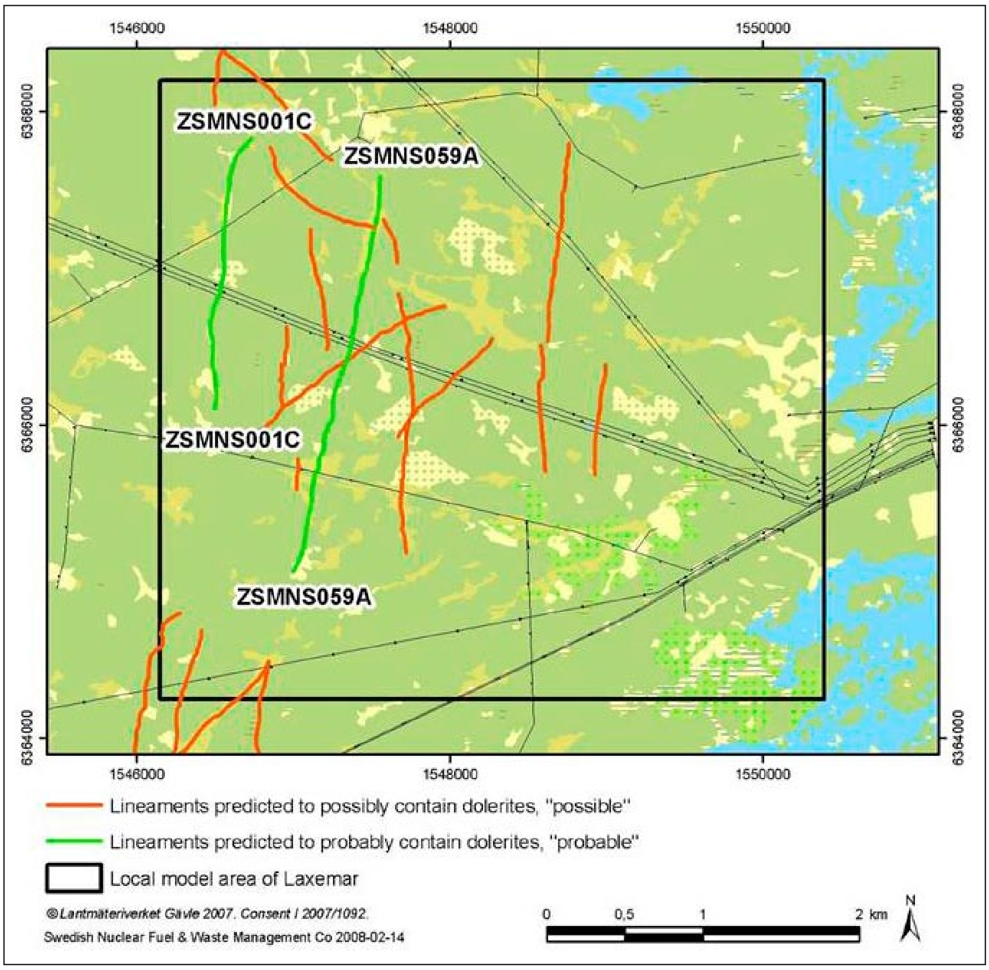


***Figure 3-5.** Overview map of the two lineaments (green lines, coinciding with deformation zones ZSMNS001C and ZSMNS059A) predicted as "probable" regarding their potential content of dolerite. There are also a number of lineaments (red lines) predicted as "possible" regarding their potential content of dolerite.*

3.3 Description of hydrological objects

3.3.1 Catchment areas

The Laxemar area is located within the SMHI catchment area no. 72/73 /SMHI 1993/. The largest streams within this catchment area are Gerseboån (located up- and downstream from Lake Götemar) and Laxemarån (discharging Lake Jämsen). According to SMHI's definition system for the main catchment areas in Sweden, the ID code "72/73" denotes that the catchment area is located between two other main catchment areas, in this case no. 72 Marströmmen (to the north) and no. 73 Virån (to the south). It can be noted that in the no. 73 catchment area, Lake Hummeln and Lake Trästen/Lake Fårbosjön discharge into each branch of the stream Virån. Further downstream, these two stream branches converge south of Lake Fårbosjön.

There are 5 subcatchment areas within the SMHI catchment area no. 72/73. The northernmost is located between the streams Gerseboån and Marströmmen (the latter stream is hence located in catchment area no. 72), one comprises the stream Gerseboån, one is located between the streams Gerseboån and Laxemarån, one includes the stream Laxemarån, and the southernmost subcatchment area is situated between the streams Laxemarån and Virån; the latter stream is located in SMHI catchment area no. 73.

As part of the site investigations in Laxemar-Simpevarp, /Brunberg et al. 2004/ identified 26 catchment areas (further divided into 96 subcatchment areas, taking into account the third order of stream branches) within an area that comprises part of the SMHI no. 72/73 catchment area (see Figure 3-6). In their catchment area delineation, /Brunberg et al. 2004/ omitted three (SMHI) subcatchment areas,

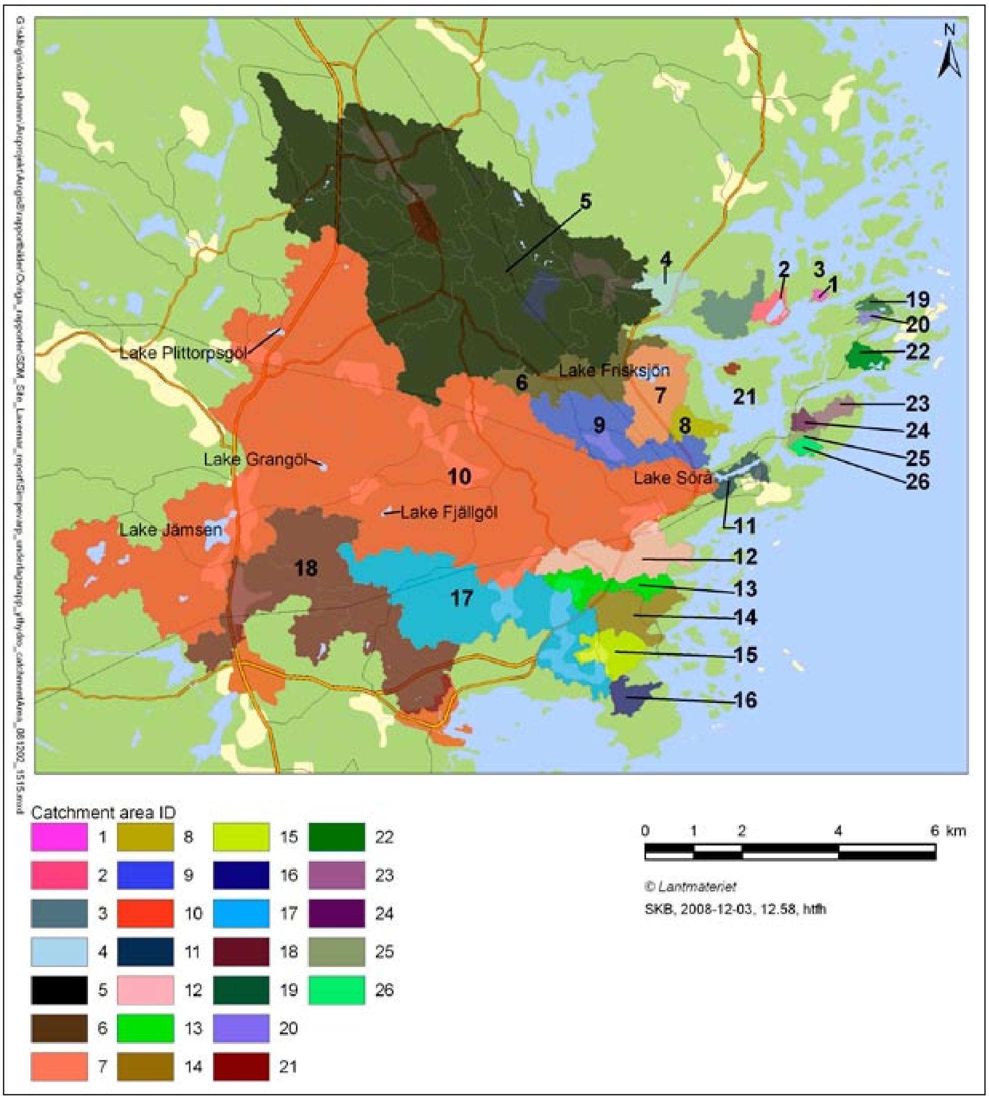


Figure 3-6. Overview map of the 26 delineated catchment areas in Laxemar /Brunberg et al. 2004/. The map also indicates the locations of the five lakes included in the /Brunberg et al. 2004/ study (Lake Grangöl was not included).

namely two that include the stream Gerseboån and areas to the north, and one subcatchment area located between the streams Laxemarån and Virån. According to SKB's system for enumeration of the delineated catchment areas, the 26 areas are identified as nos. 1–18 (located on the mainland) and nos. 19–26 on Hålö and the islands of Ävrö and Äspö. It should be noted that between these delineated catchment areas, there are also so-called "direct runoff areas", i.e. areas without any (larger) lakes or streams and hence with runoff directly to the sea. Adopting the principles of SMHI's enumeration system (see above), these direct runoff areas can be identified as no. 1/2, no. 2/3 and so forth.

In the remainder of this report, the /Brunberg et al. 2004/ catchment areas will for brevity be referred to as "CA" (e.g. CA 1 for catchment area no. 1), whereas "sub-CA" denotes a subcatchment area. Moreover, the 26 identified catchment areas have also been named by /Brunberg et al. 2004/. In order to do so, names of lakes and streams were obtained from the SMHI register of Swedish lakes and from available digital maps. In some cases, when no name was found, a name was invented based on the name of some place nearby, e.g. "Långbonäsbäcken" for the stream located in CA 1.

The sizes and land uses of the delineated catchment areas are shown in Table 3-1. Additional information, e.g. the spatial distribution of QD and morphometrical parameters, can be found in /Brunberg et al. 2004/.

Table 3-1. Sizes and land uses (%) of the 26 delineated catchment areas (CA) in Laxemar /Brunberg et al. 2004/. The numbering system for all CA is shown in Figure 3-6.

CA	Stream[1] (or lake)	Area (km^2)	MA1: Water surface	MA2: Coniferous and mixed forest	MA3: Wetland normal –coniferous forest	MA4: Agricultural land	MA5: Remaining open land	MA6: Cut forest	MA7: Wetland normal – decidous forest	MA8: Wetland normal – remaining open land	MA9: Wetland difficult – conifer-ous forest	MA10: Wetland difficult – decidous forest	MA11: Wetland difficult – remaining open land	MA19: Decidous forest
1	Långbonäs-bäcken	0.070	0	81	0	0	1	0	0	0	18	0	0	0
2	Bodvikebäcken	0.380	20	78	1	0	0	0	0	0	0	0	1	0
3	Sörviksån	1.000	0	95	1	3	1	0	0	0	0	0	0	0
4	Bjurhidebäcken	0.632	0	94	1	4	1	0	0	0	0	0	0	0
5	Kärrviksån	27.154	0	86	1	4	3	2	0	1	0	0	2	1
6	Mederhultsån	2.003	0	83	0	12	5	0	0	0	0	0	0	0
7	Kåreviksån/Lake Frisksjön	2.062	6	86	0	5	2	0	0	0	0	0	1	0
8	Pistlanbäcken	0.499	1	95	0	0	1	0	0	3	0	0	0	0
9	Ekerumsån	2.834	0	81	0	12	4	3	0	0	0	0	0	0
10	Laxemarån/Lakes Fjällgöl, Jämsen, Plittorpsgöl	40.976	1	84	1	5	5	2	0	1	0	0	0	1
11	Lake Sörå	0.523	65	18	65	0	0	17	0	0	1	0	0	0
12	Glostadsbäcken	2.054	0	76	0	3	3	0	0	1	0	0	4	12
13	Stålglobäcken	1.033	0	79	0	14	5	2	0	1	0	0	0	0
14	Stekebäcken	1.338	0	81	0	6	7	1	0	5	0	0	0	0
15	Södra Uvöbäcken	0.967	0	55	0	6	12	0	0	9	0	0	0	18
16	Svartebäck	0.504	0	96	1	1	2	0	0	0	0	0	0	0
17	Uthammarsån	7.019	0	76	1	10	8	0	0	0	0	0	0	5
18	Släthultebäcken	8.958	0	81	2	5	7	0	0	0	0	0	1	3
19	Flakvarpebäcken	0.184	8	46	0	0	0	0	0	1	0	0	14	31
20	Jössesbäcken	0.111	0	0	0	0	17	0	0	0	0	0	0	83
21	Äspöbäcken	0.063	0	92	8	0	0	0	0	0	0	0	0	0
22	Stekflagebäcken	0.359	7	86	0	0	2	0	0	0	0	0	6	0
23	Vadvikebäcken	0.307	0	99	1	0	0	0	0	0	0	0	0	0
24	Lindströmme-bäcken	0.192	0	96	0	0	4	0	0	0	0	0	0	0
25	Gloebäcken	0.131	97	0	97	0	0	3	0	0	0	0	0	0
26	Skölkebäcken	0.165	0	96	0	0	4	0	0	0	0	0	0	0

3.3.2 Lakes

Lake characteristics

There are six lakes (constituting c 1% of the total area) within the catchment areas delineated by /Brunberg et al. 2004/ (cf. Figure 3-6). The bullet list below summarises some basic data on these six lakes. According to /Brunberg et al. 2004/, there are four additional lakes in the upstream (western) part of CA 10. These four lakes were not included in the /Brunberg et al. 2004/ study, partly because they were judged to be completely dry from IR photos (i.e. they are likely former lakes), but also due to unclear hydrological conditions (see /Brunberg et al. 2004/ for details).

- Lake Jämsen (sub-CA 10:30–32): Catchment area size 6.96 km^2. The inlet is located in the southern part of the lake, downstream from the lakes Stora Grytsjön and Lilla Grytsjön, whereas its outlet is in the northern part, discharging into the stream Laxemarån.
- Lake Frisksjön (sub-CA 7:2): Catchment area size 1.85 km^2. The lake is located along the stream Kåreviksån, with the inlet in the south and the outlet in the east.
- Lake Sörå (sub-CA 11:1): Catchment area size 0.52 km^2. Lake Sörå is a former sea bay. The lake has no stream inlet, whereas there is a man-made outlet to the Baltic Sea below a small road.
- Lake Plittorpsgöl (sub-CA 10:26): Catchment area size 0.68 km^2. The lake has a stream inlet to the north, and a small outlet towards Laxemarån in the south. The lake is located on the western side of highway E22, and the outlet stream is drained in a pipe below the highway.
- Lake Fjällgöl (sub-CA 10:16): Catchment area size 0.30 km^2. The lake has a small stream inlet in the southern part, and an outlet to the north towards the stream Laxemarån.
- Lake Grangöl (sub-CA 10:19): This lake was not included in the /Brunberg et al. 2004/ investigation. However, it can be noted that it is of approximately the same size as Lake Fjällgöl. It has a small stream inlet in the west and an outlet in the eastern part towards the stream Laxemarån.

The lakes in Laxemar can be characterised as relatively small brownwater lakes (i.e. rich in humic substances). The lakes are relatively shallow, with average depths in the range 1–4 m and maximum depths in the range 2–11 m. Lake Jämsen is the largest (size 0.24 km^2) and deepest lake, followed by Lake Frisksjön (0.13 km^2) and Lake Sörå (0.10 km^2). One can also note that Lake Plittorpsgöl is deep relative to its size. The limited lake depths implies that vertical mixing likely is complete, mainly driven by wind shear. Except for Lake Sörå (which has no stream in- or outlet), the inlets and outlets of the lakes are located at opposite ends. This implies that the lakes can be assumed to be well-mixed also horisontally, driven by both surface-water flow and wind shear. Due to generally small stream discharges (see Section 3.3.3), velocities induced by this flow is likely small compared to velocities induced by wind shear.

It can be noted that the wetland Gäster (see Figure 2-12 in Section 2.2.4) is a previous lake, of which the level was lowered in several stages during the 19th and early 20th centuries; the last lake-lowering operation was performed in 1920. A project has recently (mid-2008) been finalised to raise the lake-water level up to the pre-1920 level.

In the field, it is obvious that the lake threshold of Lake Frisksjön (historic name: Lake Sandbördssjön) has been lowered. However, no documentation has been found regarding the execution of this operation. Moreover, Lake Sörå was originally a sea bay, which in the beginning of the 1970s became bounded by a dam wall and thereby transformed to a lake. Lake Sörå (also denoted as "Söråmagasinet") is used as a reserve water supply by OKG (Kenneth Gustafsson, OKG, pers. comm. 2005). Occasionally, on the order of a few days each year or every second year, water is pumped from Ström on the stream Laxemarån into Lake Sörå in order to maintain the available water storage in the lake (for further information, see Section 2.2.4).

Morphometrical data

Morphometrical data for the five lakes (not Lake Grangöl) are presented in Table 3-2. This table also provides the ID codes of the associated lake-level gauging stations. The theoretical turnover times presented in the table are based on the ratio between the estimated lake volume and the average discharge, where the latter is estimated as the size of the catchment area multiplied by the average long-term regional specific discharge /Larsson-McCann et al. 2002/. It can be seen that the theoretical turnover time varies between 7 months (Lake Fjällgöl) and more than 2 years (Lake Sörå). However, it should be noted that the actual turnover time of Lake Sörå likely is shorter, due to the use of the lake as a reserve water supply for the nuclear power plant.

Table 3-2. Morphometry parameters[1] for the five lakes investigated by /Brunberg et al. 2004/.

Lake	Frisksjön	Fjällgöl	Plittorpsgöl	Jämsen	Sörå
Lake catchment/ Lake no.	7:2	10:16	10:26	10:30	11:1
Water elevation (m a. s. l.)	1.37	–	24.79	25.11	2.07
Area (km^2)	0.13	0.03	0.03	0.24	0.10
Max. depth (m)	2.8	2.0	7.2	10.9	4.9
Mean depth (m)	1.7	1.1	3.7	3.7	2.0
Volume (Mm^3)	0.223	0.029	0.124	0.877	0.199
Shore length (m)	2,632	864	933	4,036	2,992
Mean discharge (m^3·s^{-1})[3]	0.0098	0.0016	0.0036	0.0369	0.0028
Theoretical turn-over time (days)[3]	264	218	399	275	829
Fetch (m)	705	116	349	959	936
Width (m)	248	55	119	603	184
Dynamic sediment ratio	0.21	0.14	0.05	0.13	0.16
Depth ratio	0.61	0.57	0.50	0.34	0.40
Relative depth ratio	9.89	15.29	49.31	28.02	19.22
Shoreline development factor	2.06	1.51	1.43	2.35	2.66
Lake threshold (m.a.s.l.) Sicada delivery #Sicada_08_059 (delivery Mar. 11, 2008)	1.29	Not surveyed	24.60	24.65	Not surveyed
Lake-level gauging station	PSM000348[2]	–	PSM000344	PSM000342	PSM000359

[1] The terms used are defined as follows /Brunberg et al. 2004/: Fetch: Maximum length; the longest straight line over the water surface. Width: Maximum width; the longest straight line perpendicular to the maximum length line. Dynamic sediment ratio: The square root of the area divided by the mean depth. Depth ratio: The mean depth divided by the maximum depth. Relative depth ratio: The ratio of maximum depth to mean diameter represented by the square root of the lake area. Shoreline development factor: Shore length divided by circumference of a circle with an area equal to that of the lake.

[2] PSM000348 is located in the stream Kåreviksån, immediately downstream from the lake.

[3] Calculated using SMHI's estimate of the specific discharge in the area, see /Brunberg et al. 2004/.

Bottom sediments

The bottom stratigraphy below the lakes has large influence on the water exchange between the lakes and groundwater in the underlying QD. The bottom sediments of the lakes Sörå, Frisksjön, Jämsen and Plittorpsgöl were investigated by /Nilsson 2004/. Sörå and Frisksjön are relatively shallow and recently isolated from the Baltic Sea, whereas Jämsen and Plittorpsgöl are deeper and considerably older.

The investigation shows that the lake bottoms in the area are dominated by low-permeable sediments such as clay and gyttja. The bottom of the shallow lakes (Frisksjön and Sörå) typically contains deep layers (several metres) of gyttja and clay. The bottom stratigraphy below the deeper lakes (Jämsen and Plittorpsgöl) appears to be more complex, but nevertheless dominated by gyttja and clay. At many investigated locations below the deeper lakes, the gyttja and clay layers have intermittent layers of silty-clayey gyttja, silty clay, and in some cases sandy clay and/or thin layers of sand.

/Johansson et al. 2007/ report on drilling and installation of groundwater monitoring well SSM000242 below Lake Frisksjön. Along the borehole, the top-down QD stratigraphy is gyttja, clay and till, with a total QD depth of 14.50 m. It can be noted that /Sohlenius et al. 2006b/ investigated the surface coverage of low-permeable bottom sediments below Lake Frisksjön, concluding that there is till and/or exposed rock (i.e. no overlying clay and gyttja layers) at many locations along the near-shore parts of the lake.

Hence, the investigations indicate that the lake bottoms are dominated by low-permeable layers, which in turn implies that there likely is limited interaction between surface water of the lakes and groundwater in the QD below the bottom sediments. Locally, there may be more favourable conditions for such interaction along the periphery of the lakes.

The regolith depth and stratigraphy model (RDM) /Nyman et al. 2008/, which constitutes an important input to the quantitative water flow modelling of the Laxemar site (see Chapter 4), can be used as an illustration of the conceptual model of lake-groundwater interactions. As can be seen in the RDM cross section at Lake Frisksjön (Figure 3-7), the top-down QD stratigraphy below the lake is conceptualised as a surface-affected layer, gyttja clay/clay gyttja, postglacial sand/gravel, glacial clay and till, with a total QD depth of c 6 m.

Lake-water level time series

Figure 3-8 shows time-series plots of daily average lake-water levels in Jämsen, Plittorpsgöl, Frisksjön and Sörå. During the considered period (May/Jul. 2004–Dec. 2007), the lake-water levels were always (well) above the sea-water level, including the near-coastal Lake Sörå. Hence, all lakes are located above sea level, which implies that no sea-water intrusion takes place. There is a strong co-variation among the lake-water levels, with maxima during spring and minima during late summer and autumn.

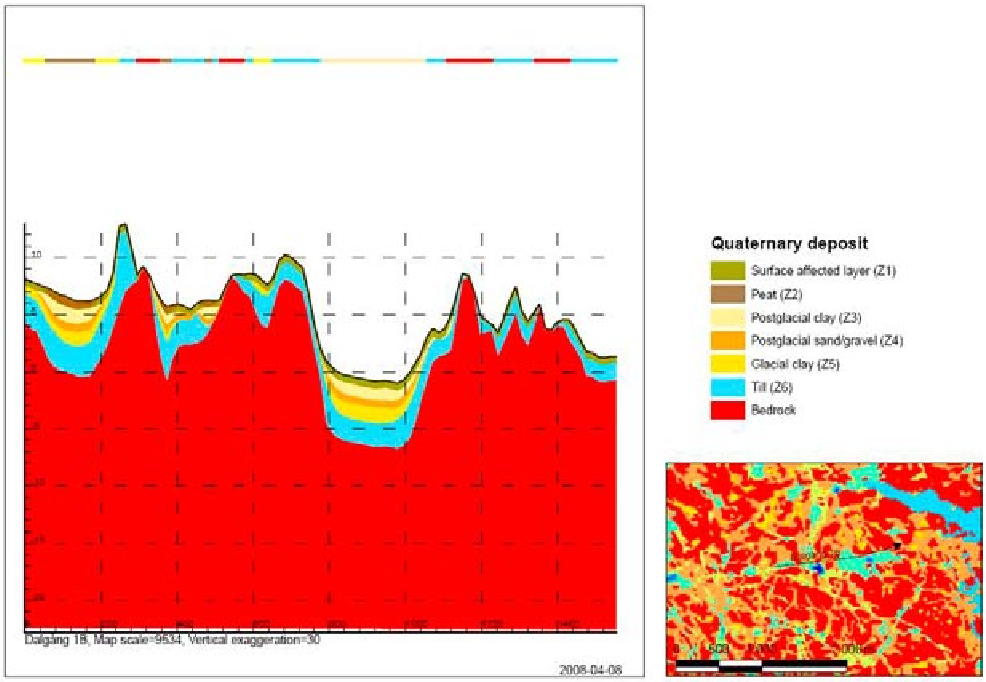


Figure 3-7. *Example cross-section from the RDM at Lake Frisksjön /Nyman et al. 2008/.*

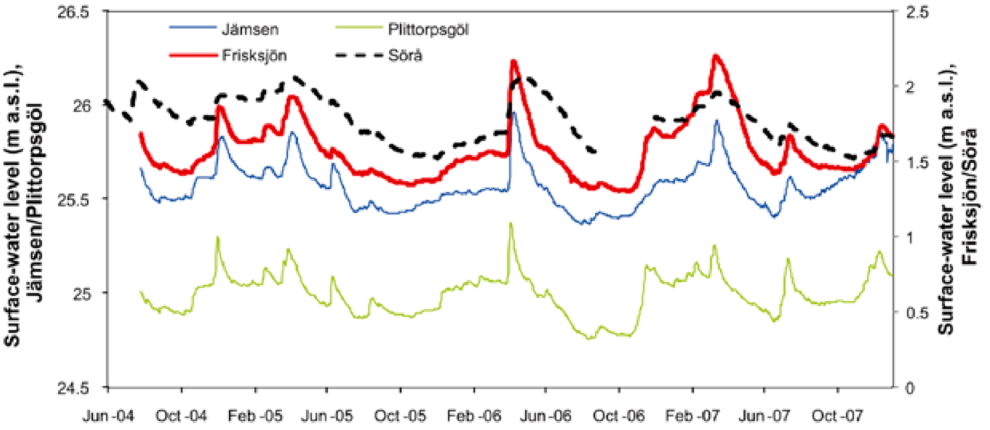


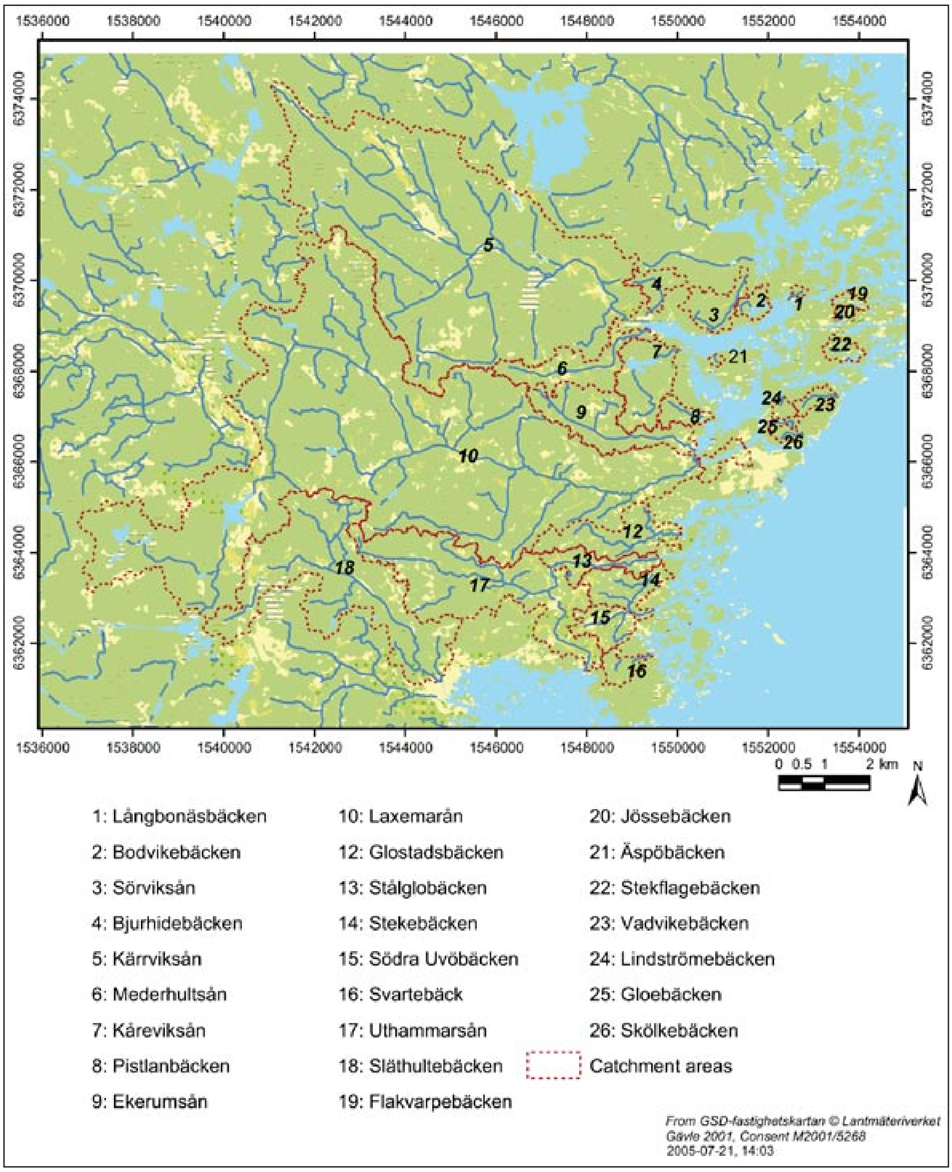
Figure 3-8. *Time-series plot of daily average lake-water levels in Jämsen and Plittorpsgöl (left vertical axis), and Frisksjön and Sörå (right vertical axis).*

It can be noted that the water-level variations are relatively small: Jämsen 25.36–25.97 (average 25.56), Plittorpsgöl 24.75–25.37 (average 24.99), Frisksjön 1.29–2.19 (average 1.57), and Sörå 1.51–2.05 (average 1.77) m.a.s.l. One can also note that the variability pattern of Lake Sörå deviates from the other three lakes, most likely because it is a man-made storage pond, with no stream inlet. In particular, the variability pattern is "smoother" compared to the other lakes, indicating that the more pronounced water-level fluctuations of Jämsen, Plittorpsgöl and Frisksjön are caused by temporally variable stream in- and outflow.

3.3.3 Streams and other surface-drainage systems

General stream characteristics

The names and locations of the main streams in Laxemar are shown in Figure 3-9. Using the topography as the only input, /Werner et al. 2005/ found that the spatial resolution of the 10-m DEM /Brydsten and Strömgren 2005, Strömgren and Brydsten 2008/ was not sufficient to properly reproduce the locations of many streams. Specifically, many streams in Laxemar are affected by land improvement and drainage operations; streams have been deepened at many locations, which locally may lead to relatively large differences between actual stream locations and bottom elevations and those that are inferred based on the Real Estate Map (Swedish: Fastighetskartan) and the DEM.



From GSD-fastighetskartan © Lantmäteriverket Gävle 2001, Consent M2001/5268
2005-07-21, 14:03

Figure 3-9. *Overview map showing the names and locations of the main streams in the Laxemar area /Brunberg et al. 2004, Werner et al. 2006/.*

Figure 3-10. *Photograph of the stream Laxemarån, at a location where the stream bank is regularly flooded /Löfgren (ed.) 2008/.*

Figure 3-11. *Photograph of a typical stream stretch affected by land improvement and drainage operations for agricultural purposes /Löfgren (ed.) 2008/.*

/Brunberg et al. 2004/ present some basic characteristics of the main streams in Laxemar. In order to gain data and information required for the site description and the site descriptive modelling, supplementary field investigations of some selected stream stretches have been performed subsequent to the /Brunberg et al. 2004/ investigation. These supplementary field investigations include description of bottom substrates and land improvement and drainage operations /Carlsson et al. 2005/, field checks of actual stream locations and characteristics /Bosson and Berglund 2005, Svensson 2005/, and a detailed geodetical survey /Strömgren et al. 2006/.

Geometric properties and bottom characteristics of streams

The overview map in Figure 3-12 shows the stream stretches along which a detailed geodetical survey was performed by /Strömgren et al. 2006/. The surveyed streams include Laxemarån (CA 10), Mederhultsån CA 6), Kåreviksån (CA 7), Ekerumsån (CA 5), and eight tributaries to Laxemarån (in sub-CA 10:2–7, 10:10 and 10:11). X-, Y- and Z-coordinates were surveyed approximately every 50 m of the deepest part of the stream furrows. Inter-point distances were longer in relatively flat areas, whereas the distance was shortened to c 10 m in areas with a steep topography. Moreover, /Strömgren et al. 2006/ surveyed stream cross sections every 200–300 m. It should be noted that all stream stretches that were surveyed are available in the Real Estate Map, which means that the survey does not include any previously unmapped streams.

Figures 3-13 to 3-16 show surveyed stream-bottom elevations along four of the main streams in the area (Laxemarån, Ekerumsån, Mederhultsån and Kåreviksån), whereas Figure 3-17 provides an exemplifying cross section of the stream furrow at Laxemarån /Strömgren et al. 2006/. Based on these figures, the geometrical characteristics of the main streams in Laxemar can be described as follows:

Laxemarån: The stream Laxemarån in CA 10 has a length of almost 15 km. It starts at the outlet from Lake Jämsen, located at an altitude of c 25 m.a.s.l. The stream-bottom topography is initially steep but more gentle the remaining parts towards the Baltic Sea. The width of the stream furrow is mostly 5–7 m and its depth 1–2 m. The stream furrow is wider (8–9 m) and also deeper (2–3 m) in the vicinity of the small village Lilla Basthult. Laxemarån flows though pipes at road crossings downstream from Lake Jämsen. The stream furrow is rather indistinct along stretches that cross wetlands.

Ekerumsån: The stream Ekerumsån i CA 9 has a length of c 3.8 km. It starts south of the village Mederhult, at an altitude of c 13 m.a.s.l. The width of the stream furrow is mostly 4–5 m and its depth 1–2 m. The furrow is wider (7–8 m) and deeper (2–3 m) along some stretches. The stream furrow is rather indistinct close to the stream outlet to the Baltic Sea. Ekerumsån flows though pipes along some stretches in its upper- and lowermost parts.

Mederhultsån: The stream Mederhultsån i CA 6 has a length of c 3.7 km. It starts c 1 km west of the village Mederhult, at an altitude of c 13 m.a.s.l. The stream-bottom topography is initially steep but the slope is gentler along the downstream stretches. As can be noted in Figure 3-15, there are some thresholds along the stream. The width of the stream furrow is typically 3–6 m and its depth 1.5–2 m. The width and depth of the stream furrow are smaller along the most downstream parts. Mederhultsån flows in pipes along some stretches (up to some hundred metres).

Kårevikån: The stream Kåreviksån in CA 7 has a length of c 2.8 km. It starts at an altitude of c 10 m.a.s.l. The width (typically 2.5–5 m) and depth (0.7–1.5 m) of the stream furrow vary along its stretch. The stream furrow is indistinct downstream from Lake Frisksjön in the vicinity of the stream outlet to the Baltic Sea.

The tributaries to Laxemarån: The lengths of the tributaries to Laxemarån surveyed by /Strömgren et al. 2006/ are between 0.4 km (sub-CA 10:6) and 2.2 km (sub-CA 10:4). The width of the stream furrow varies between c 1.5–2 m (sub-CAs 10:2, 10:4, 10:10 and 10:11) up to as much as 8 m (stretch of stream in sub-CA 10:6), whereas the depth typically is in the interval 0.3–2 m.

As illustrated in Figure 3-18, it has been observed that flooding regularly occurs along some stream stretches during high-discharge periods, primarily in flat areas. The extent of these flooded areas were investigated in four CAs /Strömgren et al. 2006/, in terms of stream stretches prone for flooding (see Figure 3-18). The results of the investigation show that the fraction of the total stream length that is considered prone for flooding is 2% for Mederhultsån, 13% for Kåreviksån, 4% for Ekerumsån, and 12% for Laxemarån /Nordén et al. 2008/.

Similar to the lakes (cf. Section 3.3.2), the bottom sediments and the QD stratigraphy below the streams have large influence on the water exchange between the surface water in the streams and groundwater in the underlying QD. As shown in the conceptual semi-3D illustration in Figure 3-19, representing a large valley in Laxemar, the type of QD and the QD stratigraphy varies along the streams. The illustration shows the influence of the geometry and the hydrogeological properties of the QD on the conditions for groundwater discharge to the surface system, including the interaction between near-surface groundwater and surface water. Typical QD types encountered along the

Figure 3-12. *Surveyed stream stretches (thick blues lines), including some tributaries of Laxemarån /Strömgren et al. 2006/.*

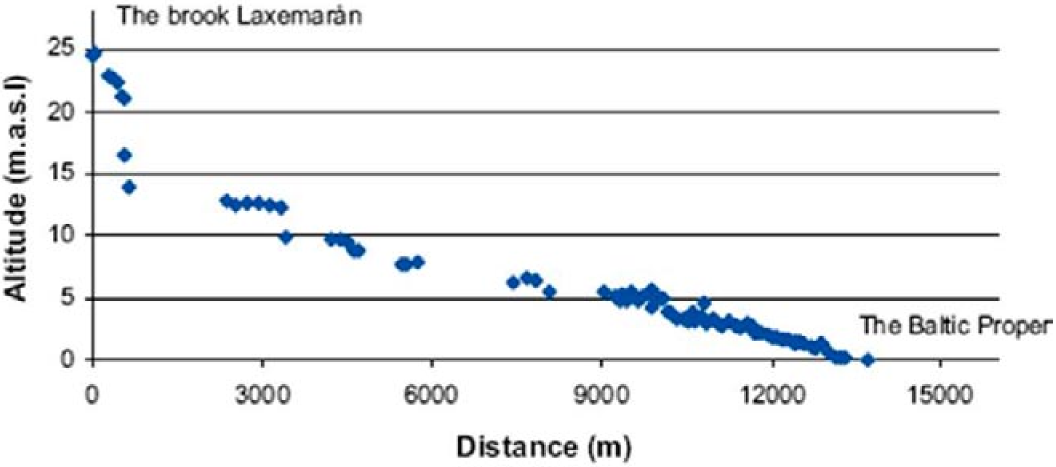


Figure 3-13. *Surveyed stream-bottom topography along Laxemarån /Strömgren et al. 2006/.*

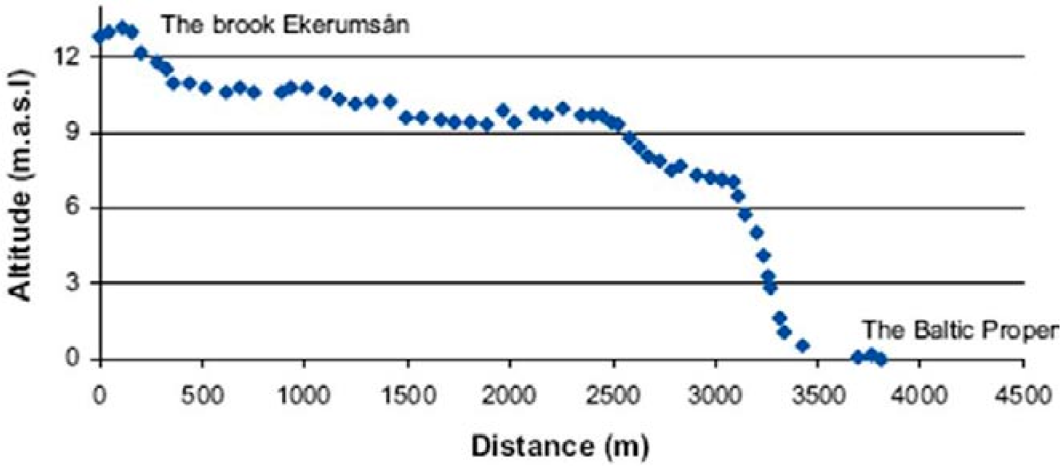


Figure 3-14. Surveyed stream-bottom elevations along Ekerumsån /Strömgren et al. 2006/.

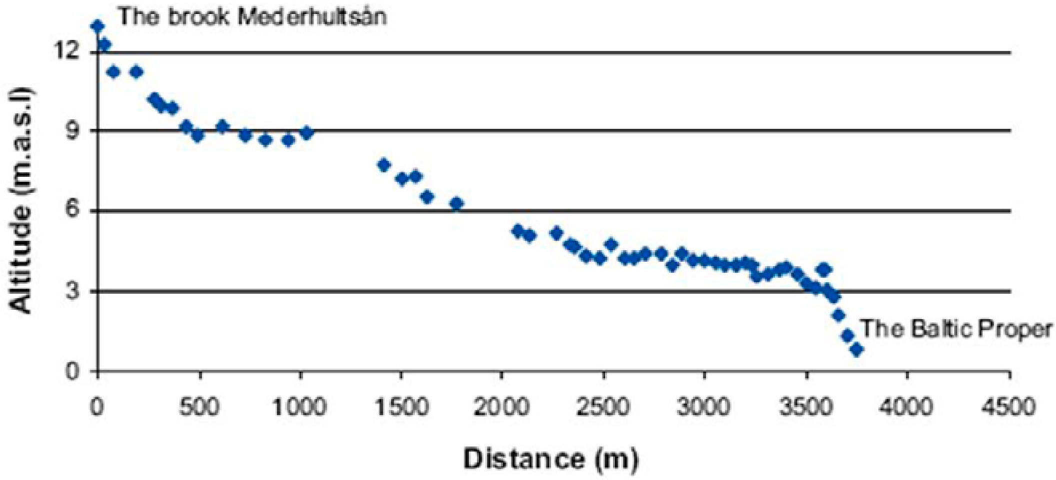


Figure 3-15. Surveyed stream-bottom elevations along Mederhultsån /Strömgren et al. 2006/.

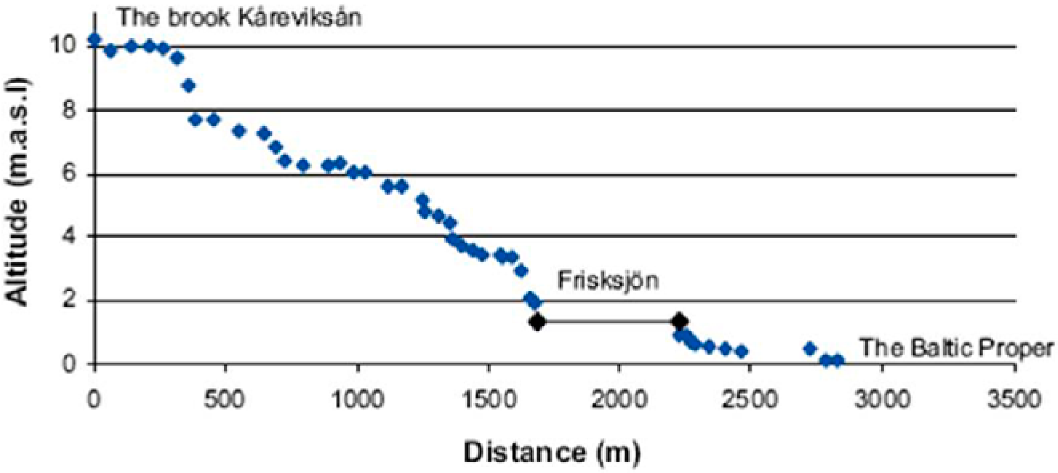


Figure 3-16. Surveyed stream-bottom elevations along Kåreviksån, passing through Lake Frisksjön /Strömgren et al. 2006/.

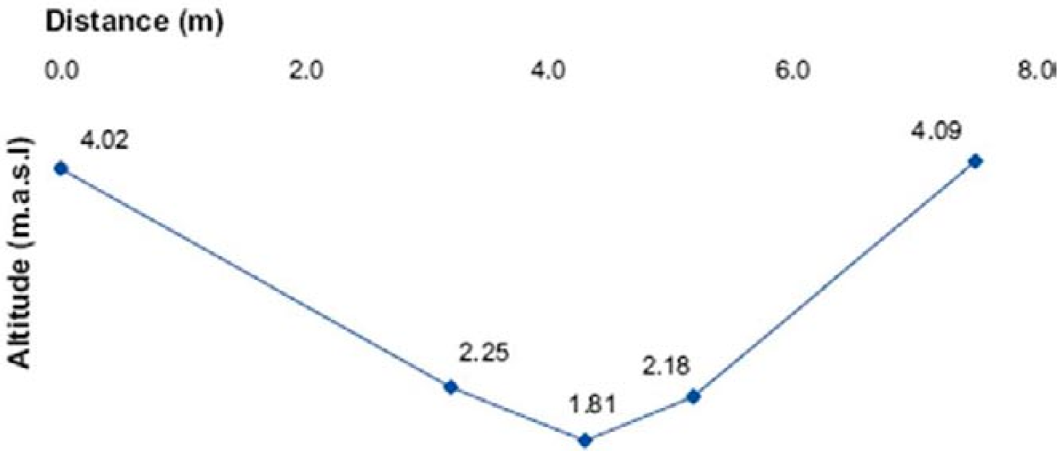


Figure 3-17. *Exemplifying cross section of the stream furrow of Laxemarån /Strömgren et al. 2006/.*

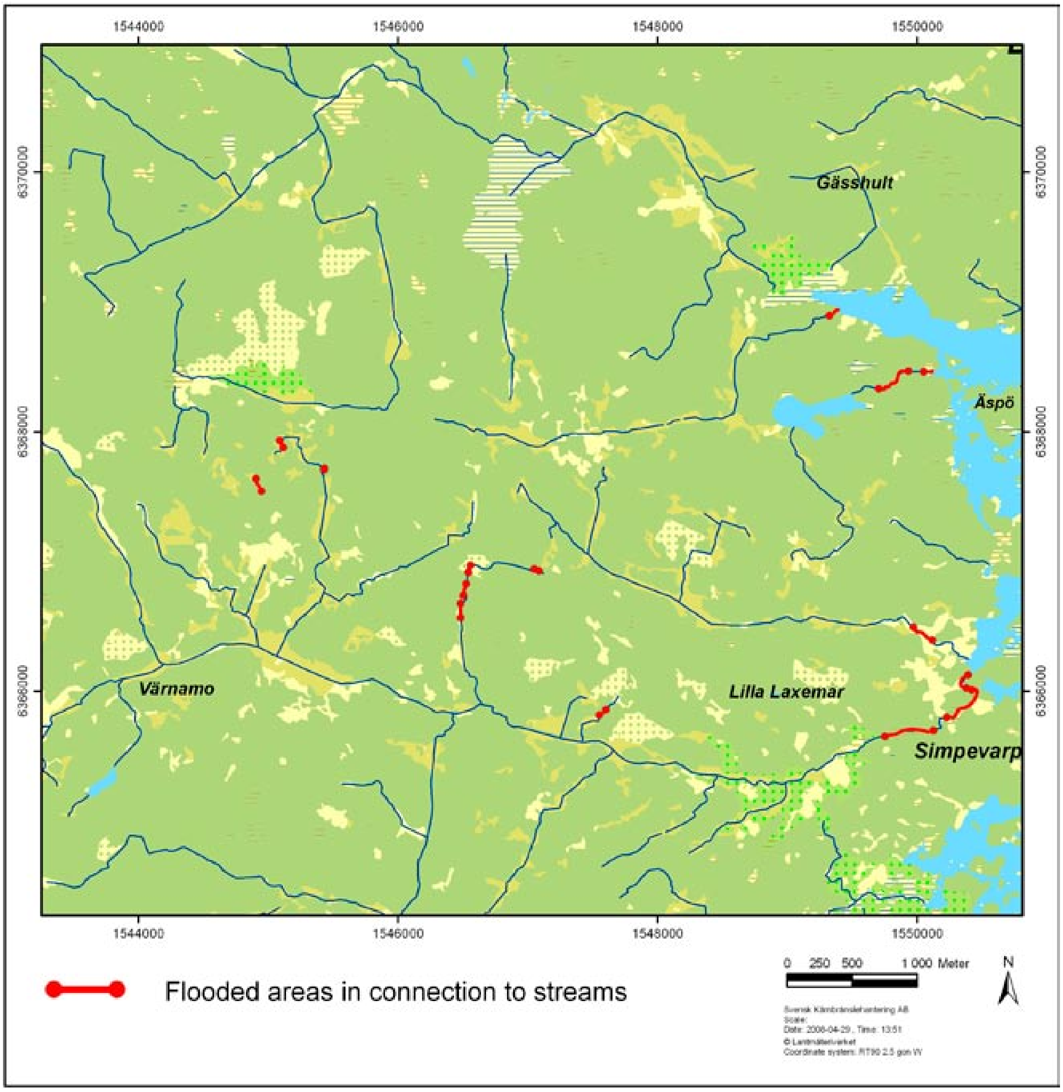


Figure 3-18. *Stream stretches prone for flooding in catchment areas 6, 7, 9 and 10 /Nordén et al. 2008/.*

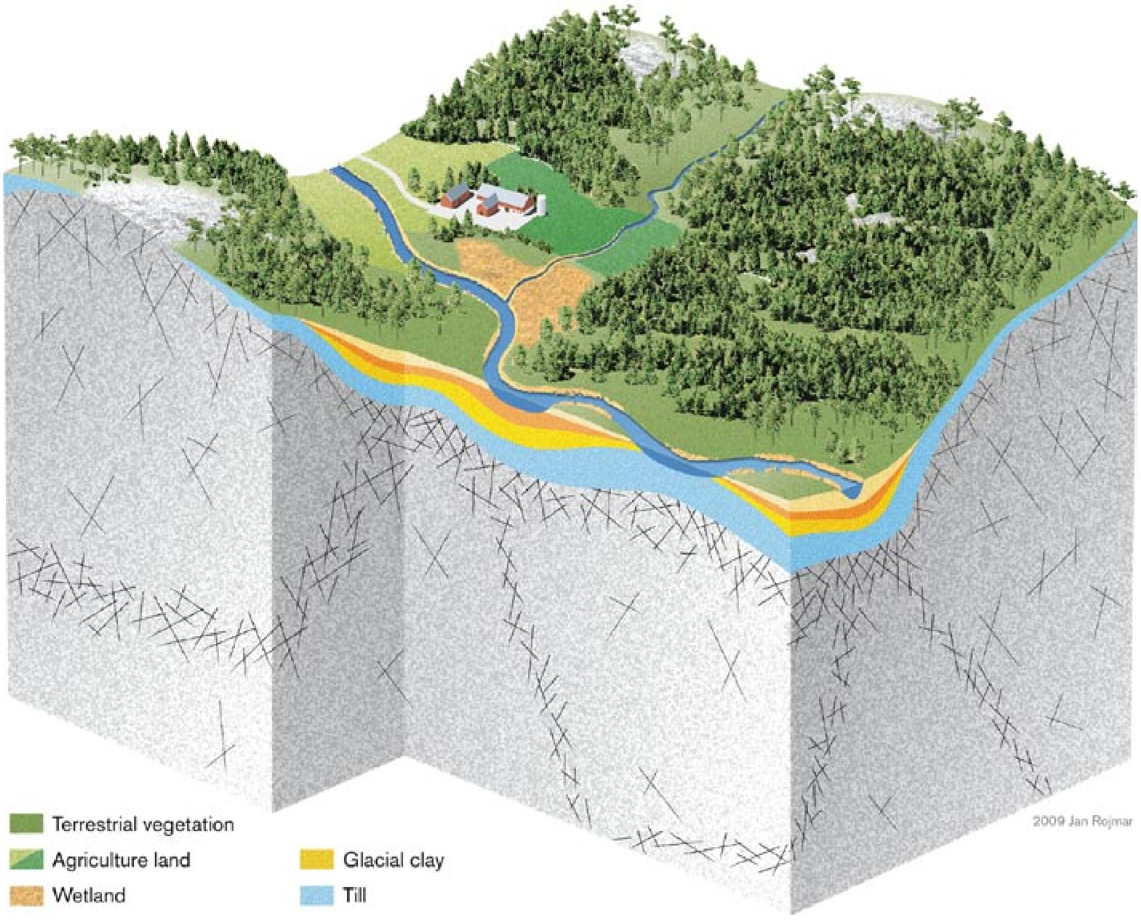


***Figure 3-19.** Conceptual semi-3D illustration of a large valley in Laxemar. The illustration shows the influence of the geometry and the hydrogeological properties of the QD on the conditions for groundwater discharge to the surface system, including interaction between near-surface groundwater and surface water.*

streams include fen peat, clay gyttja and glacial clay, but also more conductive QD types such as postglacial sand/gravel and till. This implies that the conditions for groundwater-surface water interaction vary along the streams. In areas with low-conductive QD below the streams, these interactions are likely limited. As shown in /Werner et al. 2008/, joint evaluations of stream discharges and groundwater levels in the QD in the vicinity of the streams indicate that there is an (unconfined) groundwater level “threshold” for initiation of discharge, likely related to the local drainage depth (i.e. the depth to the bottom of the stream).

Investigation of the bottom characteristics of some selected stream stretches /Carlsson and Brunberg 2005/ indicate spatially variable bottom sediments, ranging from clay/organic material to stones and gravel. As mentioned above, most streams are affected by land improvement and drainage operations. For instance, many stream stretches are deepened, and the surface water flow is diverted in culverts or pipes along many stretches, most notably along the stream Mederhultsån (see Figure 3-20). Hence, it can be concluded that the local conditions for groundwater-stream interactions are influenced not only by the type of bottom sediments and the type of QD below the stream, but also the presence or absence of culverts and underground pipes. Hence, the conditions for such interactions in the Laxemar area are variable, both between and along streams.

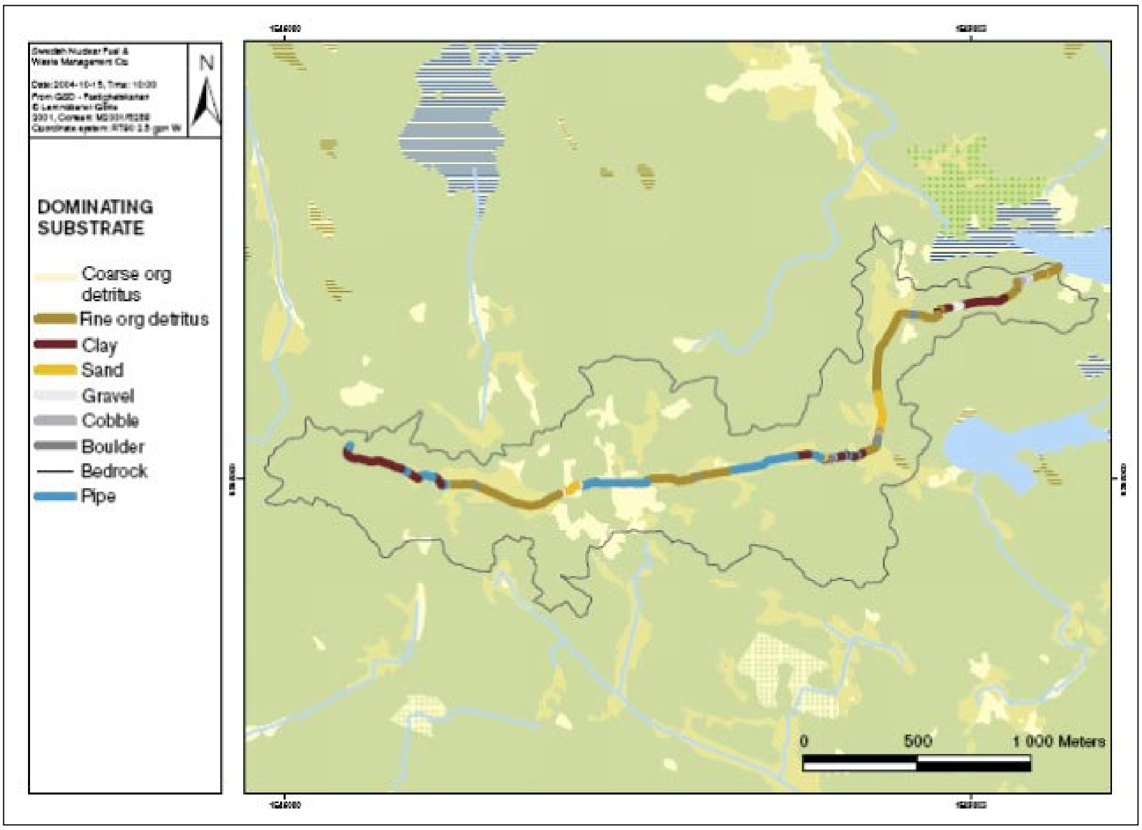


Figure 3-20. Example illustration (stream Mederhultsån) of variable stream-bottom conditions and flow in pipes /Carlsson and Brunberg 2005/.

Land improvement and drainage operations

A characteristic feature of the province of Småland, and, in fact, in particular the municipality of Oskarshamn, is the vast amount of land improvement and drainage operations. Near-surface ditches and covered drains obviously have a potentially large influence on near-surface groundwater flow (this is why they are constructed) and need to be taken into account in descriptive and quantitative flow models. For instance, previous MIKE SHE modelling showed that many low-lying areas were flooded in the model (but not in reality) if such ditches and covered drains were not included in the model /Werner et al. 2006/. Supplementary field checks of the locations of streams not included in the Real Estate Map are reported by /Svensson 2005, Bosson and Berglund 2005/.

Traditional agricultural land improvement and drainage operations in Sweden involved detail drainage of individual fields (and hence also individual real estates) connected to a main drain. The main drain and the associated design of ditches and covered drains were legally regulated, whereas detail drainages were not; they usually were used for drainage of single real estates /Nilsson and Almqvist 1978/. Hence, many old main drainages are likely available on official maps, whereas field ditches and covered drains are not.

/Nyborg et al. 2004/ provide an overview of the land improvement and drainage operations conducted in the Laxemar-Simpevarp area during the last c 100 years (see Figure 3-21). Based on that investigation, original maps were provided from the Agricultural Engineer at the County Administrative Board of Kalmar. From this vast map material (not reproduced here), it can be concluded that most streams in the Laxemar-Simpevarp area are subject to land improvement and drainage operations, typically with drain widths on the order of 0.3–0.4 m and depths of c 1.3 m (i.e. in agreement with current actual widths and depths according to the /Strömgren et al. 2006/ geodetical survey).

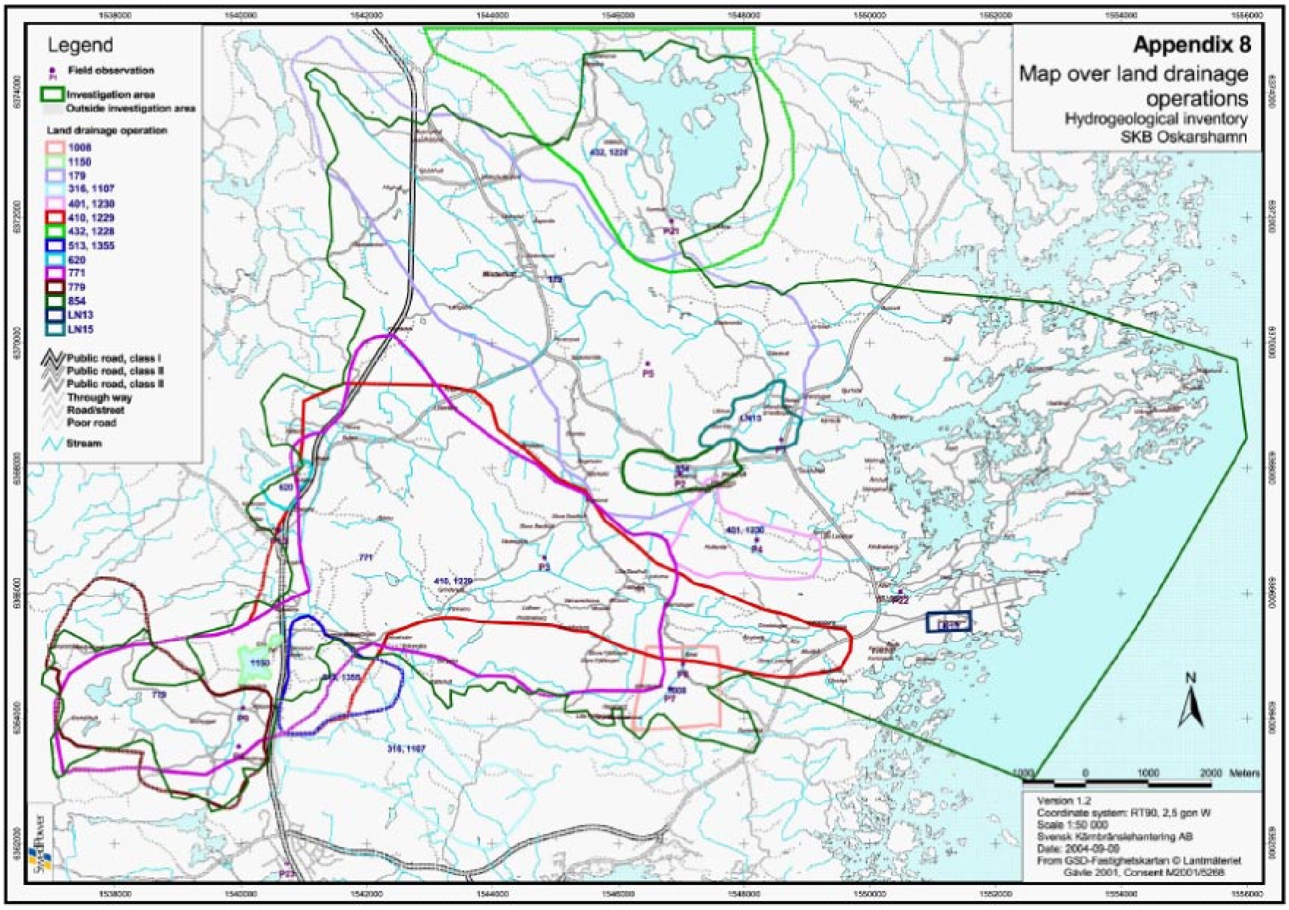


Figure 3-21. Overview map of land improvement and drainage operations in the Laxemar-Simpevarp area /Nyborg et al. 2004/.

The ID codes in the legend of Figure 3-21 denote the different identified land improvement and drainage operations, which briefly can be summarised as follows:

- LN 13: Simpevarp drainage operation (year 1955). This operation was located to the Simpevarp peninsula.
- LN 15: Gässhult drainage operation (year 1955). This operation concerned the stream Kärrviksån, immediately upstream of the stream outlet to the Baltic Sea.
- 179: Lake-lowering of Lake Gäster in Gässhult (year 1918). This operation also concerned the stream Kärrviksån.
- 432: Lake-lowering of Lake Götemar (year 1933).
- 1150: Jämserum drainage operation (year 1937). This operation concerned lake-lowering of Lake Jämsen and associated drainage operations.
- 1344: Jämserum drainage operation (year 1937). This operation concerned an area east of Lake Jämsen and downstream to the stream Släthultebäcken. The drainage depth was somewhat larger than in the other operations (c. 1.50–1.70 m).
- 779: Köksmåla drainage operation (year 1943). This operation concerned part of the stream between the lakes Jämsen and Trästen, and was an elongation south of the Jämserum drainage operation (1150; see above).
- 1230: Lilla Laxemar and Mederhult drainage operations (years 1933 and 1935). This operation concerned parts of the stream Ekerumsån.
- 854: Mederhult drainage operation (year 1949). This operation concerned the westernmost parts of the stream Mederhultsån.
- 771: Plittorp-Stora Basthult drainage operation (year 1944), which concerned part of Laxemarån.
- 620: Plåttorp drainage operation (year 1939). This operation concerned an area that drains into the stream Laxemarån.

- 1107: Släthult drainage operation (year 1927). This drainage operation concerned the stream Släthultebäcken.
- 1008: Stora Laxemar drainage operation (year 1922). This operation concerned an area that drains into the stream Laxemarån.
- 1229: Ström-Åby drainage operation (year 1933). This operation concerned the stream Laxemarån, from Kvarnstugan in the west to Ström in the east.

Stream-discharge data

Figure 3-22 presents time-series plots of daily average surface-water discharges at the nine discharge-gauging stations in the Laxemar area; their locations are shown in the overview map in Figure 2-5 in Section 2.2.2. According to these plots, stream discharges in Laxemar are characterised by large temporal variations. There are relatively long periods during a year with little or no discharges, interrupted by relatively short discharge periods. To generalise, most of the smaller streams in Laxemar are dry during approximately half of the year, from late spring/early summer (c May–Jun.) up to late autumn/early winter (c Nov.–Dec.). The exception is the gauging station PSM000341 in the stream Vadvikebäcken. Of the monitored streams, there is flow throughout the year in the streams Laxemarån, Kåreviksån downstream from Lake Friskjön and Kärrviksån. The stream Ekerumsån is dry during the summers.

/Werner et al. 2008/ summarise the discharge data in terms of minimum, maximum and average discharges up to December 31, 2007. According to that data summary, the average discharge varies between 0.5 $L \cdot s^{-1}$ (Gloebäcken on the island of Ävrö) and almost 300 $L \cdot s^{-1}$ (Laxemarån). As shown in /Werner et al. 2008/, the annual minimum stream discharge is larger in the larger streams, and the streams with small or zero minimum discharges are also associated with the smallest maximum discharges. In a relative sense, inter-annual variations are larger for the smaller streams compared to the larger streams, i.e. the streams with the largest maximum and average discharges.

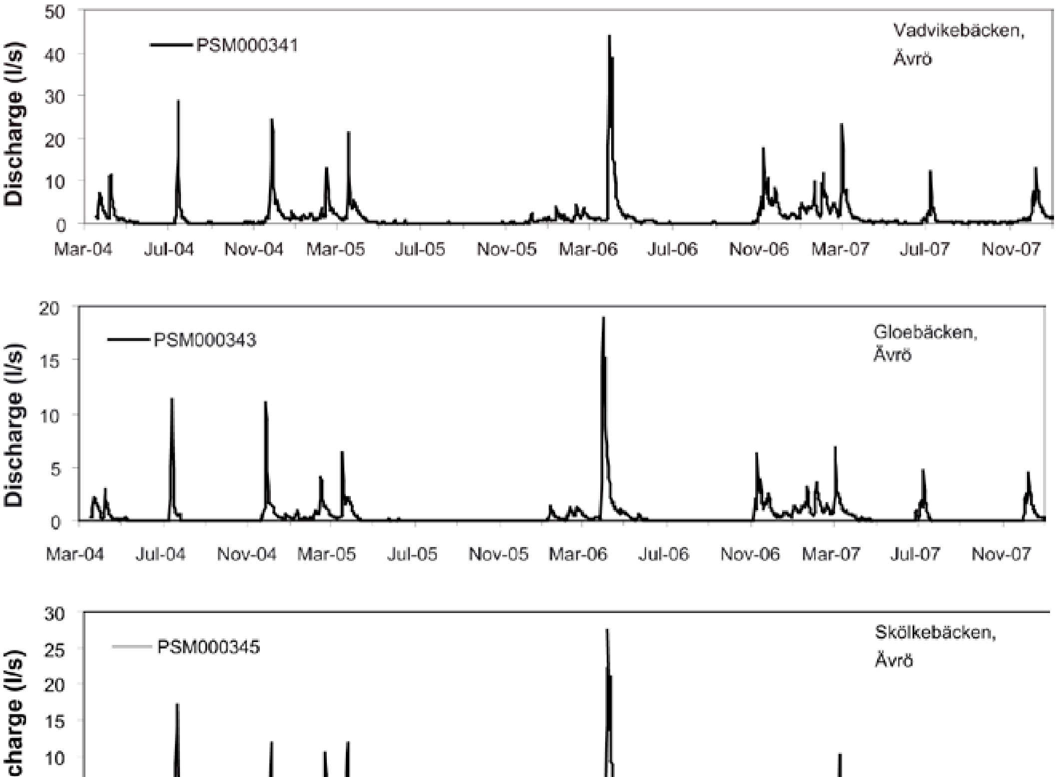


Figure 3-22a. *Time-series plots of daily average surface-water discharges at the discharge-gauging stations PSM000341, -343 and -345.*

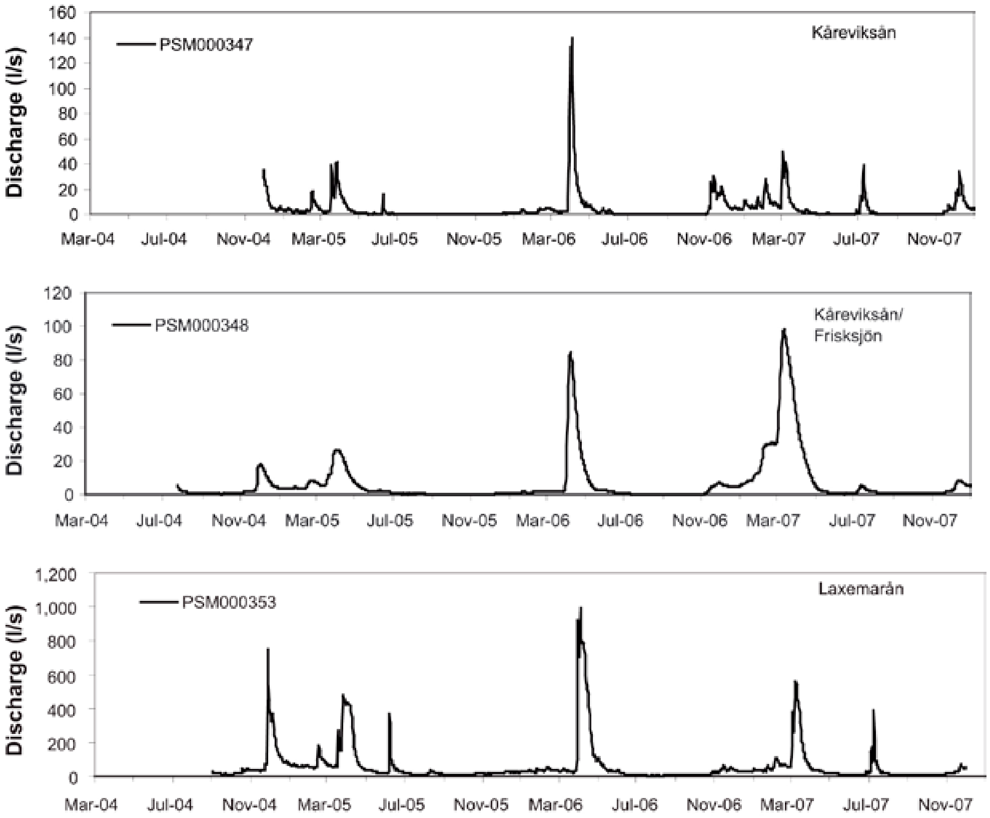


Figure 3-22b. *Time-series plots of daily average surface-water discharges at the discharge-gauging stations PSM000347, -348, and 353.*

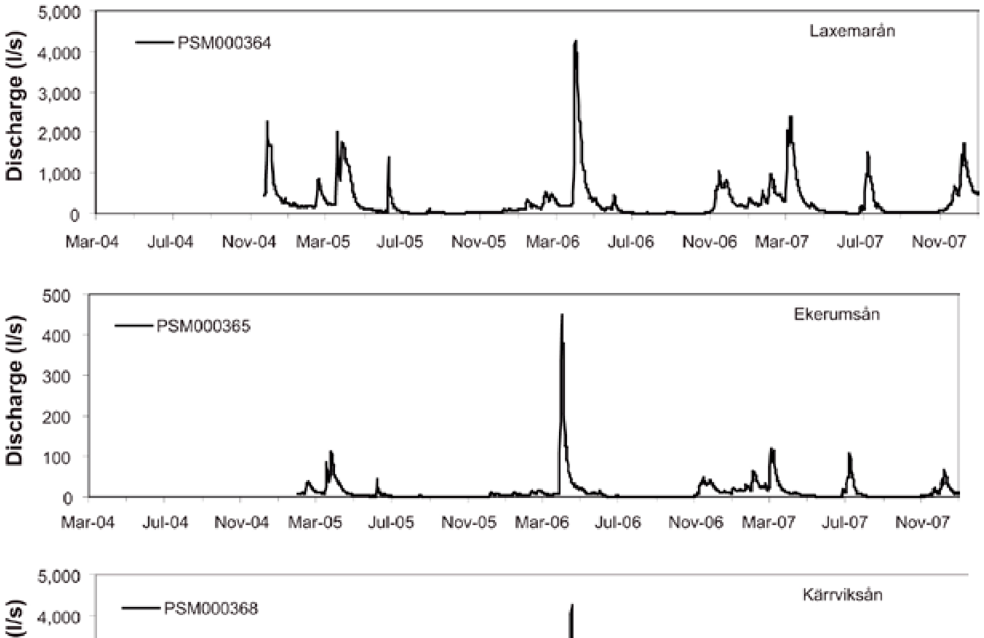


Figure 3-22c. *Time-series plots of daily average surface-water discharges at the discharge-gauging stations PSM000364, -365 and -368.*

Normalising the discharge ($L \cdot s^{-1}$) with the size of the catchment area (km^2) yields the so-called specific discharge ($L \cdot s^{-1} \cdot km^{-2}$), which commonly is used to facilitate comparisons of hydrological characteristics between catchment areas. Based on the discharge data shown in Figure 3-22 /Werner et al. 2008/ calculated the specific discharge, taking into account time periods of different lengths (see examples in Figure 3-23). Due to uncertainties related to the discharge data from discharge-gauging station PSM000348 located at the outlet from Lake Frisksjön, /Werner et al. 2008/ calculated "site-average" specific discharges both with and without the PSMS000348 data.

For the whole available data periods (up to August 31, 2007), the average specific discharges calculated for the different gauging stations vary between c 134 (gauging station PSM000353) and 231 $mm \cdot y^{-1}$ (gauging PSM000364), with an average of 167 $mm \cdot y^{-1}$ (excluding the PSM000348 data; see above). As shown in /Werner et al. 2008, the specific discharge demonstrates relatively large inter-annual variations, and as already mentioned also during individual years. The overall results show that based on the available discharge data up to the end of year 2007, the site-average specific discharge can be estimated to be on the order of 160–170 $mm \cdot y^{-1}$. This in accordance with the "regional" long-term (1961–1990) average of 150–180 $mm \cdot y^{-1}$, estimated by /Larsson-McCann et al. 2002/ prior to the site investigations.

3.3.4 Wetlands

Wetlands can be defined as terrestrial-aquatic transitions, i.e. areas either with a groundwater table at or near the ground surface, or areas covered by "shallow" surface water. There exist a variety of more or less strict definitions and classification systems for wetlands, most commonly based on ecological parameters. For instance, it has been suggested that wetlands must have one or more of the following three attributes: (l) at least periodically, the land supports mainly hydrophytes (aquatic plants), (2) the substrate is mainly undrained hydric (moist) soil, and (3) the substrate is saturated with water or covered by shallow water at some time during the growing season each year /Cowardin et al. 1979/.

From a hydrological viewpoint, wetlands can be divided into mires and marches. Mires are peat-forming wetlands, not influenced by surface water, whereas marches are influenced by surface water and do not form peat. In turn, mires can be divided into two main types, namely fens and (raised) bogs. According to this classification, fens are wetlands that at least partly are supplied by inflowing surface water and/or groundwater discharge, whereas precipitation is the only water supply for bogs /Kellner 2003/.

The relative surface coverages of different types of wetlands were calculated for each of the identified 26 catchment areas in the Laxemar area by /Brunberg et al. 2004/. The total wetland area per catchment area can then be found by adding the land-use classes MA3 and MA7–11 in Table 3-3 (see explanations of land-use types in Table 3-4). Hence, the relative coverage (in %) of wetland areas includes parts of the other calculated land-use classes. The relative and total wetland areas for each catchment area are summarised in Table 3-3. As can be seen in the table, there are wetlands in 20 of the 26 catchment areas; there are now wetlands in CAs 6, 9, 20, and 24–26. In total, wetlands cover c 3% (2.7 km^2/101.2 km^2) of the delineated catchment areas /Brunberg et al. 2004/.

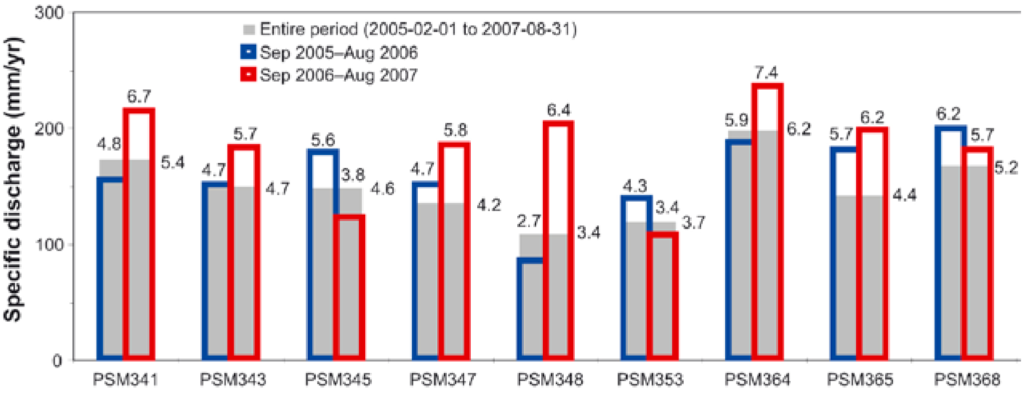


Figure 3-23. *Bar plot of the specific discharge for three different time periods. The specific discharge is expressed both in* $mm \cdot y^{-1}$ *(see y-axis scale) and* $L \cdot s^{-1} \cdot km^{-2}$ *(data above the bars).*

Table 3-3. Basic data for wetlands in the Laxemar area /Brunberg et al. 2004/.

Catchment	Relative wetland area (%)	Total wetland area (km²)	% coverage of total catchment area per type of wetland					
			MA3	MA7	MA8	MA9	MA10	MA11
1	18	0.0126	0	0	0	18	0	0
2	2	0.0076	1	0	0	0	0	1
3	1	0.01	1	0	0	0	0	0
4	1	0.00632	1	0	0	0	0	0
5	4	1.08616	1	0	1	0	0	2
6	0	0	0	0	0	0	0	0
7	1	0.02062	0	0	0	0	0	1
8	3	0.01497	0	0	3	0	0	0
9	0	0	0	0	0	0	0	0
10	2	0.81952	1	0	1	0	0	0
11	1	0.00523	0	0	1	0	0	0
12	5	0.1027	0	0	1	0	0	4
13	1	0.010033	0	0	1	0	0	0
14	5	0.0669	0	0	5	0	0	0
15	9	0.08703	0	0	9	0	0	0
16	1	0.00504	1	0	0	0	0	0
17	2	0.14038	1	0	0	0	0	1
18	3	0.26874	2	0	0	0	0	1
19	15	0.0276	0	0	1	0	0	14
20	0	0	0	0	0	0	0	0
21	8	0.00504	8	0	0	0	0	0
22	6	0.02154	0	0	0	0	0	6
23	1	0.00307	1	0	0	0	0	0
24	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0

Table 3-4. Explanations of the land-use types of Table 3-3 /Brunberg et al. 2004/.

Column	English	Swedish
MA3	Wetland normal – coniferous forest	Sankmark normal – barrskog
MA7	Wetland normal – deciduous forest	Sankmark normal – lövskog
MA8	Wetland normal – remaining open land	Sankmark normal – annan öppen mark
MA9	Wetland difficult – coniferous forest	Sankmark svår – barrskog
MA10	Wetland difficult – deciduous forest	Sankmark svår – lövskog
MA11	Wetland difficult – remaining open land	Sankmark svår – annan öppen mark

The landscape development process typical for near-coastal areas of Sweden involves the natural succession stages sea bay, lake, fen, and subsequently bog and agricultural land/forest. The Laxemar area is located in a region where most wetlands are formed by so called lake terrestrialisation /Kellner 2007/, i.e. wetlands formed after a lake stage. This implies that due to the continuous land rise, new lakes and thereafter wetlands will form in Laxemar /Sohlenius and Hedenström 2008/. However, many present and former wetlands in the area have not experienced a lake stage, but were formed directly after the area was separated from the sea.

In wetlands, peat can be formed as a result of incomplete plant-material degradation, due to acidic and anaerobic (oxygen-free) conditions. Many of the wetlands in the Laxemar area have been above sea level long enough for a distinct peat layer to form /Sohlenius and Hedenström 2008/. Some of the near-coastal wetlands in Laxemar do not contain peat, since they were relatively recently separated from the sea /Sohlenius and Hedenström 2008/. Peat is shown as Histosol (HI) on the soil map /Lundin et al. 2005/, see Figure 3-24. Histosol is a soil type formed from materials with a

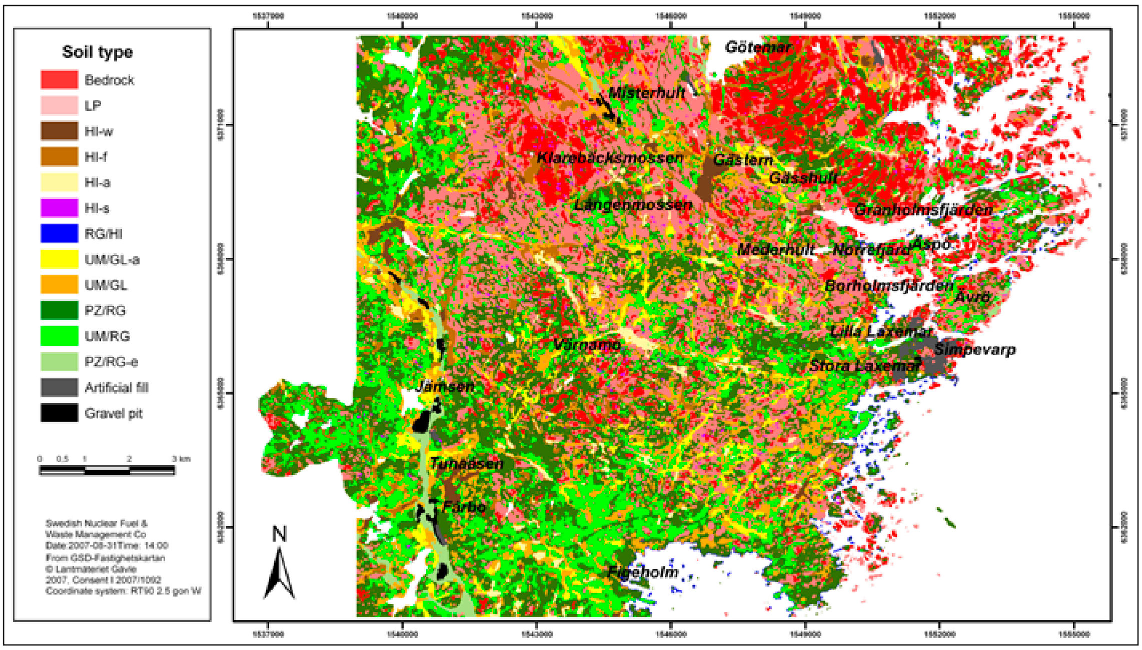


Figure 3-24. *Soil map of the Laxemar area /Lundin et al. 2005, Sohlenius and Hedenström 2008/.*

high content of organic matter, and is therefore the dominating soil type in the wetlands. As for the streams (cf. Section 3.3.3), many former wetlands in the Laxemar area are affected by land improvement and drainage operations to gain land for purposes of agriculture and forestry. These operations imply that there at present are larger peat areas than wetland areas, and that the peat in drained areas is partly or completely oxidised, which likely has caused peat compaction. The Histosol soil type is probably common also in drained wetlands, even though Umbrisol/Gleysol (UM/GL in Figure 3-24) may have been formed in some of these areas /Sohlenius and Hedenström 2008/.

Bogs are usually found in high-elevated areas, whereas fens occur in low-lying areas. There are numerous small wetlands (most of them of the bog type) in the parts of Laxemar dominated by till and exposed/shallow rock. Moreover, most of the mires are of the fen type, i.e. they receive water also from surrounding land areas. However, some of the mires are bogs, i.e. the precipitation is the only water supply. The bogs located in the high-elevated areas are generally characterised by thin QD, compared to the larger present and former wetlands located to the valleys. However, it is possible that small "pockets" with thicker QD occur also below the small wetlands /Sohlenius and Hedenström 2008/.

The natural succession stages imply that the QD stratigraphy below the wetlands resembles that of the lakes (cf. Section 3.3.2) and the sea bays (cf. Section 3.3.5). As indicated above, the post-deglaciation land upheaval results in the transformation of sea bays to lakes. Subsequently, the lakes are transformed to wetlands due to sedimentation and vegetation growth. In general, peat areas formed by this process are underlain by gyttja and clay /Kellner 2007/. Gyttja is formed by the degradation of organic material in lakes and the sea. Often there is a thin layer of sand or gravel between the clay and gyttja layers, due to outwashing of glacial deposits during land upheaval.

According to the regolith depth and stratigraphy model (RDM) /Nyman et al. 2008/, areas with peat on the QD map are typically underlain by gyttja clay, postglacial sand/gravel and glacial clay above till. /Nyman et al. 2008/ also define "shallow peat areas" (which mainly are located to high-altitude areas), characterised by peat directly above the till.

The QD stratigraphy below wetlands and peat areas in the Laxemar area was investigated by /Nilsson 2004/. The investigation included "true wetlands" (overgrown by reed, and with gyttja as the predominant type of QD), "true peat areas" (fens and bogs), and areas on "dry land", with just a thin layer of peat or water-laid sediments overlying the till or bedrock /Nilsson 2004/. The investigation shows that a typical top-down stratigraphy in wetlands and peat areas is peat (when present), clay gyttja and gyttja, silt/sand/gravel, postglacial clay, and glacial clay. According to the investigation, the individual QD layers below the wetlands are on the order of 0.5–2 m, except from the silt/sand/gravel layer, which generally is very thin. Hence, this investigation indicates that the bottom layers of the wetlands and peat areas consist of low-permeable materials, which would imply a limited interaction between groundwater below and surface water in the wetlands.

Three wetlands were investigated by means of drilling and installation of monitoring wells /Johansson et al. 2007/: Klarebäcksmossen, Gäster and Kärrsvik; see Figure 3-24. In terms of their age (i.e. elapsed time since they were separated from the sea), these three wetlands represent old/inland conditions (Klarebäcksmossen), intermediate conditions (Gäster) and recent/near-coastal conditions (Kärrsvik, located at the coast below Gässhult in Figure 3-24). Klarebäcksmossen was separated from the Baltic Sea c 11,250 years ago, and Gäster c 3,000–3,500 years ago /Nilsson 2004/. Klarebäcksmossen is a typical example of a bog, whereas Gäster (a lowered lake) and Kärrsvik are typical fens.

The oldest of the investigated wetlands, Klarebäcksmossen, contains bog peat in its raised central parts and fen peat along the lower-lying periphery (see Figure 3-25). In the figure, one can note that no layer of glacial clay has been detected below the wetland. The investigations of the mid-age wetland Gäster (a previously lowered lake, see Figure 3-26) reveal a QD stratigraphy in accordance with the RDM /Nyman et al. 2008/. Further, no layer of glacial clay has been detected below the most recent/near-coastal Kärrsvik wetland.

Figure 3-27 to 3-29 show time series of daily average groundwater levels in m.b.g.s. (metres below the ground surface) in six groundwater monitoring wells installed below wetlands. The figures are presented in a west-to-east order. Wells SSM000245 and -246 are installed in the wetland (bog) Klarebäcksmossen. This is the westernmost and oldest of the three investigated wetlands, since it is located farthest from the sea. Wells SSM000028 and -243 are installed in the intermediate-age wetland Gäster, whereas wells SSM000029 and -244 are installed in a wetland at Kärrsvik, located close to the coast and therefore the youngest of the three wetlands.

In Klarebäcksmossen (Figure 3-27), the screen of well SSM000245 is installed in peat and underlying thin layers of gyttja-bearing peat, clayey gyttja, sandy till and into the underlying rock. The well is installed at a somewhat lower elevation (22.76 m.a.s.l.) than the screen of SSM000246 (24.08 m.a.s.l.), installed in peat. The groundwater level is somewhat higher in well SSM000246, which hence indicates that there is groundwater recharge at Klarebäcksmossen (note that the vertical hydraulic head gradient is small). This is expected for (raised) bogs, which usually are ombrogenic /Kellner 2003, 2007/.

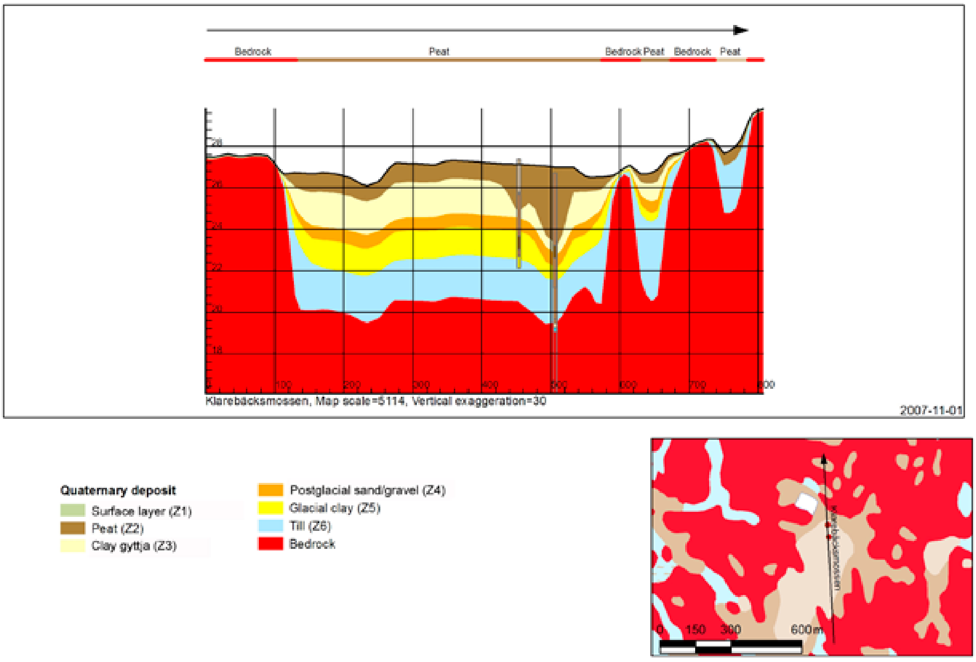


Figure 3-25. *Cross-section from the RDM at the wetland Klarebäcksmossen /Nyman et al. 2008/.*

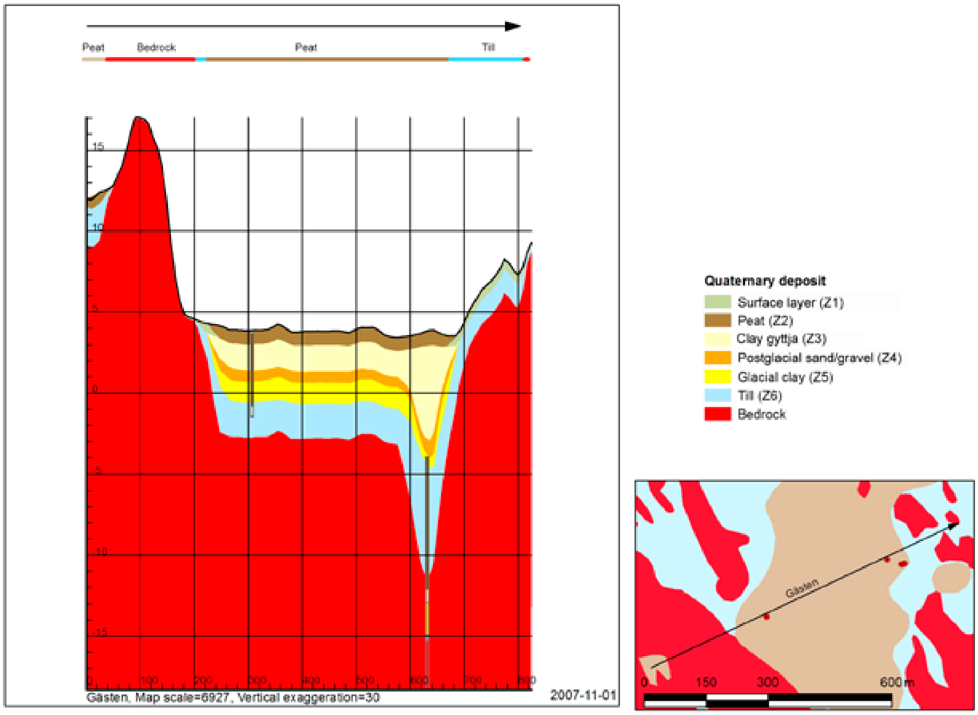


Figure 3-26. *Cross-section from the RDM at the Gäster wetland /Nyman et al. 2008/.*

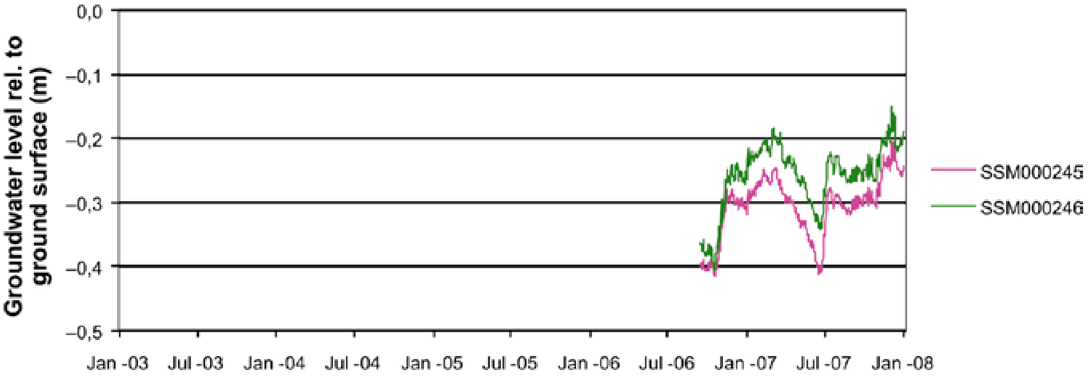


Figure 3-27. *Time-series plot of daily average groundwater levels below the Klarebäcksmossen wetland.*

Figure 3-28. *Time-series plot of daily average groundwater levels below the Gäster wetland.*

Figure 3-29. *Time-series plot of daily average groundwater levels below the Kärrsvik wetland.*

In Gäster (Figure 3-28), the screen of well SSM000243 is installed at a much lower elevation (–7.22 m.a.s.l.) in cobble-bearing clay and sandy till compared to the screen of SSM000028 (1.59 m.a.s.l.), installed in gyttja above the clay and till layers. The groundwater level is higher in well SSM000243, which hence indicates that there is groundwater discharge at Gäster.

In Kärrsvik (Figure 3-29), the screen of well SSM000244 is installed in sandy till at a lower elevation (–9.59 m.a.s.l.) than the screen of SSM000029 (–4.74 m.a.s.l.), installed in silty fine sand below peat and gyttja layers. The groundwater level is higher in well SSM000029, which indicates groundwater recharge in the wetland at Kärrsvik (the vertical head gradient is small).

3.3.5 Coastal basins

The coastal waters serve as an intermediary link between terrestrial areas and the open sea. The coastal waters of the Laxemar area are located in the transition zone between northern Kalmarsund and the Baltic Proper. Kalmarsund is a funnel-like strait, delimited by the large island of Öland on the eastern side and by the mainland on the western side, whereas the strait has open boundaries towards the north (wide) and south (narrow).

The coastline of Laxemar is irregular. It contains many islands and semi-enclosed, landlocked basins. The sea bottom along the Laxemar coast gradually slopes in the offshore (northeast) direction. The bathymetry of the Laxemar coastal area is illustrated in Figure 3-30, including the model grid used in the water-exchange modelling (see further below).

The sub-sea distribution of QD and exposed/shallow rock at Laxemar /Elhammer and Sandqvist 2005, Sohlenius and Hedenström 2008/ is shown in Figure 1-3 in Section 1-2. Similar to the terrestrial areas, the sea floor outside Laxemar is characterised by a relatively flat bedrock surface with numerous valleys. Glacial clay, at most locations overlain by a layer (< 1 m) of gravel or sand, is the dominant type of QD in the marine areas. For instance, in the area south of the Simpevarp peninsula, more than 40% of the sea floor is covered by glacial clay /Sohlenius and Hedenström 2008/. Moreover, the thickness of the glacial clay is often considerably greater in the marine areas compared to the terrestrial areas. Some areas below the sea have a high proportion of till, but till generally covers a much smaller proportion of the sea floor. Gyttja clay, likely with a thickness corresponding to that in the terrestrial areas, is currently deposited in the narrow bays (i.e. along sub-sea valleys) such as Granholmsfjärden along the coast.

Figure 3-31 shows a time-series plot of daily average sea-water level (m.a.s.l.) measured at the gauging stations PSM000369–371 (their locations are shown in Figure 2-4). The maximum and minimum daily average sea levels during the considered period (May 2004–Dec. 2007) were –0.52 and 0.71 m.a.s.l. respectively, whereas the average sea-water level was 0.03 m.a.s.l. The largest daily sea-level changes occurred on Nov. 1, 2006 (c. +0.26 m) and Dec. 22, 2004 (c. –0.23 m).

The water exchange of semi-enclosed coastal basins is induced by forces acting at different spatial and temporal scales; for an overview, see /Engqvist and Stenström 2004/. In the Baltic Sea, the influence of tides is generally insignificant, whereas density fluctuations is the dominant cause of water exchange for the present type of coastal basins /Engqvist and Omstedt 1992/. Such density

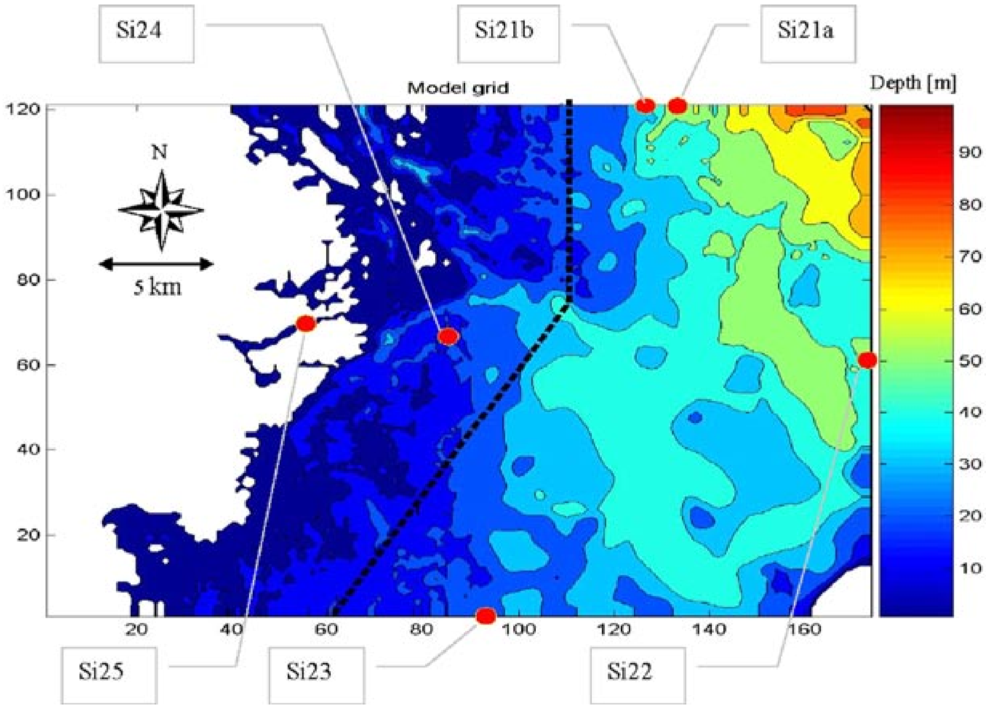


***Figure 3-30.** Bathymetric map of the Laxemar coastal area, showing the depth (m) of the sea /Engqvist and Andrejev 2008/. The map grid is the local model grid for the water-exchange modelling. The red dots show locations of oceanographic measurement stations. The island of Öland (the white area) can be seen in the southeast corner of the map.*

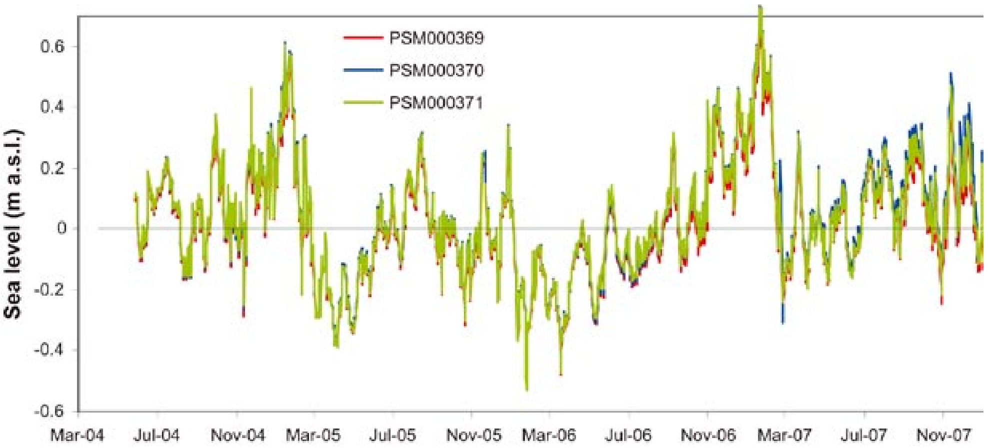


***Figure 3-31.** Time-series plot of daily average sea-water levels between May 27, 2004 and Dec. 31, 2007.*

fluctuations are induced by large-scale or local wind patterns, combined with freshwater discharge from streams. These processes vary seasonally but also on shorter time scales. Large volumes of freshwater discharge may induce estuarine circulation, which at least temporally may be an important mode of water exchange for channels connecting semi-enclosed embayments and the sea. Atmospheric heat transfer acts to stabilise (heating) or destabilise (cooling) density stratifications. Moreover, wind shear acts to increase the depth of the well-mixed surface layer, and large-scale wind patterns can also cause up- or down-welling events by means of so-called Ekman dynamics.

Due to the wide, open boundary towards the north (see Figure 3-30), Kalmarsund is strongly affected by the large-scale circulation of the Baltic Sea. This is notably the case for southbound coastal currents, with seasonal density fluctuations due to variations of the collective discharge from major streams to the Bothnian Bay and to the northern part of the Baltic Sea.

In Laxemar, the freshwater discharge to the sea is relatively moderate, with primarily the two streams Laxemarån and Gerseboån discharging into the coastal area. Salinity and temperature measurements indicate that stratification is strengthened during the heating period from April to August, during which period the thermocline occasionally is interrupted by strong vertical mixing events or by possible up-/down-welling episodes /Engqvist and Andrejev 2008, Wijnbladh et al. 2008/. During the cooling period (September to April), mixing yields vertically well-mixed conditions down to depths of about 20 m.

Cooling water for the Simpevarp power plant is withdrawn from two separate depths and locations south of the plant. During the period Apr. 2004–Apr. 2005, the cooling-water withdrawal rate was c 90 $m^3 \cdot s^{-1}$ /Engqvist and Andrejev 2008/. The cooling water, with an average temperature excess of c 10°C, is subsequently discharged into a small bay north of the plant. The impact of the cooling-water discharge on the local circulation is discussed briefly below and in more detail in /Engqvist and Andrejev 2008/.

As shown in Figure 3-32, the Laxemar coastal area is for water-exchange modelling purposes geographically subdivided into totally 19 non-overlapping sub-basins. The sub-basin delineation is based on the sea bathymetry /Wijnbladh et al. 2008/. Various quantities, including the so-called average age (AvA; see below) have been calculated using the 3D numerical model AS3D and the model CDB /Andrejev and Sokolov 1997, Engqvist 1997, Wijnbladh et al. 2008/.

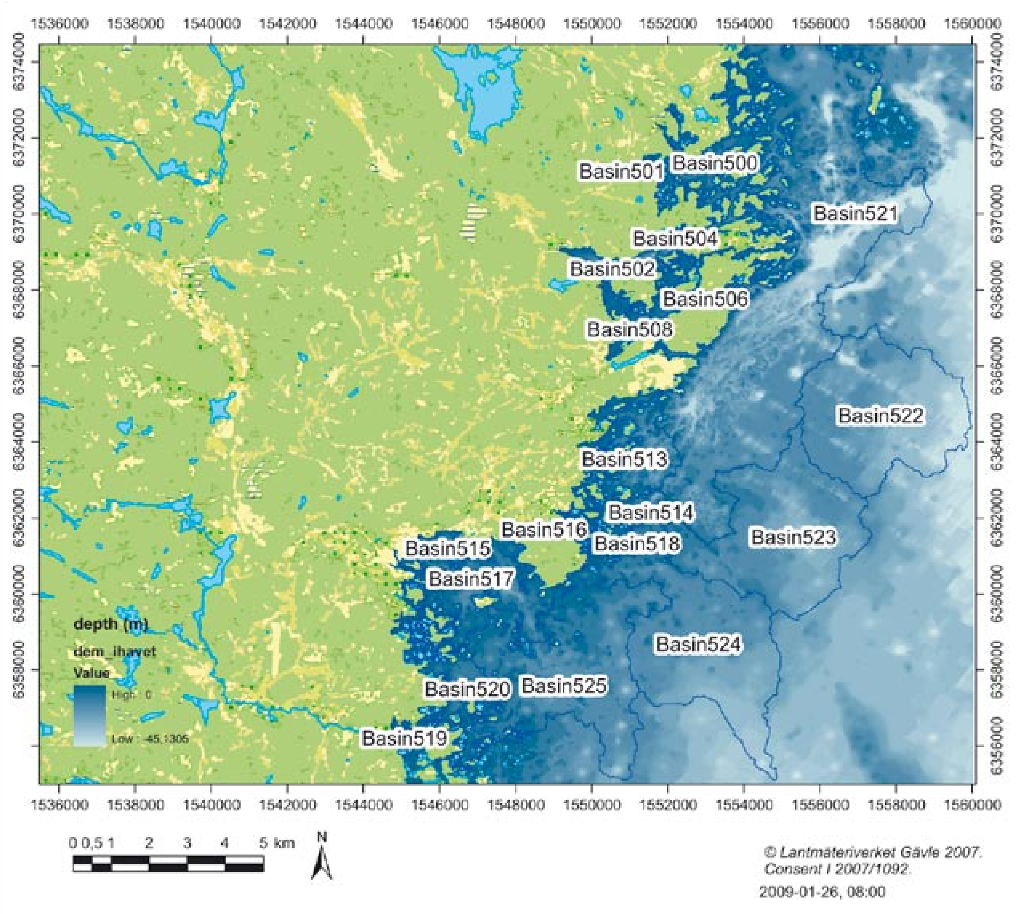


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Figure 3-32. Sub-basin delineation of the Laxemar coastal area /Wijnbladh et al. 2008/.

The AS3D model was set up on two different scales; one local model with a fine-resolution grid (0.1 by 0.1 nautical miles, or c. 0,185 by 0,185 km), and one of the entire Baltic Sea (with a coarser grid of 2 by 2 nautical miles). Due to the scarcity of oceanographic measurements (cf. red dots in Figure 3-30) the Baltic Sea-scale model is used to provide boundary conditions (currents, salinity and temperature) for the local-scale model. However, the semi-enclosed, landlocked basins are not deemed appropriate for 3D modelling /Wijnbladh et al. 2008/. Therefore, 9 of the 19 sub-basins were modelled using a separate model, denoted CDB (Coupled Discrete Basins) /Engqvist 1997/.

In the AS3D and CDB modelling /Wijnbladh et al. 2008/, data were used from the year 1981, whereas model validation was performed using data from the period 2004–2005 /Engqvist and Andrejev 2008/. In year 1981-simulations, the dynamics induced by the cooling-water withdrawal/discharge was not included, since the aim of that simulation was to characterise the water exchange on a long-term basis. However, the cooling water dynamics were included in the model validation simulations.

Table 3-5 exemplifies results of the AS3D (denoted 3D in the table) and CDB modelling, in terms of computed so-called AvA times (days) for each of the delineated sub-basins (see Figure 3-32). Considering a particular "water parcel" present in a sub-basin at a particular instant in time, the "age" of the parcel can be defined as the time that has passed since it entered the sub-basin /Bolin and Rodhe 1973/; the average age (AvA) is the average of the ensemble of parcels present in the sub-basin.

From Table 3-5, one can note that the longest AvA times (a few days up to almost one month) are computed for the semi-enclosed, landlocked basins (500–508) and the secluded sub-basins (515–516 and 519). The relatively long AvA times are due to that the water circulation of these sub-basins is constrained to narrow strait passages, which yield comparatively low advective in- and outflows /Wijnbladh et al. 2008/. According to the water-exchange modelling, the sub-basins farther from the coast are characterised by shorter AvA times (one day or shorter), which reflect a stronger and more persistent advective throughflow. It can be noted that sub-basin 521 is influenced by the cooling-water pumping (c 90 $m^3 \cdot s^{-1}$). According to the modelling, the effect of this pumping is a slight temperature increase, which is rapidly dissipated and cannot be detected only a few grid cells away from the cooling-water outlets.

Table 3-5. Model-computed average age (AvA) for the delineated sub-basins in the Laxemar coastal area /Wijnbladh et al. 2008/.

Sub-basin	AvA (d)	Model type
500	4.26	CDB
501	15.8	CDB
502	24.4	CDB
504	5.88	CDB
506	2.78	CDB
508	10.3	CDB
513	0.29	3D
514	0.31	3D
515	6.86	CDB
516	9.25	CDB
517	1.03	3D
518	0.40	3D
519	7.98	CDB
520	0.40	3D
521	0.81	3D
522	0.19	3D
523	0.27	3D
524	0.14	3D
525	0.31	3D

3.4 Description of hydrogeological flow domains

3.4.1 Overall conceptual model and identification of type areas

The conceptual models of the regolith /Sohlenius and Hedenström 2008/ and the rock /Rhén et al. 2008, 2009/ constitute an underlying framework for interpretation of time-series data and near-surface hydrogeological properties data /Werner et al. 2008/, and also for the development of quantitative water flow models /Bosson et al. 2008b, Rhén et al. 2008, 2009/. Prior to moving to the descriptions of hydrogeological flow domains in Sections 3.4.2–3, this section provides a brief summary of the conceptual models of the regolith and the rock in Laxemar. In order to obtain a framework for description of the overall patterns of groundwater recharge and discharge, these descriptions are here used to define hydrogeological type areas.

Conceptual model of the regolith

The conceptual model of the regolith in Laxemar, also including descriptions of the upper part of the rock, is presented in /Sohlenius and Hedenström 2008/. They define the term "regolith" as the loose deposits overlying the rock. All known regolith in Laxemar was deposited during the Quaternary period, which implies that the regolith also can be referred to as Quaternary deposits (QD). From a geological point of view, the QD are divided into two main groups; glacial and postglacial. Glacial deposits (the oldest group) were deposited during the latest deglaciation (c. 12,000 years BC), either directly from the ice or by melt water, whereas postglacial deposits were deposited subsequent to deglaciation. Due to the compression of the rock by the glacial inland ice, the Laxemar area was covered with water subsequent to deglaciation. This implies that the Laxemar area is located below the so-called highest coastline.

The geographical distribution of QD in the Laxemar area (including both terrestrial and marine areas) is illustrated in the detailed QD map in Figure 1-3 in Section 1.2. Approximately 35–40% of the terrestrial part of the Laxemar-Simpevarp regional model area consists of exposed or shallow rock. The dominant (and oldest) type of QD in Laxemar is glacial (sandy-gravelly) till, which was deposited directly from the melting ice during deglaciation. Particularly in low-lying areas, glacial clay is deposited above the till. The area also contains four glaciofluvial deposits (in the form of eskers), which also originate from melting ice. The glaciofluvial material in these eskers is well sorted, and it contains more rounded particles than the glacial till. Both till and glaciofluvial deposits are assumed to rest directly on the rock.

Subsequent to deglaciation, the Laxemar area was subject to submarine waves and currents. Under these circumstances, postglacial sediments (gyttja/clay gyttja/gyttja clay and postglacial sand/gravel) were deposited above the glacial deposits in valleys and other sheltered positions. Gradually, the post-deglaciation land upheaval transformed sea bays to lakes, which subsequently were transformed to wetlands due to sedimentation and vegetation growth. However, many wetlands in the Laxemar area have been formed without passing a lake stage. Peat has also accumulated in low-lying areas. As described in Section 3.3.3, many of these areas have been subject to land improvement and drainage operations.

As introduced in Section 3.2.3, /Nyman et al. 2008/ present a conceptual-geometrical model of the QD in Laxemar, here referred to as the RDM (regolith depth and stratigraphy model). This model contains a 3D representation of the QD, including both the total QD thickness and the individual thicknesses of totally 6 QD layers. Figure 3-33 illustrates the RDM, in the form of map of total regolith (QD) depths in the central part of Laxemar.

/Sohlenius and Hedenström 2008/ define 3 regolith type areas in Laxemar, based on the topography, the QD map and the RDM. These type areas can be summarised as follows:

Type area I – Topographically high areas: This type area is dominated by exposed/shallow rock and till. In the regolith type area definition, this type area also includes hummocky moraine areas (located in the south-western and central parts of Laxemar). These areas are characterised by thicker QD (till) compared to the exposed/shallow rock areas.

Type area II – Valleys: This type area is characterised by relatively thick QD, including postglacial deposits (peat, clay gyttja, sand/gravel) overlying glacial deposits (glacial clay and till). The till at the terrestrial valley bottoms appears to be more sorted compared to till in the other areas, according to field observations. The reason for this is unknown. The valleys generally coincide with lineaments (deformation zones) in the rock, and the rock is hence more densely fractured compared to the other type areas.

Type area III – Glaciofluvial deposits: The large esker (Tuna esker) and the three small eskers constitute their own type area. The QD in these eskers are well-sorted, mainly sand and gravel. These deposits are assumed to rest directly on the rock.

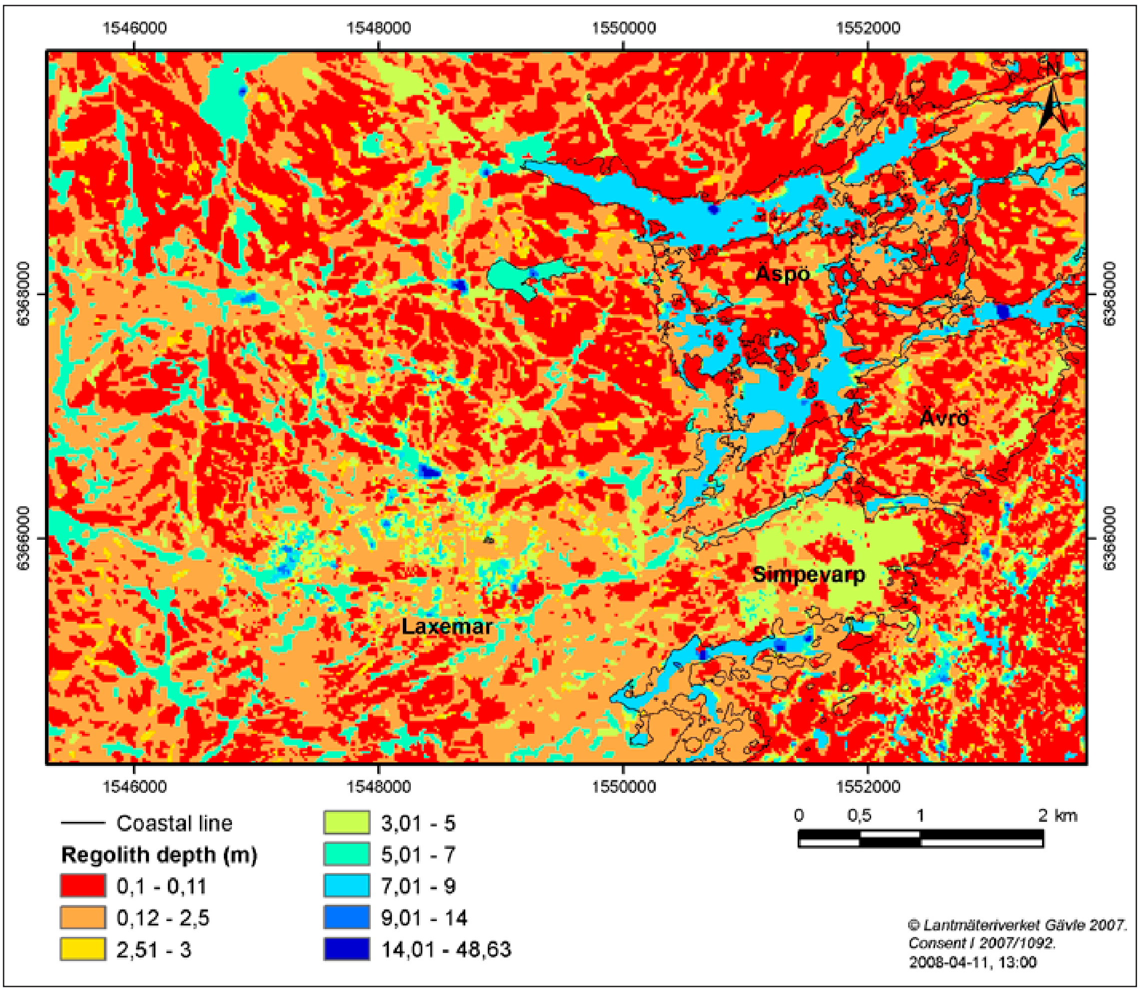


Figure 3-33. *Map of total regolith (QD) depths in the central part of Laxemar according to the RDM /Nyman et al. 2008/.*

Conceptual model of the rock

The conceptual hydrogeological model of the rock in Laxemar is presented in /Rhén et al. 2008, 2009/. For the present purposes, this model can be summarised in the form of the generalised conceptual section in Figure 3-34. The hydrogeological properties of the rock are further described in Section 3.4.3.

In general, the hydraulic conductivity of the rock decreases with depth, both within the deterministically defined deformation zones and in the rock between these zones. The deformation zones are mostly subvertical and roughly about one order of magnitude more conductive than the surrounding rock (100-m scale; see Section 3.4.3). As can be seen in the figure, the deformation zones have a variable thickness, and they are typically wider closer to the rock surface. In the rock mass between the deformation zones, there is a more pronounced depth decrease of the intensity of subhorisontal fractures compared to subvertical fractures.

From a conceptual point of view, the rock in Laxemar can hydrogeologically be divided and described in terms of the following depth intervals, here denoted dZ1–dZ4 (cf. Figure 3-34).

- dZ1 (0–150 m): Near-surface rock, characterised by a high frequency of conductive fractures.
- dZ2 (150–400 m): Intermediate-depth rock, characterised by an intermediate frequency of conductive fractures.
- dZ3 (400–650 m): Rock at repository level, characterised by a low frequency of conductive fractures.
- dZ4 (650 m –): Deep rock, characterised by a sparse network of conductive fractures.

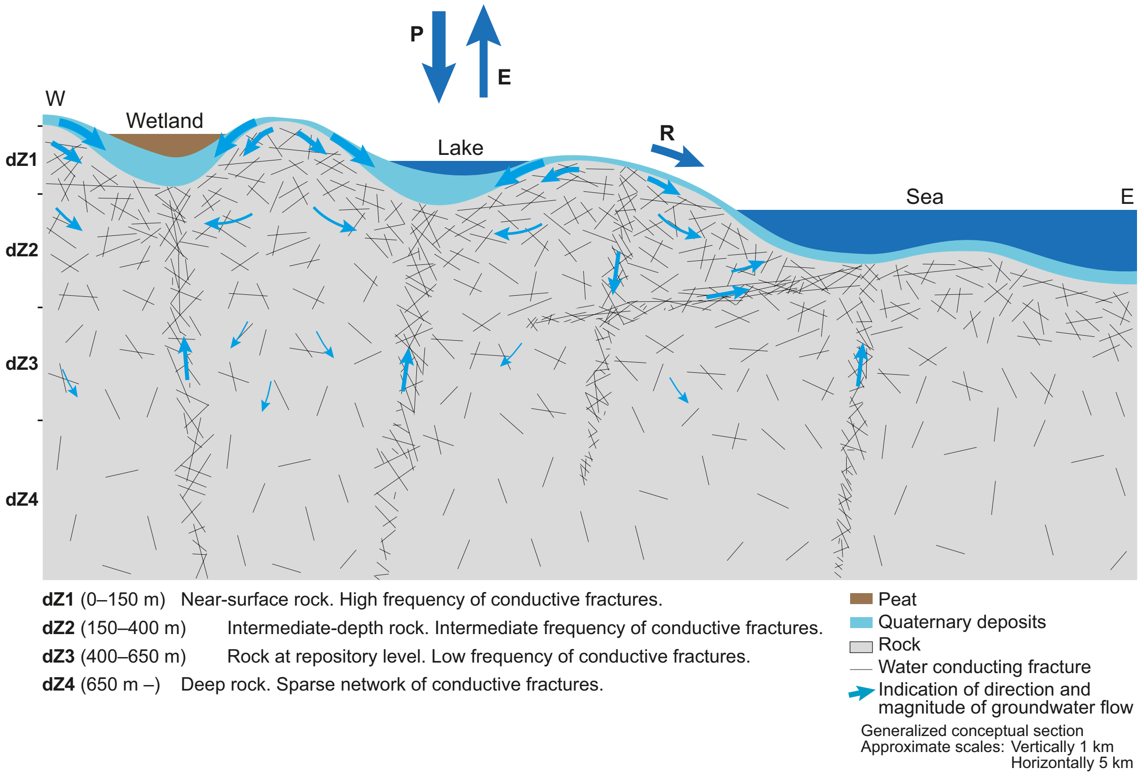


Figure 3-34. *Generalised conceptual section illustrating the conceptual model of hydrology and hydrogeology in Laxemar. Note the different horisontal (5 km) and vertical (1 km) scales, and that the thickness of the QD is exaggerated in the figure. In the figure, P represents precipitation, E is evapotranspiration, and R denotes runoff.*

Near-surface hydrogeological types areas

Four main hydrogeological type areas are defined here, which conform to the subdivision of the regolith described above: High-altitude areas, valleys (large and small, i.e. two subtype areas), glaciofluvial deposits, and hummocky moraine areas. As mentioned previously, the hydrogeological type areas are mainly used as a framework for description of the overall patterns of groundwater recharge and discharge.

Below follows a description of the key aspects and components outlined in Section 3.1 to be part of the conceptual model: Hydrological objects, hydrogeological flow domains, source areas (infiltration and recharge), and recipient areas and processes and properties between source/recipient areas (sub-flow systems and discharge). The geographical extent of the type areas can be illustrated by the extent of the type areas identified in the description of regolith and near-surface rock /Sohlenius and Hedenström 2008/ according to Figure 3-35. Note that type area Ib in this figure equals the present type area IV (hummocky moraine areas), and that type area II in Figure 3-35 here is divided into subtype areas IIa and IIb.

Type area I – High-altitude areas

A large fraction (c 35–40%) of the terrestrial parts of the Laxemar-Simpevarp area contains exposed or shallow rock /Sohlenius and Hedenström 2008/. The geographic extent of this type area (both in terrestrial and marine areas) can be approximated by type area Ia in Figure 3-35 and "precambrian bedrock" on the detailed QD map (see Figure 1-3 in Section 1.2). The extent of exposed rock areas is likely overestimated in the terrestrial areas, as some of the areas mapped as exposed rock also include areas with boulders covered with vegetation /Sohlenius and Hedenström 2008/. The high-altitude areas contain wetlands in the form of small bogs or fens in local depressions, whereas rock is the dominating hydrogeological flow domain. This type area has no or only thin QD (< 0.5 m, thicker at the locations where bogs or fens are present), dominated by a surface-affected layer of till and/or organic material (lichen or mosses).

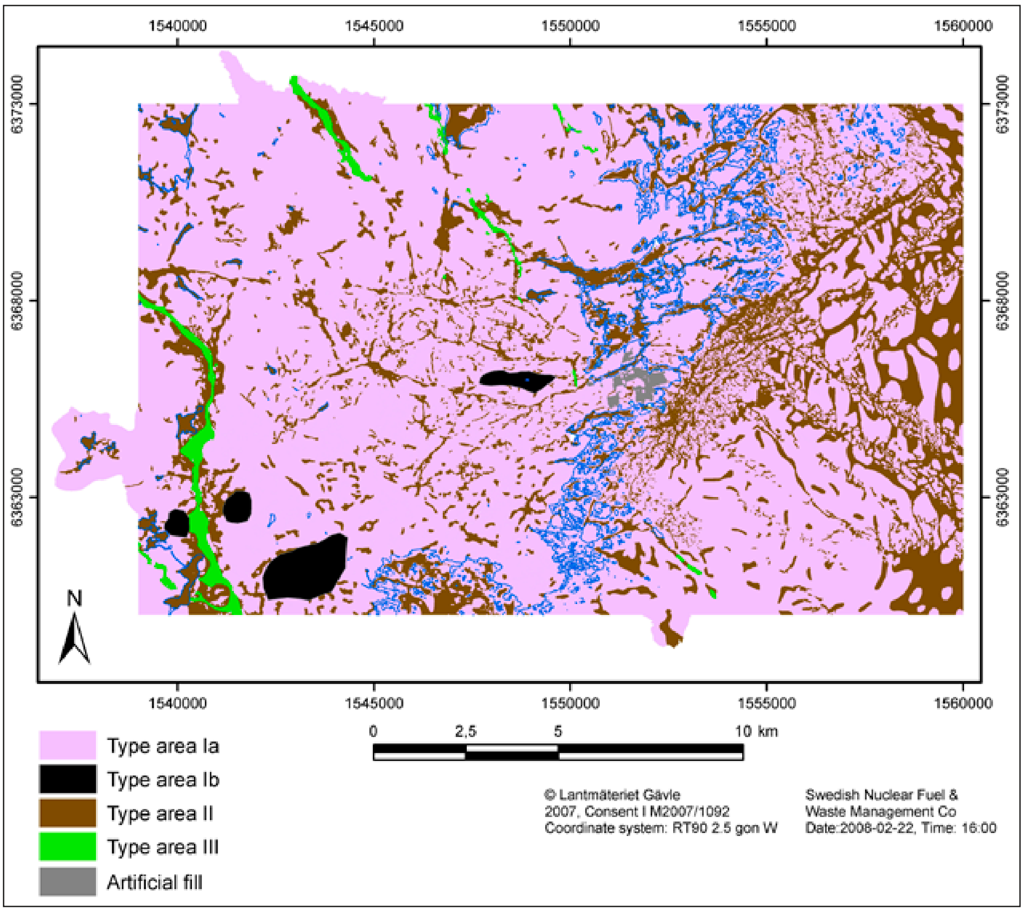


Figure 3-35. *Illustration of the geographical extent of the regolith type areas /Sohlenius and Hedenström 2008/. Note that type area Ib in the figure corresponds to the present type area IV (hummocky moraine areas), and that type area II (valleys) here is divided into two subtype areas, IIa and IIb.*

The processes of groundwater recharge and overland flow (surface runoff) predominantly take place in the high-altitude areas. However, it should be noted that evaluation of monitoring data /Werner et al. 2008/ indicates that the lakes Frisksjön and Jämsen to some extent also may contribute to groundwater recharge, in the central parts of Lake Frisksjön and during dry periods along the periphery of Lake Jämsen.

The locations where rain and melting snow infiltrate depend on both the rain/snowmelt intensity and the local infiltration capacity. This implies that the largest part of rainfall and snowmelt likely forms surface runoff in areas with exposed/shallow rock, either directly on the exposed rock surface or in the thin QD above the rock. Along its flow paths, the surface runoff subsequently infiltrates either in exposed rock fractures or in till, which has larger thickness and hence larger transmissivity further downslope. Rain and melting snow that infiltrate exposed rock fractures act as a source of groundwater recharge to the deeper parts of the rock. Hence, water that infiltrate into the rock in higher-altitude areas may enter deeper and larger-scale flow systems in the rock.

Type area IIa – Large valleys

The terrestrial parts of the Laxemar area contain three major stream valleys (Laxemarån, Mederhultsån and Ekerumsån), whereas other valleys in the area are relatively small. In the terrestrial parts, the valleys contain lakes, streams and wetlands and the hydrogeological flow domains QD and rock. The large valleys contain relatively thick QD, on the order of 5–10 m. Locally, the QD thickness may be more than 30 m, and up to 50 m in marine (sub-sea) valleys. The largest parts of the valleys contain postglacial deposits (peat, clay gyttja or postglacial sand) at the surface. The top-down QD stratigraphy in the valleys is typically peat-clay gyttja-postglacial sand/gravel-glacial clay-till. Close to the coast, the marine valleys are also characterised by this QD stratigraphy (the bottom of the sub-sea valleys are dominated by clay gyttja), whereas glacial clay and postglacial sand dominate the valley bottoms outside the archipelago; these valley bottoms are characterised by erosion and transportation of sediments.

The processes of groundwater discharge and formation of surface-water flow primarily take place in the valleys. Hydrogeological properties data on the QD in the large valleys /Sohlenius et al. 2006a, Morosini et al. 2007b/ indicate that the till is more well-sorted and has a higher hydraulic conductivity (approximately one order of magnitude) in the large valleys compared to the till in other areas. The phenomenon of well-sorted till in the deepest parts of the large valleys cannot be fully explained /Sohlenius and Hedenström 2008/. At many locations, the large valleys coincide with outcropping deformation zones, and locally, there is a diffuse interface between QD and rock /Sohlenius et al. 2006a, Morosini et al. 2007b/. For illustrations of typical QD and near-surface rock characteristics in the bottom of large valleys, see Figure 3-36.

The presence of a layer of low-permeable glacial clay between the till and the overlying postglacial deposits (Figure 3-36) is a key component in the conceptual description of groundwater discharge and formation of surface-water flow in the valleys. Specifically, the glacial clay layer may act to separate two flow sub-domains in the QD; an upper subdomain consisting of postglacial deposits above the glacial clay and a lower subdomain, consisting of till directly overlying the rock. Upward groundwater flow from the rock to QD hence takes place along outcropping deformation zones into the "lower QD subdomain", at locations likely consisting of QD with a higher hydraulic conductivity compared to the till in other parts of the area. At locations where the till is overlain by glacial clay, the latter layer is thought to limit the magnitude of groundwater discharge to the ground surface.

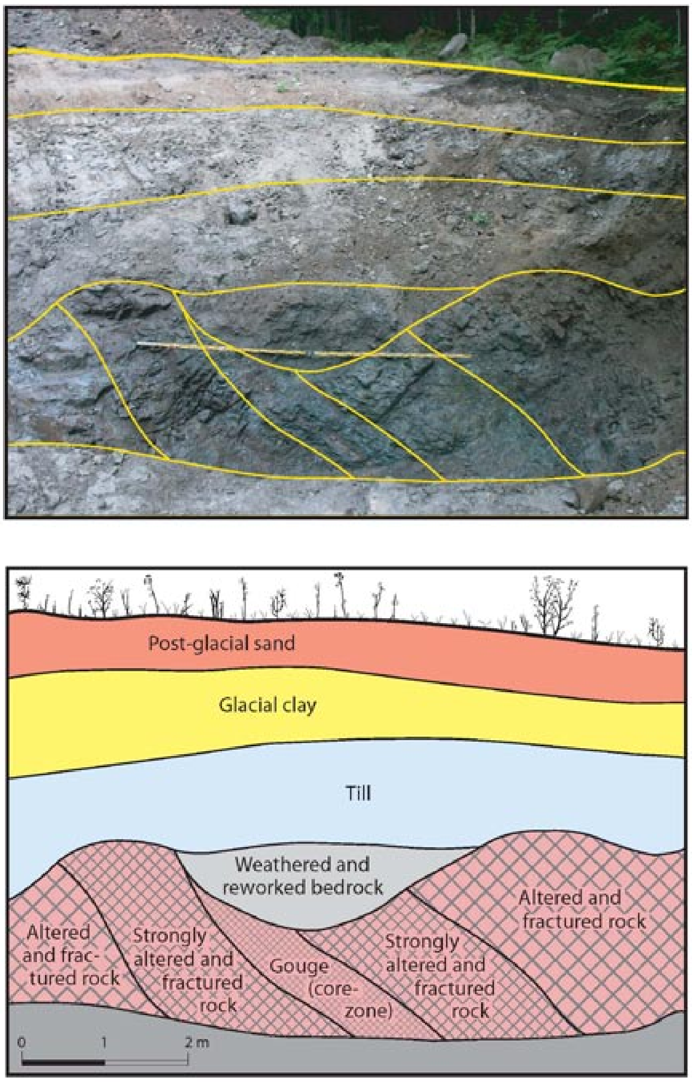


Figure 3-36. *Photograph and schematic illustration of rock alterations, which were observed during the documentation of the excavation across a large valley in Laxemar. The illustration shows the stratigraphical distribution of the QD overlying the rock /Sohlenius et al. 2006a/.*

Type area IIb – Small valleys

The identified main differences between small and large valleys (type area IIa) are that the former are associated with smaller catchment areas and smaller (or no) streams. The small valleys are generally more shallow and narrow, and contain thinner QD. In addition, evaluation of hydraulic conductivity data from the QD in large and small valleys /Werner et al. 2008/ indicates a lower hydraulic conductivity of the till in the small valleys compared to the bottom of the large valleys.

Type area III – Glaciofluvial deposits

There are four glaciofluvial deposits in the Laxemar area, of which the Tuna esker (Swedish: Tunaåsen) is the largest (see Figure 1-3 in Section 1.2, and type area III in Figure 3-35). This type area is associated with the flow domains QD and rock, of which groundwater flow in QD along the esker dominates. The QD depth is on the order of 15 m (Tunaåsen) and 5 m (the smaller eskers Gässhultsåsen, Misterhultsåsen and a nameless esker). The QD stratigraphy is generally complex, containing stones, gravel, sand and silt. Since glaciofluvial deposits generally have been formed along topographic depressions (so-called deglaciation streams), they act as groundwater recharge areas. Hydraulic gradients are normally small within eskers, due to that the glaciofluvial material (sand, gravel) is characterised by a high hydraulic conductivity.

Type area IV – Hummocky moraine areas

In the conceptual description of the regolith /Sohlenius and Hedenström 2008/, the so-called hummocky moraine areas are included in the type area of high-altitude areas (type area Ib in Figure 3-35). In the present description, these hummocky moraine areas are described as a separate type area, in order to emphasise the differences to the high-altitude areas from a hydrogeological-hydrological viewpoint.

The hummocky moraine areas are associated with the hydrogeological flow domains QD and rock. The QD thickness is on the order of 2 m (locally thicker) and is dominated by till. The till has hydraulic properties corresponding to those of small valleys. The hummocky moraine areas are characterised by an undulating topography and small moraine hills that probably were formed by a more or less stagnant ice during the deglaciation. These topographic characteristics imply a small scale near-surface groundwater recharge-discharge pattern. The fact that the hummocky moraine areas contain few (and small) surface waters emphasise the influence of the low-permeable QD above the till in the large valleys; the low-permeable QD are an important prerequisite for the formation of surface-water flow.

3.4.2 Quaternary deposits

Hydrogeological properties

According to the conceptual description of the regolith /Sohlenius and Hedenström 2008/, sandy-gravelly till is overlying the rock in more or less the whole regional model area, also in most areas with exposed/shallow rock (which may have a QD depth of up to c 0.5 m). The exceptions are some of the exposed/shallow rock areas, in which organic soil and a relatively thin vegetation layer is directly overlying the rock. The sandy-gravelly till is characterised by a relatively high hydraulic conductivity, c $4 \cdot 10^{-5}$ $m \cdot s^{-1}$ /Werner et al. 2008/. Furthermore, as mentioned previously and also illustrated in the vertical N-S section in Figure 3-37, there are indications that the hydraulic conductivity of the QD overlying the rock in the deepest parts of the large (i.e. wide and deep) valleys is about one order of magnitude higher than that of till in other parts of the area.

Moreover, permeameter tests on till indicate an anisotropic hydraulic conductivity, with an anisotropy ratio (K_h/K_v, where subscripts h and v denote horisontal and vertical, respectively) that may be on the order of 15–30. However, it should be noted that permeameter tests are associated with a smaller tested volume than that of e.g. slug tests providing hydraulic conductivity data. Generic data are used to support the estimates of the hydrogeological properties for QD types other than till /Werner et al. 2008/.

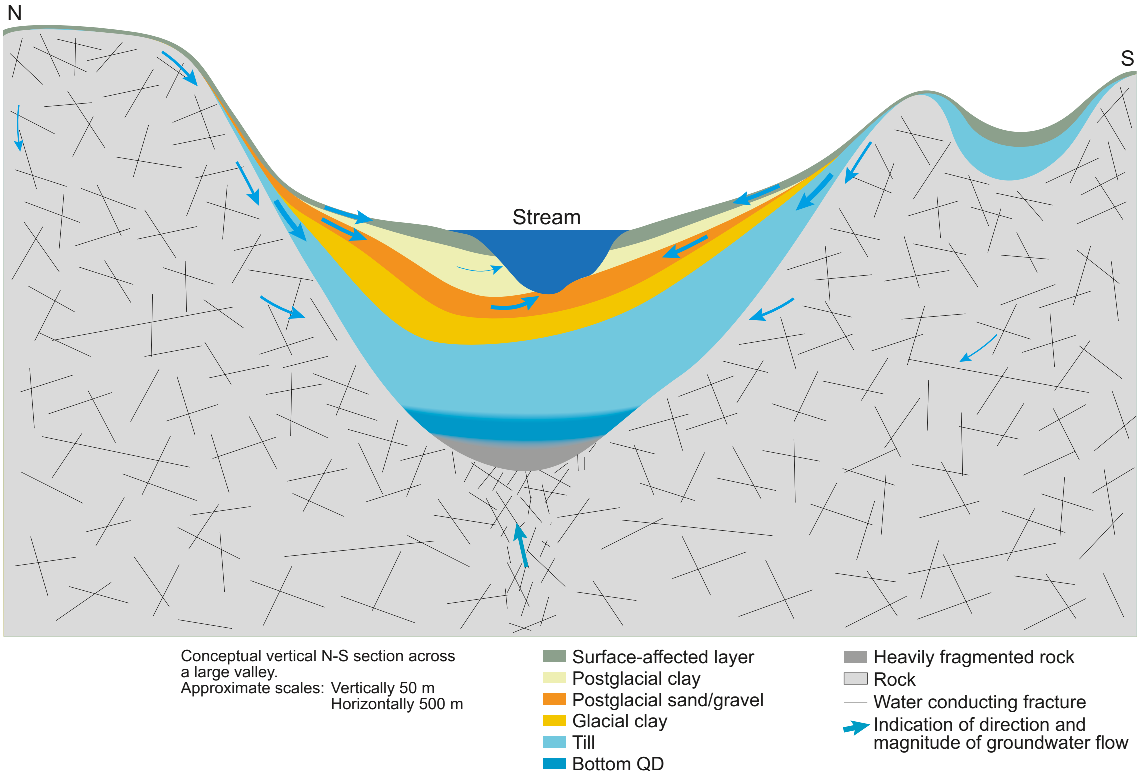


Figure 3-37. *Conceptual vertical N-S section across a large valley in Laxemar. Note the different horisontal (500 m) and vertical (50 m) scales, and that the size of the stream is exaggerated in the figure. "Bottom QD" represents more conductive QD that locally overlay the rock in the deepest parts of the large valleys.*

The hydogeological properties of the QD and/or the interface between QD and rock are evaluated from PSD (particle-size distribution) curves (47 QD samples), slug tests (70 tests), and hydraulic single-hole (8 tests) and interference tests (6 tests) in groundwater monitoring wells. Furthermore, permeameter tests (47 tests) were performed in the laboratory on undisturbed QD samples. /Werner et al. 2008/ provide a detailed presentation of the above test results. It should be noted that there are few site-specific data for QD types other than till. With a few exceptions (e.g. /Kellner 2003, 2007, Ferone and Devito 2004/), there are also few generic data for QD types such as peat and gyttja. This implies that in the present QD parameterisation, generic data are used to support the estimates of the hydrogeological properties for types of QD other than till.

Based on available hydrogeological properties data, /Werner et al. 2008/ presented a detailed hydrogeological parameterisation of the regolith. The parameterisation follows the geometrical representation of the QD according to the RDM (regolith depth and stratigraphy model) /Nyman et al. 2008/. The parameter assignment by /Werner et al. 2008/ is to be considered as a starting point for the quantitative water flow modelling. A summary table of the hydrogeological parameterisation of the QD is presented in Table 3-6 in Section 3.4.3, including a summary of the hydrogeological properties of the rock.

Groundwater-level data

This section summarises the groundwater-level data available in the Laxemar 2.3 data set and some main conclusions that can be drawn based on these data; /Werner et al. 2008/ provide more detailed presentations and analyses. For an overview of the locations of the wells and the available time-series data, see Section 2.2.3.

Considering all available groundwater-level data, but only taking into account time series longer than 150 data days (which implies that 5 of the totally 76 data series are not included), the overall average groundwater level is c 8.0 m.a.s.l. and the overall average depth to the groundwater table in the QD is c 0.8 m.b.g.s. The lowest and highest average groundwater level, respectively, is –0.8 m.a.s.l. (SSM000018) and 26.4 m.a.s.l. (SSM000245 and -246). The average amplitude (the "double" amplitude, i.e. maximum minus minimum groundwater level) is 1.29 m. The smallest amplitudes are observed for wells SSM000245 (0.17 m) and –246 (0.22 m), whereas the largest amplitude is observed for well SSM000039 (3.44 m). The groundwater level amplitudes are hence generally small; say, on the order of 1 m. Groundwater levels fluctuate on relatively small temporal scales. For many wells, these small-scale fluctuations are overlain by more or less typical seasonal variations; high groundwater levels during autumn, winter, and spring, and declining groundwater levels during the summer.

Considering individual areas (Laxemar, Hålö and the island of Ävrö), the within-area difference of the average groundwater level is largest in Laxemar (approximately –1 to 26 m.a.s.l.). The observed larger variability in Laxemar is likely due to due to larger topographic variations in that area compared to the other areas. It can be noted that in Laxemar, there is a much smaller range of depths to the groundwater table than of absolute groundwater levels (see the discussion below on the topographic influence on groundwater levels).

Figure 3-38 illustrates the temporal distribution of the depth to the groundwater level, in terms of the cumulative frequency distribution of daily values, whereas Figure 3-39 shows plots of average groundwater levels versus ground-surface elevations. Note that these figures only include wells with data periods longer than 150 days (cf. Section 2.2.3). These figures illustrate that the groundwater level is located at shallow depths and that there hence is a strong correlation between the (elevation of) the groundwater level and the ground-surface elevation.

Considering all daily data in Figure 3-38, the groundwater table is located within 2 m below ground during 90% of the time, whereas all daily site-average groundwater table depths are 2 m or less; the groundwater table depth is c 1 m or less for about 50% of the time. In Figure 3-39, there are 11 wells that on average are artesian; on average for these wells, the groundwater level is located c 0.2 m above ground. The largest average depth to the groundwater table is found at well SSM000230 (red dot in Figure 3-39).

/Werner et al. 2008/ present further investigations of the relationship between groundwater levels in the QD and the local topography of the ground surface, also taking into account the elevation of the rock surface. These investigations indicate that there seems to be no (positive) correlation between the depth to the groundwater table and the depth to the rock surface, whereas the results further emphasise the strong correlation between the groundwater level and the ground-surface elevation. Further, there appears to be some correlation to the elevation of the rock surface, indicating that the ground-surface topography is a suitable indicator not only of groundwater levels in the QD but also of the topography of the rock surface.

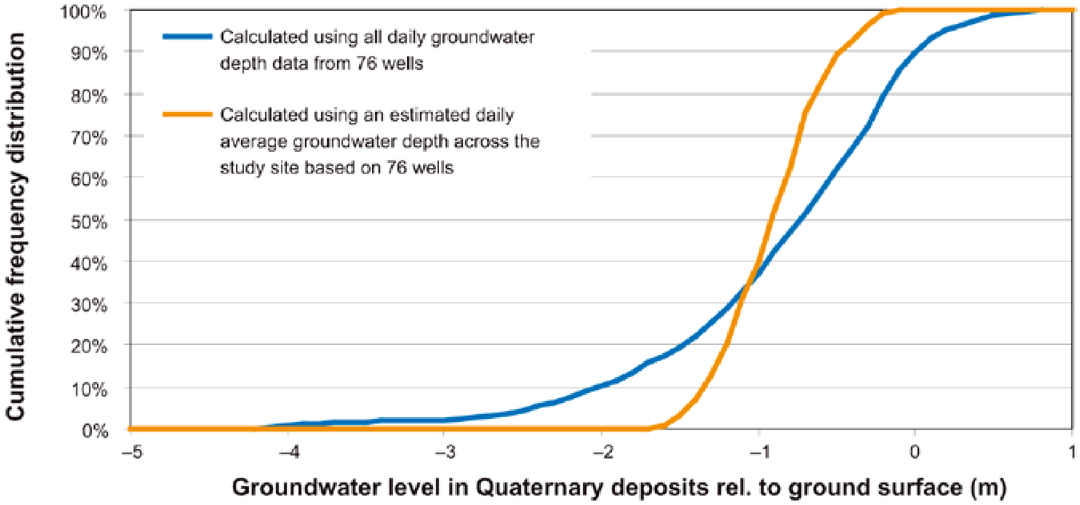


Figure 3-38. *Cumulative distribution function (CDF) plot, illustrating the temporal distribution of the groundwater table depth. The blue CDF is based on all daily groundwater level data, whereas the orange CDF uses the daily average of all groundwater wells.*

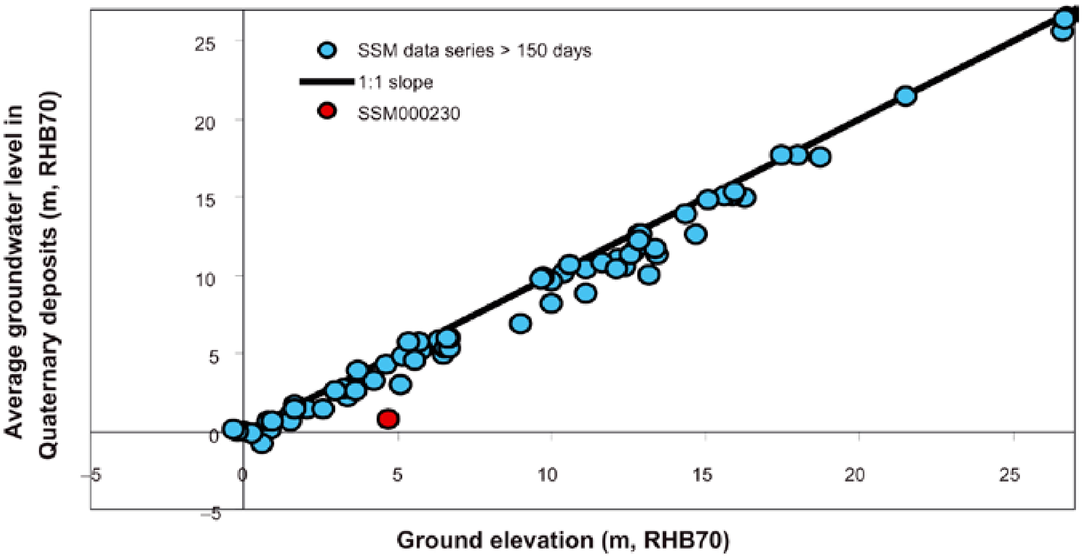


Figure 3-39. Scattergram of average groundwater level versus ground-surface elevation (m.a.s.l.).

3.4.3 Near-surface rock

Hydrogeological properties

Single-hole test methods that have been used to obtain hydrogeological properties data from core boreholes in Laxemar include PSS and PFL. PSS denotes double-packer tests (using a so-called Pipe String System), whereas PFL (Posiva Flow Log) are flow-logging pumping tests. Moreover, the HTHB pumping test and impeller flow logging method (Swedish: Hydrauliskt Testsystem för Hammarborrhål; English: Hydraulic Test System for Percussion Boreholes) has been used in open percussion boreholes /Rhén et al. 2008/. In most cases, no tests have been performed in the upper c 5–10 m of the rock. One reason for this is that the borehole casing generally makes it impossible to test the upper part of the borehole. Further, water extraction was used during the tests in most boreholes, implying a drawdown in the borehole.

At two locations, around core boreholes KLX09 and KLX11A, several short core boreholes were drilled with the objective of investigating possible minor deformation zones and also providing geological and hydrogeological data for the near-surface rock. From these short boreholes, there is hence information on geological features as well as hydrogeological near-surface characteristics /Rhén et al. 2008/. Water injection was also made in the uppermost sections of core boreholes KLX11B–F.

As mentioned in Section 3.4.1, hydrogeological test data for the rock indicate that the hydraulic conductivity of the rock decreases with depth, both within deformation zones and within the rock mass between the deformation zones. This depth trend is most pronounced in the upper c 100–200 m of the rock. The deformation zones are mostly subvertical and typically one order of magnitude more conductive compared to the surrounding rock /Rhén et al. 2008, 2009/. Many deformation zones coincide with and outcrop in valleys, which at many locations also are associated with more conductive QD above the rock compared to other parts of the area (cf. Section 4.3.1).

In the rock mass between the deformation zones, above 150 m.b.s.l. there is a slightly higher intensity of sets of horisontal flowing fractures compared to vertical sets. This circumstance, in combination with relatively low stress levels close to the surface (smaller rock load), probably results in the observed change of the anisotropy with depth; the horisontal conductive fractures are significant or dominant in the near-surface rock, but at deeper levels the sets of horisontal fractures generally become less significant compared to the vertical sets.

Hydraulic tests on 100-m scale indicate that the rock above c 150 m.b.s.l. has a geometric average hydraulic conductivity of c $2·10^{–7}$ $m·s^{–1}$ when considering the entire data set (deformation zones and the rock between them); this value is also applicable to the rock mass between deformation zones. For the elevation interval 150–400 m.b.s.l. the geometric average hydraulic conductivity is c $2·10^{–8}$ $m·s^{–1}$ for the entire data set. The rock mass between the deformation zones in this depth interval has a geometrical average hydraulic conductivity of c $0.8·10^{–8}$ $m·s^{–1}$ /Rhen et al. 2008/ (see summary in Table 3-6).

Due to the lack of near-surface borehole data, the hydrogeological properties of the uppermost part of the rock need to be assessed qualitatively, e.g. based on the current understanding of the influence from geological (glacial) processes. Generally, one can assume a glacial influence in the upper c 100–150 m of rock. It can be speculated that the uppermost part of the rock (say, the uppermost 5–10 m) is more fractured and more conductive compared to deeper parts of the rock. This can be explained by the influence from the latest glaciation. In particular, the glacial influence may be pronounced on south-eastern slopes of the rock surface, due to the ice movement from NW towards SE, i.e. plucking on the lee side of the ice advancement. According to /Rhén et al. 2008/, hydrogeological properties data that can confirm such a hypothesis are difficult to collect and presently not available. However, trenches have been excavated in the QD across some deformation zones in the valleys /Sohlenius et al. 2006a/. It was found that part of the near-surface rock is heavily weathered and fractured, and thereby possibly more conductive than the more intact rock further below.

It can therefore be assumed that a large fraction of the groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper (say, 10 m) of the rock. Groundwater flow in the deeper parts of the rock primarily occur in a system of connected deformation zones, and the associated groundwater discharge takes place at locations where this system connects to zones that outcrop in the valleys. Groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones. At least in a qualitative sense, interference tests have indicated the existence of such hydraulic connections between outcropping deformation zones and Quaternary deposits, see e.g. /Werner et al. 2008/.

This section is concluded by Table 3-6, presenting a brief summary of the hydrogeological characteristics of the QD and the rock in Laxemar, using rough estimates of the hydraulic conductivity as a descriptive parameter.

Point water heads in the rock

This section summarises the point water head data available in the Laxemar 2.3 data set and some main conclusions that can be drawn based on these data. For more detailed presentations and analyses of the point water head data set, see /Werner et al. 2008/. For an overview of the locations of the boreholes and the available time-series data, see Section 2.2.3.

Table 3-6. Characteristics of hydrogeological flow domains in Laxemar. The hydraulic conductivity (K) is used as a descriptive parameter. Data for the rock are described in more detail in /Rhén et al. 2008, 2009/.

Flow domains	Description	K ($m \cdot s^{-1}$)
Surface layer	Surface-affected layer (general)	$4 \cdot 10^{-4}$
	Shingle	$1 \cdot 10^{-2}$
Postglacial QD	Bog peat	$4 \cdot 10^{-6}$
	Fen peat	$4 \cdot 10^{-6}$
	Gyttja	$1 \cdot 10^{-8}$
	Gyttja clay/clay gyttja	$1 \cdot 10^{-7}$
	Sand/gravel	$1–5 \cdot 10^{-3}/1 \cdot 10^{-2}$
Glacial QD	Glacial clay	$1 \cdot 10^{-8}$
	Till/artificial fill	$4 \cdot 10^{-5}$
	QD in deepest part of large valleys	$4 \cdot 10^{-4}$
Rock	Near-surface rock (depth 0–10 m)	No data, likely more conductive than deeper rock
	Rock (HRD and HCD, > 150 m.b.s.l.)	$2 \cdot 10^{-7}$ (test scale 100 m)
	Rock (HRD and HCD, 150–400 m.b.s.l.)	$2 \cdot 10^{-8}$ (test scale 100 m)
	Rock mass (HRD, 150–400 m.b.s.l.)	$0.8 \cdot 10^{-8}$ (test scale 100 m)
	Deformation zones	Approx. 10 times more conductive than the surrounding rock mass (100-m scale)

The data set shows that the overall average point water heads are highest in Laxemar, and slightly above the sea-water level closer to the coast. Considering average point water heads per area (Laxemar, Simpevarp, Ävrö), the lowest and highest average point water heads, respectively, are –0.6 to 20.1 m.a.s.l. (percussion boreholes) and –2.1 to 15.5 m.a.s.l. (core boreholes) in Laxemar. Moreover, the corresponding data are 0.19 to 0.50 m.a.s.l. (percussion boreholes) and –13.0 to 0.5 m (core boreholes; borehole section KSH02.1 is an outlier, having notably low point water head) on the Simpevarp peninsula, and –5.6 to 10.9 m.a.s.l. (percussion boreholes) and –2.0 to 6.2 m.a.s.l. (core boreholes) on the island of Ävrö. Note that these analyses consider all borehole sections, i.e. also short time series with less than 150 data days.

There are relatively small temporal fluctuations of point water heads in rock. Taking into account borehole sections with 150 data days or more, the average point water head amplitude (i.e. maximum minus minimum) is 1.9 m in the percussion boreholes and 1.5 m in the core boreholes. The smallest fluctuations are observed for HLX31 (borehole section HLX31.1b; 0.7 m) and KLX19A (borehole sections KLX19A.1–2; 0.5 m), whereas the largest fluctuations are observed for HLX11 (borehole section HLX11.2; 4.2 m) and KLX02 (borehole section KLX02.8; 4.4 m).

Figure 3-40 investigates possible correlations between point water heads in percussion boreholes and the topography of the ground surface, plotting average groundwater levels versus ground-surface elevations. Note that this scattergram only includes borehole sections with more than 150 data days. For boreholes with packers, data are used for the upper borehole section. Two artesian percussion boreholes can be observed, namely HLX15 and HLX28, with average point water heads in the upper borehole sections approximately 0.9 m above the ground surface. Overall, there seems to be less correlation between point water heads in the upper parts of the rock and ground-surface elevations, as compared to groundwater levels in the QD (Figure 3-39), even though there is a general trend indicating such a correlation according to Figure 3-40.

/Werner et al. 2008/ present further investigations of the relationship between point water heads and ground surface and rock elevations. The results indicate that there is a general trend with at least some correlation between point water heads in the upper parts of the rock and ground-surface elevations. However, there is no correlation between the “point water depth” and the rock-surface depth. It is interesting to note that there seems to be a zone of unsaturated rock along some boreholes, i.e. locations where the point water head is below the rock surface /Werner et al. 2008/.

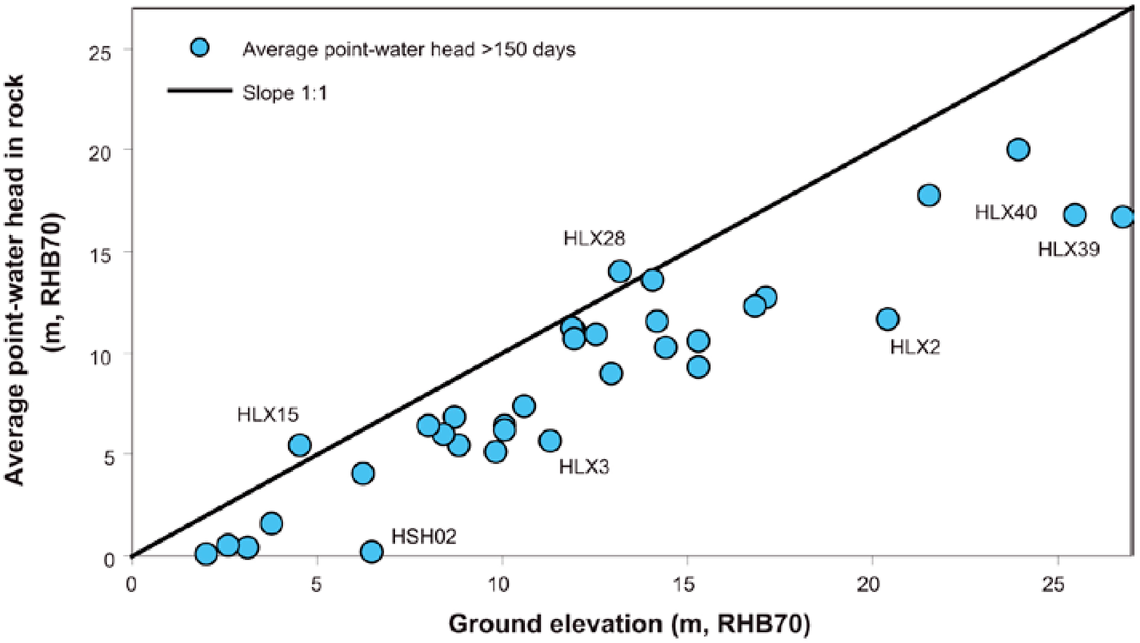


Figure 3-40. Plot of ground elevation versus average point water heads in percussion boreholes. Note that for boreholes with packers, data for the upper borehole section are used. Also note that only borehole sections with more than 150 data days are shown.

Interpretation of the prevailing horisontal and vertical head gradients in a variable-density groundwater flow system requires transformation of measured point water heads (h_{ip}) to fresh water heads (h_{if}) and environmental water heads (h_{in}), respectively /Lusczynski 1961, Acworth 2007, Post et al. 2007/. Density measurements (made at the Äspö HRL) on groundwater samples from Laxemar indicate that in general, density differences have only minor effects on groundwater head gradients in the Laxemar area. For further details, see /Werner et al. 2008/.

3.5 Joint description of the flow system

In order to provide a systematical description of the integrated hydrological and near-surface groundwater flow system in the Laxemar area, this section joins the hydrogeological objects and hydrological flow domains described in Sections 3.3 and 3.4. Flowing water is the primary target of the description, i.e. the main functional units are the flow system and its sub-systems, i.e. not the hydrological objects and hydrogeological flow domains themselves. The groundwater flow systems connect recharge areas with discharge areas, but such systems may use only a part of a hydrogeological flow domain or may cut across such a domain. A groundwater flow system is characterised by boundary types, volume, form, energy conversion capacity, system flux and hierarchical place /Engelen and Jones (eds.) 1986/. The systems approach adopted here, hence focussing on the flow system and its sub-systems, is considered to facilitate the transfer of the conceptual model to quantitative water flow models.

3.5.1 Boundary conditions

The upper boundary

The meteorological conditions constitute the upper (top) boundary of the hydrological and hydrogeological system. Water is naturally added to this system by rainfall and snowmelt, and abstracted by evaporation and transpiration. This implies that the most important meteorological parameters for a description of hydrology and hydrogeology include precipitation (P) and potential evapotranspiration (PET), since these parameters provide basic information on the site-specific driving forces of the hydrological cycle.

In the region where Laxemar is located, the precipitation demonstrates a near-coastal gradient, with less precipitation at the coast compared to areas further inland. Based on long-term meteorological data from surrounding stations, the Swedish Meteorological and Hydrological Institute (SMHI) has estimated the 30-year (1961–1990) annual average precipitation to 553 mm for the Äspö station (on the coast) and 630 mm for the Plittorp station (approximately 10 km further inland).

The data evaluation by /Werner et al. 2008/ shows that the long-term "site-average" annual average precipitation can be estimated as 600 mm, with c 7% more precipitation at the inland station Plittorp compared to the station on the island of Äspö on the coast. Potential evapotranspiration seems to vary less in space, likely due to relatively small spatial variations of governing factors such as air temperature and global radiation; the annual average potential evapotranspiration can be estimated to be c 530–540 $mm \cdot y^{-1}$ /Werner et al. 2008/.

For hydro-meteorological conditions typical for Sweden, snow accumulation during winter, snowmelt in spring and seasonally variable potential evapotranspiration imply that the actual "source term" for groundwater recharge and surface runoff demonstrates strong seasonal variations. This phenomenon is also demonstrated by the discharge-gauging data from the streams (cf. Section 3.3.3). In its simplest form, this source term can be estimated as R/S-PET, in which R is rainfall and S is snowmelt. /Werner et al. 2008/ developed a relatively simple model of snow accumulation and snowmelt, and used this model in conjunction with precipitation and air temperature data to derive a rainfall/snowmelt time series.

Figure 3-41 shows the calculated source term for the period October, 2003–December, 2007. The upward bars in Figure 3-41 hence represent the actual "source term" for surface runoff, infiltration and groundwater recharge; snowfall accumulates on the ground and does not act as a source term until the snow melts. Even on an annual basis, snowmelt (S) represents an important source term, contributing with totally c 26% of the sum of rainfall plus snowmelt (R + S) during the considered period. According to the model of snow accumulation and snowmelt, the maximum snowmelt occurred on Dec. 5, 2004, when 22 mm of water as snow melted in one day /Werner et al. 2008/.

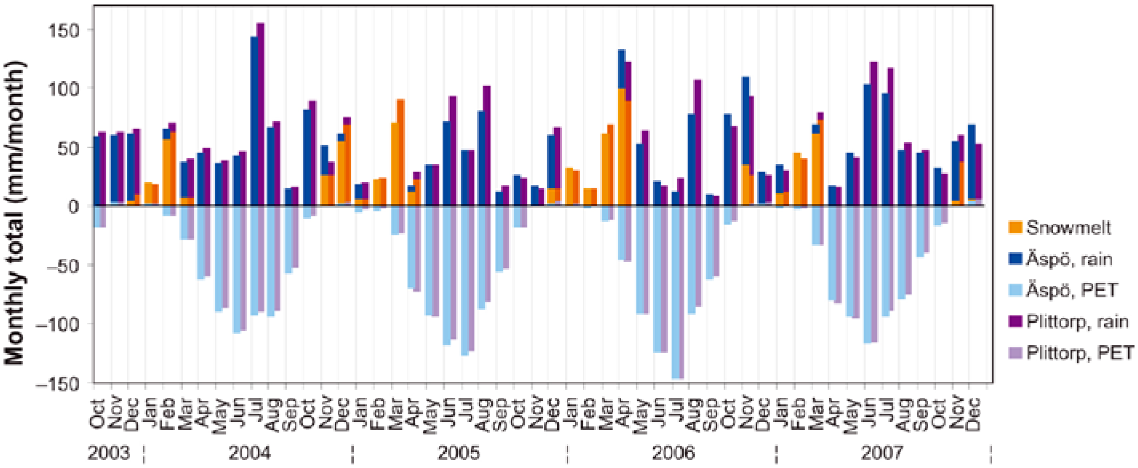


Figure 3-41. Time-series plot of monthly sums of snowmelt, rainfall and PET, respectively, during the period October 2003–December, 2007.

The time-series plot in Figure 3-41 clearly shows that the temporal distribution of the actual source term appears quite different depending on if snow accumulation/snowmelt is taken into account or not. Using the precipitation (P) as a measure of the source term does not properly represent the temporal distribution of the source term; snowmelt during parts of the winter, but foremost during spring, yields a large contribution to the surface runoff/infiltration/groundwater recharge source term. The temporal distribution of this source term is not properly represented by precipitation (P) only. Moreover, using P as the source term overestimates the actual source term during cold winter periods, when precipitation is accumulated in the form of snow.

The inland boundaries

As illustrated in Figure 3-39 in Section 3.4.2, there is a strong correlation between groundwater levels in the QD and ground-surface elevations. According to /Werner et al. 2008/, average groundwater levels in the QD range from c –0.8 to 26 m.a.s.l. whereas there is only a 4.5 m range in terms of groundwater levels below the ground surface. Conceptually, it can hence be assumed that the 3D "groundwater surface" in the QD generally follows that of the ground surface. Based on this, it can be assumed that the identified surface-water divides /Brunberg et al. 2004/ coincide with the water divides for groundwater flow in the QD. In comparison, there seems to be less correlation between point water heads in the upper parts of the rock and ground-surface elevations (see Figure 3-40 in Section 3.4.3).

/Holmén 2008/ investigated the influence of the location of the inland (western) boundary for modelling of groundwater flow in the rock in Laxemar. It was found that the influence of the boundary location depends on the spatial scale (the depth) of the groundwater flow system under study. Specifically, it was concluded that an inland boundary that is located too close to the considered area may lead to an underestimation of the large-scale (deep) groundwater flow in the rock. However, for the Laxemar boundary locations investigated by /Holmén 2008/, it was found that the deepest groundwater flow system only represents a small fraction of the total groundwater flow in the rock at the depth scale of the "large" flow model domain considered in the study. This small fraction is not taken into account using a small flow model domain. In terms of the flow model domains included in the study, it was concluded that the choice of the inland boundary location is not a critical issue for the hydrogeological site descriptive modelling.

The sea boundary

Concerning the sea as a hydraulic boundary (for sea-level time-series plots, see Figure 3-31 in Section 3.3.5), the average maximum and minimum sea levels during the period with available site-investigation data (May 2004–December 2007) were –0.52 and 0.71 m.a.s.l. respectively, whereas the average sea level was 0.03 m.a.s.l. (RHB 70). The largest daily sea-level changes occurred on November 1, 2006 (c +0.26 m) and December 22, 2004 (c –0.23 m). It can be noted that all lakes are located above sea level (Section 3.3.2), and there is hence no intrusion of sea water to the lakes.

According to the above, it was concluded that the groundwater divides in the QD coincide with surface-water divides. Hence, it follows that only "direct-runoff areas" along the coast have lateral boundaries towards the sea. Joint evaluations of groundwater levels in the QD, point water heads in the rock and sea-water levels /Werner et al. 2008/ show that there is a co-variation between the sea-water level and the groundwater levels in groundwater monitoring wells installed below Borholmsfjärden and a well (SSM000040) located close to the coast. Moreover, there is also some co-variation with point water heads in percussion boreholes located on the coast.

Interestingly, there is some correlation between the sea-water level and point water heads in some percussion boreholes located relatively far from the coast (on the order of one or even a few km). In most cases, these boreholes are located to areas that coincide with deformation zones in the rock /Werner et al. 2008/. However, this explanation is complicated by the fact that it is difficult to explain the relatively strong correlations for other boreholes (e.g. HLX40 and HLX41), located to areas that do not coincide with any identified deformation zone.

3.5.2 Infiltration and groundwater recharge

As described in Section 3.4.1, groundwater recharge primarily takes place in the high-altitude areas of Laxemar, dominated by shallow/exposed rock. Groundwater recharge also takes place within areas containing so called hummocky moraine and in areas with glaciofluvial deposits, characterised by smaller-scale topography and eskers, respectively. The high-altitude areas containing shallow/exposed rock are difficult to parameterise in conceptual models and also to represent properly in quantitative water flow models. In the MIKE SHE modelling, near-surface drains are activated in the high-altitude areas (see Chapter 4). Conceptually, unsaturated (Hortonian) overland flow may appear on outcropping rock, but likely over short distances (say, less than 10 m) before precipitation or snowmelt reaches open fractures or other cavities in the surface rock or a contact between rock and QD.

Precipitation and snowmelt are thought to be the dominant sources of groundwater recharge in Laxemar. Evaluation of monitoring data and near-surface hydrogeological properties data /Werner et al. 2008/ shows that the infiltration capacity of the QD in Laxemar generally exceeds the rainfall and snowmelt intensity. The maximum recorded daily rainfall occurred on Jun. 26, 2007, with 51 mm on Äspö and 44 mm at Plittorp (corresponding to c $5–6·10^{-7}$ $m·s^{-1}$), whereas the maximum calculated daily snowmelt (22 mm, corresponding to c $3·10^{-7}$ $m·s^{-1}$; see below) occurred on December 5, 2004. These rainfall/snowmelt rates can be compared to the average saturated hydraulic conductivity obtained from permeameter tests on near-surface QD samples. For all K-data for QD sampled < 1 m below ground, the arithmetic average of $K = 1.54·10^{-5}$ $m·s^{-1}$ (geometric average = $7.52·10^{-6}$ $m·s^{-1}$).

Evaluation of monitoring data /Werner et al. 2008/ shows that a proper representation of the "source term" needs to take into account the temporal distribution of rainfall, snow accumulation and snowmelt (cf. above). Specifically, snowmelt during parts of the winter but foremost during spring yields a large contribution to the surface runoff/infiltration/groundwater recharge source term, which temporal distribution is not properly represented by precipitation only. For instance, using precipitation as the source term overestimates the actual source term during cold winter periods, when precipitation is accumulated in the form of snow.

/Werner et al. 2008/ also analysed correlations between groundwater levels in the QD and point water heads in percussion boreholes in the rock on the one hand, and the "net source term" (approximated as the sum of rainfall and snowmelt minus potential evapotranspiration) on the other. These analyses show that there appears to be a "delay" in the system monitored by some of the groundwater monitoring wells and percussion boreholes; in some cases, the correlation is higher for the previous two months compared to the previous or current month. For some boreholes, the correlations to the net source term are of the same order of magnitude as the groundwater monitoring wells.

3.5.3 Sub-flow systems and discharge

Groundwater discharge takes place in valleys and other low-altitude areas, corresponding to the "valley" type area (cf. Section 3.4.1). The characteristics of the hydrogeological flow domains QD and rock (cf. Sections 3.4.2–3) imply that one can identify two main sub-flow systems for groundwater flow in the discharge areas: One system located to the upper part of the rock and the QD, which overlies a larger-scale flow system primarily associated with deformation zones (of different orientations) in the rock. According to the description of the hydrogeological flow domains rock and QD (Sections 3.4.2–3), most groundwater flow towards the discharge areas in the valleys likely takes place in the QD and in the upper (say, 10 m) of the rock. As was also mentioned above, groundwater flow in the deeper parts of the rock primarily occurs in a system of connected deformation zones, and the associated groundwater discharge takes place at locations where this system connects to zones that outcrop in the valleys. Groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones.

Except for some minor wetlands, the surface waters (lakes, streams and wetlands) are located to low-altitude areas. These surface waters are mainly underlain by glacial and post-glacial sediments. Specifically, the general bottom-up QD stratigraphy below surface waters is till and glacial clay, overlain by postglacial sediments (sand/gravel, gyttja clay/clay gyttja, overlain by fen peat and bog peat in the wetlands). As illustrated in Figure 3-42, groundwater-level measurements below lakes indicate that interaction between surface water in the lakes and the underlying QD is limited to near-shore areas; groundwater monitoring well SSM000342 is installed in the QD below Lake Frisksjön. Some parts of the streams pass through areas where there are no layers of glacial clay and postglacial sediments (cf. Figure 3-19 in Section 3.3.3), which is also the case for some near-shore areas of the lakes. The local conditions for surface water-groundwater interaction are also influenced by land improvement and drainage operations, which for instance imply that water flows in subsurface pipes along some parts of the valleys. Interaction between groundwater in the QD, groundwater in the rock and surface water is further described and illustrated in Section 4.2.5.

As illustrated in Figure 3-43 (see also Figure 3-19 in Section 3.3.3), groundwater discharge from the upper rock-QD part of the system to the surface (waters) is strongly influenced by the geographical distribution and the hydrogeological properties of the QD overlying the till. Moreover, there is also an influence on this process by the hydrogeological properties of the upper rock (including the deformation zones) and the high-conductive QD overlying the rock in the valleys. Hence, in the large valleys in Laxemar there are both groundwater discharge towards the surface and (semi)horisontal groundwater flow along the valley in the upper rock-QD system; groundwater discharge to the surface is facilitated in areas where there are no layers of glacial clay and postglacial sediments above the till.

As shown in /Werner et al. 2008/, there appear to be "groundwater level thresholds" (in terms of the depth to the groundwater level) along most streams, below which there is either no stream discharge or the discharge is very low. This threshold seems to be on the order of 0.5–2 m below the ground surface, which can be explained by the fact that the groundwater level near a stream must be above the stream bottom in order for stream discharge to occur. Confined conditions may prevail in areas where streams pass relatively conductive postglacial sediments overlying less conductive sediments, and the groundwater level needs to be within the upper more conductive material (which interacts with the stream) for stream discharge to take place. In areas with relatively conductive types of QD throughout the QD profile, the condition for discharge to occur is simply that the groundwater level is above the stream bottom.

Joint data evaluations /Werner et al. 2008/ indicate that most of the stream water originate from surface (overland) water, near-surface groundwater (here meant from the very upper part of the QD) and water originating from snowmelt. Moreover, monitoring of lake-water levels and groundwater levels near and below lakes indicates that interaction between lake water and groundwater in the underlying QD is limited to near-shore areas.

The above concepts are illustrated in Figure 3-44, which exemplifies joint evaluations of groundwater levels in the QD and point water heads in percussion and core boreholes. For further examples and analyses, see /Werner et al. 2008/. These interpretations indicate that upward hydraulic-head gradients from rock to the QD primarily prevail in connection to deformation zones in the rock. Hence, topography in combination with the geometry and the hydrogeological properties of the deformation zones and their contact with the QD are important factors for the groundwater discharge from the rock to the QD.

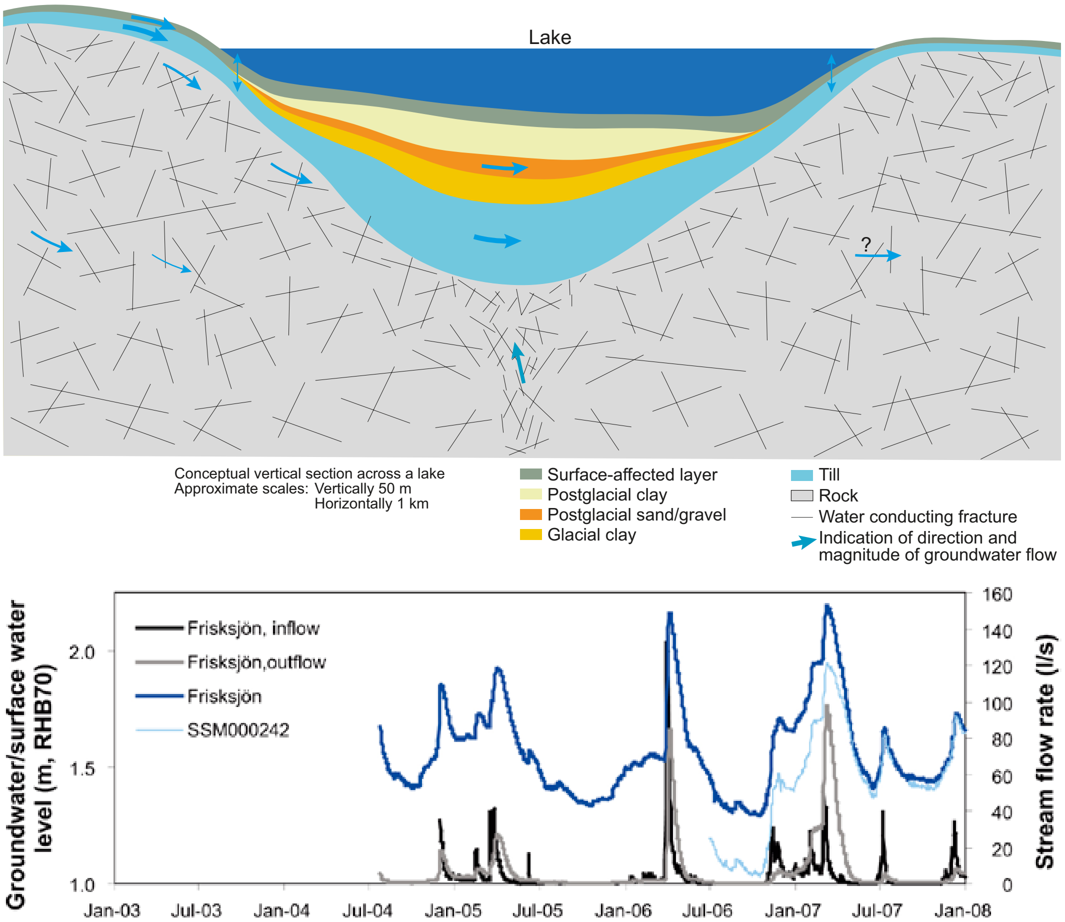


Figure 3-42. *Top: Conceptual vertical section across a lake in Laxemar, illustrating that interaction between surface water in the lakes and the underlying QD likely is limited to near-shore areas. Note the different horisontal (1 km) and vertical (50 m) scales in the figure. Bottom: Time series co-plot of daily average surface-water level in Lake Frisksjön and daily average groundwater level in well SSM000242, installed in the QD below the lake. The plot also shows the daily average stream discharge into and out from Lake Frisksjön.*

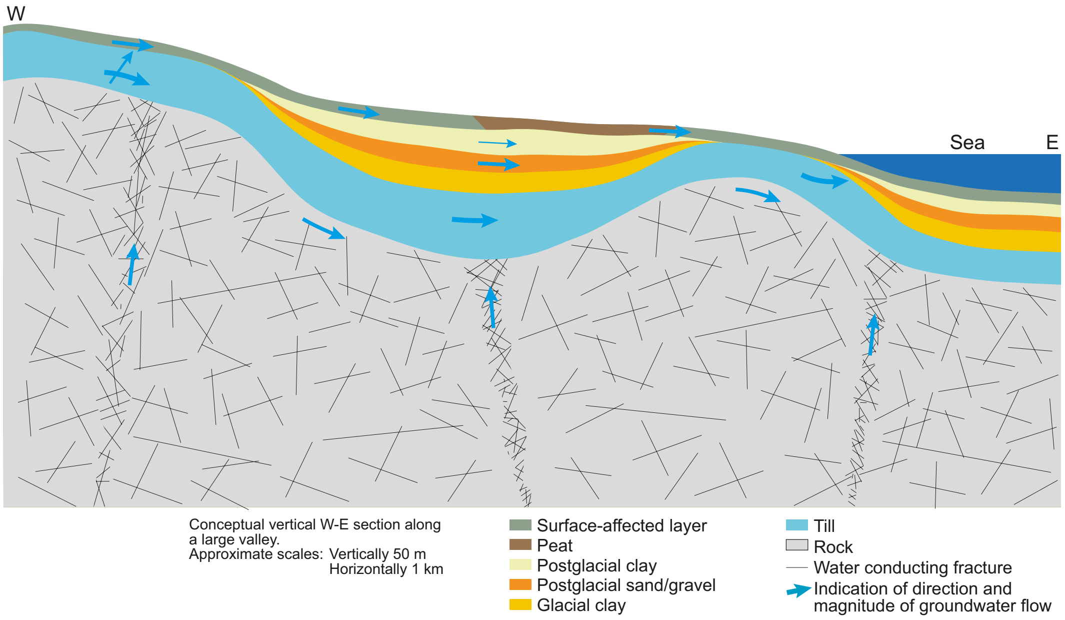


Figure 3-43. *Conceptual vertical W-E section along a large valley in Laxemar. Note the different horisontal (1 km) and vertical (50 m) scales in the figure.*

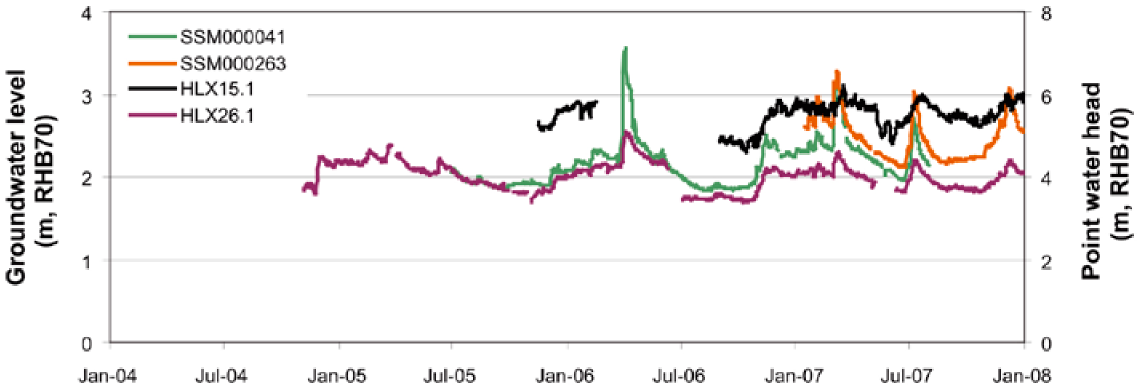


***Figure 3-44.** Time-series plots of groundwater levels in groundwater monitoring wells SSM000041 and –263 and point water heads in percussion boreholes HLX15 and HLX26 in the Laxemarån stream valley. Percussion borehole HLX15 crosses a deformation zone and is artesian, whereas HLX26 does not cross such as zone and is not artesian.*

3.5.4 Hydrochemical data for interpretation of flow systems

In this section, interpretations of hydrochemical data are used as a supplementary support for the hydrological and near-surface hydrogeological conceptual modelling. For details of the hydrochemical data and the associated interpretations, see /Tröjbom and Söderbäck 2006, Tröjbom et al. 2008/. Hydrochemical interpretations are in the present context used to discuss the following aspects of the hydrological and near-surface hydrogeological conceptual model:

- The overall conceptual model of near-surface hydrogeology in the Laxemar area.
- Infiltration and groundwater recharge.
- Sub-flow systems and groundwater discharge, in particular (1) vertical groundwater flow from the deep rock towards the ground surface, and (2) groundwater discharge in relation to other contributions to stream discharge.
- Interactions between lake water and groundwater in the underlying QD.

Overall conceptual model of near-surface hydrochemistry in the Laxemar area

Long-term processes affecting the hydrochemistry of the Laxemar area

According to /Tröjbom et al. 2008/, a long-term perspective is required to interpret hydrochemical observations, in particular those associated with groundwater in the rock. This is because the present hydrochemistry is a consequence of the past. The two most important factors influencing the hydrochemistry of the Laxemar area are the high-elevated areas with shallow or exposed rock and low-altitude areas with thicker QD, combined with the withdrawal of the Baltic Sea due to isostatic land uplift subsequent to the latest deglaciation (c 12,000 BC).

During the last glaciation, the regolith and the bedrock were infiltrated by glacial meltwater to a depth of at least 500 m. This glacial water has now been replaced to a varying extent by sea water due to density intrusion during the Littorina stage, and later due to meteoric recharge in areas above sea level. The presence of carbon with biogenic isotope signatures corresponding to a carbon-age between 6,000 and 14,000 years also implies that meteoric recharge probably has had an impact even at depths of several hundred metres in the rock.

When the inland ice retreated, the whole area was below the sea. The low-lying areas were transformed to brackish sea bays and subsequently terrestrial valleys. The gradual isolation of these former brackish bays has resulted in succession from brackish water to freshwater followed by formation of wetlands (note that many present and former wetlands in the area have not experienced a lake stage; cf. Section 3.3.4).

In low-altitude areas closer to the coast, marine remnants influence the hydrochemistry of groundwater in the QD, whereas higher-altitude areas are influenced by atmospheric deposition and weathering processes. In the low-altitude areas close to the coast, hydrochemical data indicate the presence of relict marine water in deeper parts of the QD and in the upper parts of the rock. Hydrochemical indicators (e.g. a high salinity compared with present Baltic Sea water, and negative so-called deuterium excess values) indicate that this water probably is a remnant from the Littorina stage; at this stage, sea water with a Cl concentration of c 6,500 mg·L^{-1} infiltrated into the QD and the rock. There are also hydrochemical indications suggesting ongoing flushing of the marine relicts in these areas. At most other locations in the Laxemar, this flushing is more or less completed, and concentrations of marine ions may be explained by deposition and anthropogenic sources such as road salt (see further below).

In slightly higher-lying areas, which should also have been covered by sea water after the latest glaciation, meteoric isotope signatures and low Cl concentrations indicate that marine influences have been washed out due to the meteoric recharge. This process has also affected the groundwater in the upper parts of the bedrock, resulting in signatures similar to the shallow groundwater at a few hundred metres depth. In areas located above the highest coastline of the Littorina Sea, relict marine remnants are probably almost absent. Cl concentrations in these areas can be fully explained by deposition and point sources such as road salt.

The formation of a vegetation cover subsequent to the latest deglaciation had a great impact on the hydrochemistry of the surface system. Degradation of biogenic carbon generates large numbers of H^+ ions, which drive weathering processes in the QD as well as in the rock. According to isotope measurements, a significant fraction of the carbon in the upper 400 m of the rock seems to originate from a biogenic source, probably supplied by meteoric recharge.

In the Laxemar area, the calcite content in the QD is almost negligible, which results in a quite different hydrochemistry of the surface system compared with the Forsmark site (which is characterised by very high alkalinity and Ca^{2+} concentrations in the surface system). In spite of the low calcite content, carbonates have been found to have an important role in the cycling of Ca^{2+} and HCO_3^- in shallow groundwater as well as in the upper parts of the rock.

Road salt has a significant impact on the concentrations of major ions measured in the surface waters in the area. In the catchment of the stream Laxemarån River, winter road salt spread on the E22 highway constitutes about 50% of the total Cl flux in this catchment. Summer road salt spread on gravel roads for dust control is also a potential source of Cl which has been shown to have significant influence in some areas. As much of 2/3 of the total Cl input in the Laxemar area may be of anthropogenic origin /Tröjbom et al. 2008/. Winter road salt has been identified as a major source that adds marine signatures to the dilute water in the upstream parts of the Laxemar area.

Illustrations of hydrochemical patterns

/Tröjbom et al. 2008/ used two traditional types of plots (Ludwig-Langelier and Piper) in order to identify important hydrochemical patterns in the Laxemar area. Specifically, these types of plots can be used to classify water bodies according to water types based on the (relative) chemical composition of major elements.

A Ludwig-Langelier plot (see Figure 3-45) visualises relative proportions of the major cations and anions on the horisontal and vertical axes, respectively. Observations located to the lower left corner (dominated by Ca^{2+} and HCO_3^-) represent a groundwater strongly influenced by surface water, whereas observations to the bottom right corner represent an older, “mature” groundwater (sometimes with possible marine influences) dominated by cations such as Na^+ and K^+.

Figure 3-45 shows an expected west-to-east trend across the stream Laxemarån catchment area, with Ca-HCO_3 water types at high-elevation areas (at the small inlet of Lake Jämsen, PW067) and Na-Cl water types closer to the coast (sea bay Borholmsfjärden, PW087). Exceptions from this general pattern (e.g. PW071) may be due to other sources than leaching from marine relicts that add marine ions to the surface system, such as the spreading of road salt during winters (see discussion above). In general, shallow hydrochemical groundwater observations (cf. green arrows in Figure 3-45) follow the spatial trend discussed above. However, most shallow groundwater observations indicate a less marine composition compared to the surface waters in the area; this may also be explained by the leaching of road salt. In Figure 3-45, some groundwater monitoring wells show a composition resembling modern sea water in a Ludwig-Langelier plot, e.g. wells SSM000238 and –239 located below sea sediments.

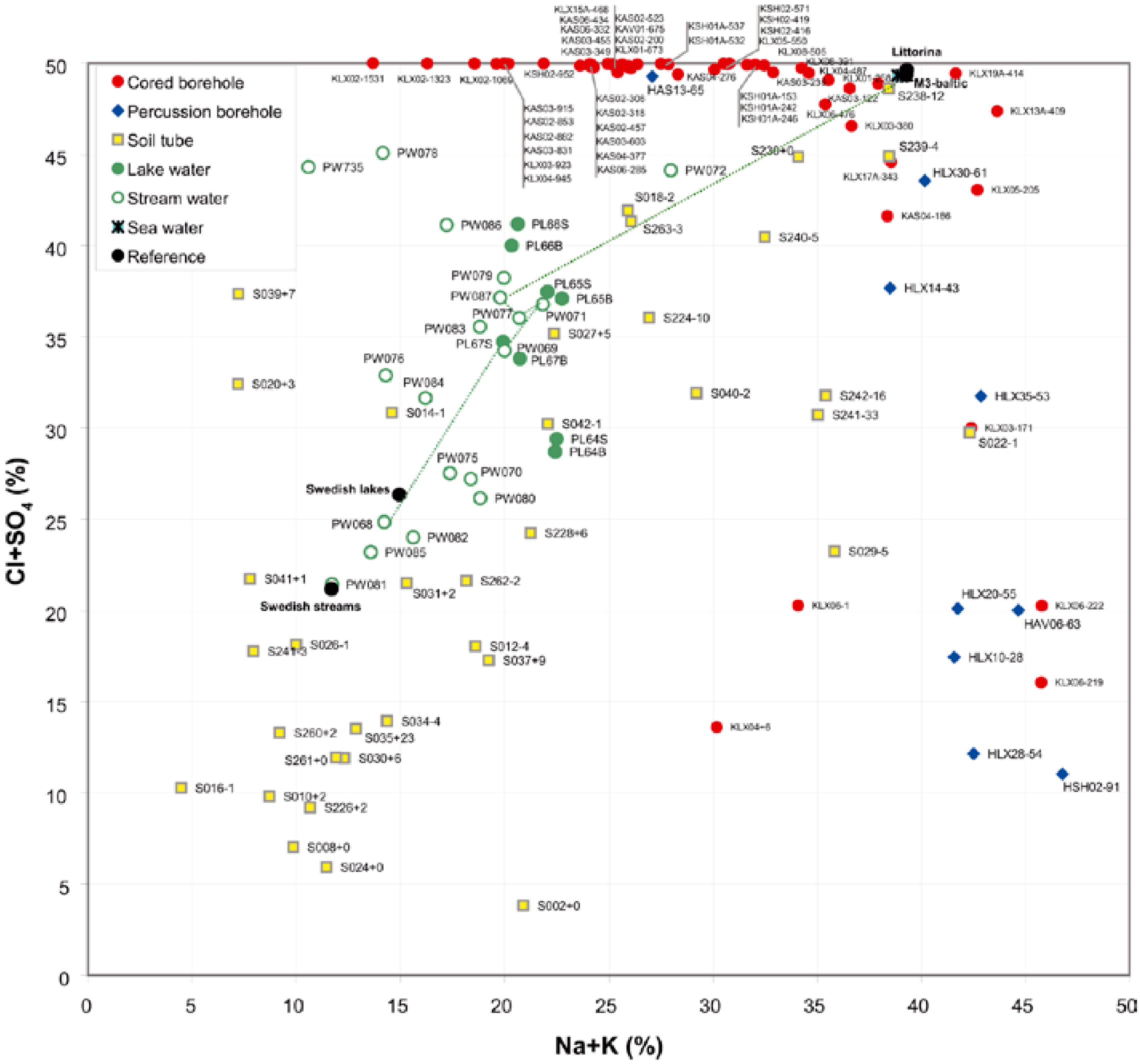


Figure 3-45. *Ludwig-Langelier plot of hydrochemical data from the Laxemar area. See /Tröjbom et al. 2008/ for details on the data selection, expressions to calculate relative amounts, and explanation of labels and trendlines. In the legend, "Soil tube" denotes groundwater monitoring well.*

A Piper plot (see Figure 3-46) is another method to visualise relative molar fractions of major ions in water samples. In such a plot, the compositional data are plotted into ternary (triangular) coordinate systems, which in a second step are projected onto the central prism. The two lower ternary plots show the relative proportions of cations (Ca^{2+}, Mg^{2+} and $Na^+ + K^+$) and anions (Cl^-, HCO_3^-, SO_4^{2-}). Note that the prism, on which the ternary plots are projected, approximately corresponds to the Langelier-Ludwig plot turned 45° counter clockwise (cf. Figure 3-45).

The Piper plot shows that the anomalous composition of the encircled stream sampling sites (PW078 and PW735) may be attributed to SO_4^{2-} rather than Cl^-. An additional pattern can be distinguished in the deep core borehole samples, with a trend towards the Ca-Cl water type. These samples also show very low relative contents of Mg^{2+} and SO_4^{2-}, compared to the general mixing trends in the surface system /Tröjbom et al. 2008/.

Infiltration and groundwater recharge

In high-elevated areas, meteoric recharge has a large influence on the observed hydrochemistry, characterised by dilute groundwater with low ionic strength. Relict marine remnants are probably almost absent in areas located above the highest coastline of the Littorina Sea. In these areas, high Cl concentrations can be explained by atmospheric deposition and point sources such as road salt.

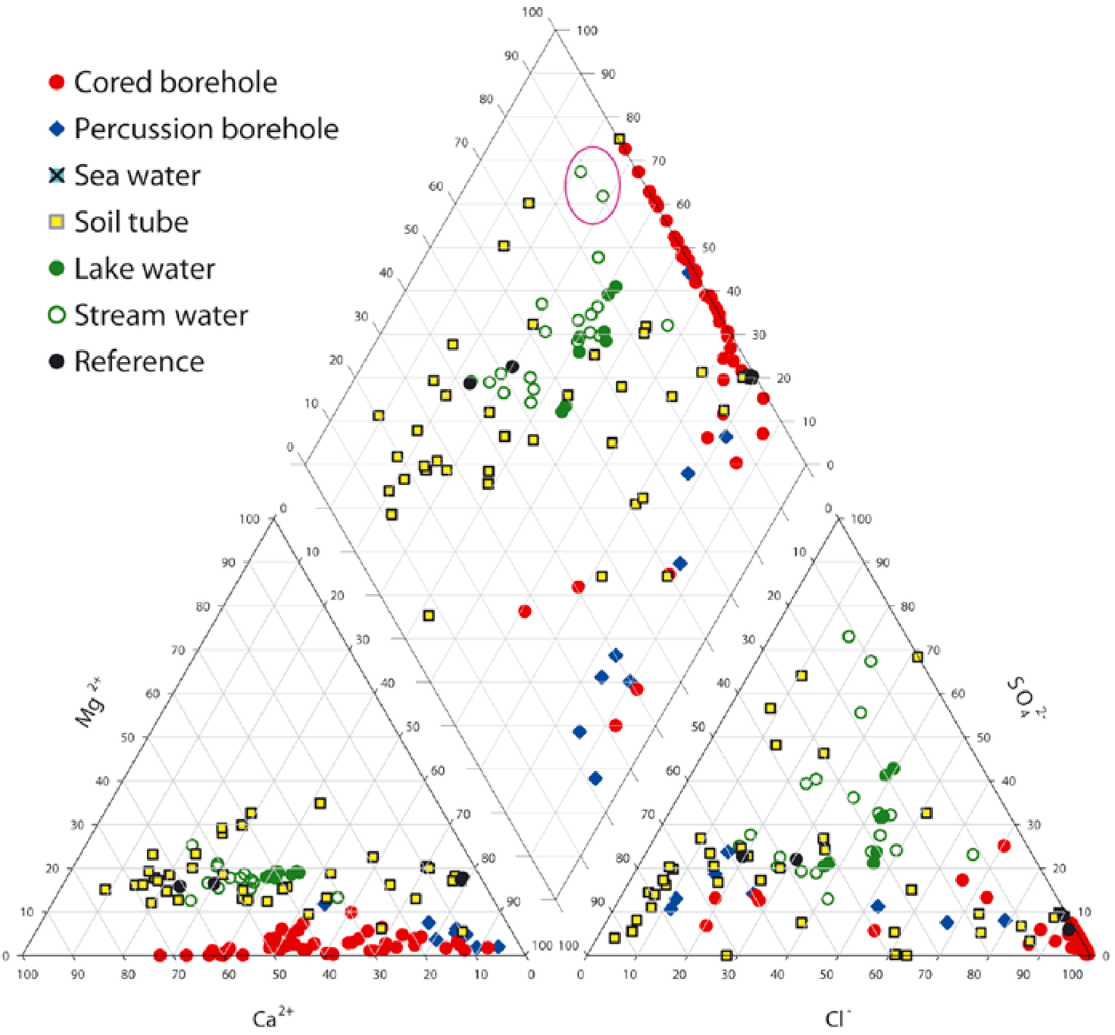


Figure 3-46. Piper plot of hydrochemical data from the Laxemar area. See /Tröjbom et al. 2008/ for details on the data selection. In the legend, "Soil tube" denotes groundwater monitoring well.

The hydrochemistry is affected by atmospheric deposition and weathering processes. In slightly lower-lying areas that were covered by sea water subsequent to the latest glaciation, meteoric isotope signatures and low Cl concentrations indicate that marine influences have been washed out due to the meteoric recharge.

Figure 3-47 and 3-48 summarise the regional-scale conceptual hydrochemical model of the Laxemar-Simpevarp area, developed by /Tröjbom et al. 2008/ to interpret hydrochemical surface- and groundwater observations. The conceptual model in Figure 3-47 is visualised in the form of a cross section, drawn along the transect shown in Figure 3-48. The transect consists of four segments. The transect starts in the Mederhultsån stream valley in the west, continues across Lake Frisksjön and the sea bays Borholmsfjärden and Granholmsfjärden, and terminates at the northern part of Granholmsfjärden.

According to the upper plot of Figure 3-47, low Cl concentrations prevail in the higher-elevated areas. This indicates flushing of meteoric water and hence groundwater recharge. Concentrations in the range 8–15 mg·L^{-1} are 2–3 times higher than the estimated background concentration from higher-lying areas. The origin of water is explored in the lower illustration of Figure 3-47, showing deuterium excess (D_{excess}) values in boxes. D_{excess} is a measure of the deviation from the so called Global Meteoric Water Line (GMWL); near-zero values indicate a meteoric origin, whereas negative values indicate influence from evaporation, for instance in lakes or sea water. According to the lower illustration of Figure 3-47, all samples that show low Cl concentrations (< 1,000 mg·L^{-1}) also show

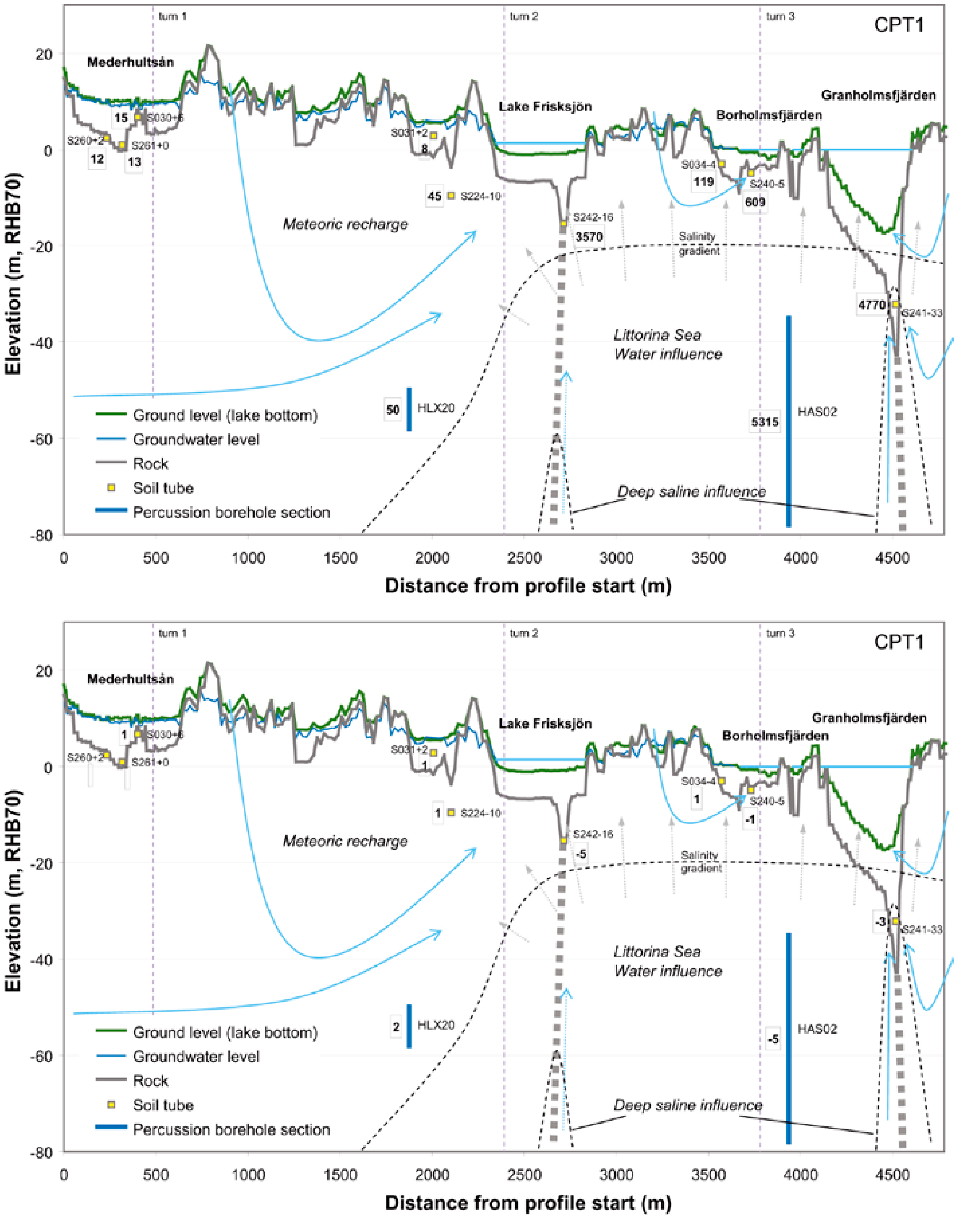


Figure 3-47. *Regional-scale conceptual hydrochemical model of Laxemar-Simpevarp /Tröjbom et al. 2008/, visualised using the transect CPT1 (cf. Figure 3-48). The plots show the elevations of the ground surface, the rock surface, and the bottoms of Lake Frisksjön and the near-coastal sea bays. In addition, the plots indicate average groundwater levels as well as the locations of groundwater monitoring wells and percussion boreholes in the vicinity of the transect. Thick dotted grey lines show approximate locations of deterministic deformation zones in the rock, according to the Laxemar 1.2 model version /SKB 2006a/, whereas blue-green arrows indicate hypothetical groundwater flow directions. The boxes in the upper plot show average Cl concentrations (mg·L^{-1}), and the boxes in the lower plot represent the so called deuterium excess D_{excess} (see /Tröjbom et al. 2008/ for further details).*

__Figure 3-48.__ Map indicating the west-to east transect (denoted CPT1) in Figure 3-47, including the locations of groundwater monitoring wells and core boreholes /Tröjbom et al. 2008/.

near-zero D_{excess} values. This indicates that meteoric recharge is the major source of the water in both shallow groundwater and the upper parts of the bedrock in the high-elevation areas. Hence, the interpretation of hydrochemical data supports the conclusion that groundwater recharge takes place in the high-elevated areas of Laxemar.

Sub-flow systems and discharge I: Indications of deep-rock discharge

/Tröjbom et al. 2008/ developed and used a so-called ion source model as the main tool to hydrochemically detect discharge of groundwater from the deep rock to the surface system. Specifically, three major ion sources were identified to affect the groundwater chemistry: (1) deep saline groundwater, (2) weathering of local minerals driven by H^+ of biogenic origin, and (3) marine ions of relict or modern origin. The Ion Source Model can also be interpreted in terms of water types. /Tröjbom et al. 2008/ identified four such water types: (1) groundwater of meteoric origin, significantly altered by reactions, (2) freshwater and dilute shallow groundwaters, influenced by biogenic CO_2 and weathering reactions, (3) marine influence (relict and modern), and (4) deep saline influence. It should be noted, however, that any classification is artificial, as most observations belong to continuous gradients between theoretical end-members. The conclusions below can be made, based on the interpretations by /Tröjbom et al. 2008/.

Deep saline groundwater in the Laxemar area is characterised by a high content of dissolved ions and a specific ion composition, enriched in e.g. Ca, Li and Br and with a low Mg/Cl ratio compared to present-day sea water. The possibilities to hydrochemically detect dilute deep groundwater signatures in near-surface groundwater and in surface water are restricted by relative concentration differences between different ion sources, as well as by the reporting limits of different elements. In that respect, many trace elements are not suitable as tracers. This is due to that even a minor dilution of an ion source in the deep rock will reduce concentrations below the reporting limit of most trace elements.

In the terrestrial parts of the Laxemar area, /Tröjbom et al. 2008/ did not note any hydrochemical “deep-rock signatures” in near-surface groundwater or in surface water. This indicates that shallow meteoric recharge-discharge patterns dominate and/or that any potential regional deep discharge into the surface system is too dilute to be detectable in surface water.

The most evident “deep rock signature” in the near-surface/surface system is found in groundwater monitoring well SSM000241, installed in the QD below the sea bay Granholmsfjärden, adjacent to deformation zone ZSMNE901A. The hydrochemistry of the water in the well is disturbed by degradation of organic matter. The Ion Source Model indicates a deviation towards a deep-saline composition of the water in the well. This conclusion is also supported by other hydrochemical indicators, such as plots of Na and Li versus Cl. In addition, the Water Origin Model indicates that there probably is discharge of meteoric water at well SSM000241.

Groundwater monitoring well SSM000242, located in till below sediments in Lake Frisksjön (see further below), shows in many respects similar chemical characteristics to SSM000241 with regard to deep saline signatures. However, there is one important difference: SSM000242 displays a stronger marine signature, with regard to both the ion composition and the isotope signature of the water. This may be interpreted as indication of stagnant conditions.

Sub-flow systems and discharge II: Contributions to stream discharge

In order to investigate underlying processes and flow paths for mass transport to streams in Laxemar, /Tröjbom et al. 2008/ analysed the correlations between stream discharges and elemental concentrations. In general, water with small amounts of dissolved ions or compounds can be expected to result in dilution in a stream. However, high-flow episodes may also lead to an increased release (e.g. due to erosion) and transport to streams of particulate matter and ions adsorbed to particles; this may lead to increasing concentrations in the stream water. Moreover, high-flow episodes may also lead to more surface runoff, which may contribute to higher concentrations of organic compounds and elements associated with organic matter. Groundwater discharge into streams may influence the concentrations of elements in different ways, depending on the element. Moreover, spatial and temporal variations of groundwater recharge may also influence the chemical conditions in the QD, which often results in changed pH or altered redox conditions. This, in turn, may lead to either release or retention of specific elements.

In their analysis, /Tröjbom et al. 2008/ used discharge data and hydrochemical data from three stream-water sampling points: PSM002079 in the upstream parts of the stream Laxemarån, PSM002087 near the Laxemarån stream outlet to the sea, and PSM002083 near the Kärrviksån stream outlet to the sea.

The hydrochemical data evaluation shows that most inorganic substances demonstrate negative correlations to stream discharges, i.e. concentrations are generally lower during periods with high stream discharges. This observation indicates that dilution is an important factor influencing elemental concentrations in the stream water, and that groundwater discharge is a minor part of the stream water during high-discharge periods. Positive correlations were found for most organic substances, i.e. concentrations are generally higher during periods with high stream discharges. This indicates that surface runoff constitutes large part of the stream water during high-flow periods. In summary, the evaluation of hydrochemical data indicates that during high-flow periods, the largest part of the stream discharge consists of surface runoff, whereas groundwater discharge has a smaller contribution to the stream discharge.

Interactions between lakes and groundwater in the underlying QD

Groundwater monitoring well SSM000242 is installed in till (the upper part of the well screen is installed in clay) below Lake Frisksjön, whereas well SSM000035 is installed in till at the shore of Lake Jämsen. These two wells therefore provide important information on the interaction between lake water and the groundwater in the underlying QD. The hydrochemical interpretations by /Tröjbom et al. 2008/ associated to these two wells are summarised below.

The two plots in Figure 3-49 compare the isotopic signatures (^{2}H and ^{18}O) in the lake water and in groundwater monitoring well SSM000242 below Lake Frisksjön (left plot) and SSM000035 at the shore of Lake Jämsen (right plot). According to these plots, there are rather dissimilar ^{2}H/^{18}O ratios. According to /Tröjbom et al. 2008/, this probably indicates that groundwaters sampled from these two groundwater monitoring wells have different origins. As noted by /Tröjbom et al. 2008/, it should be kept in mind that contamination by surface waters during installation of the wells may have influenced the measurements.

Hydrochemical data from groundwater monitoring well SSM000242 show that the Cl concentration is high (3,570 mg·L^{-1}), almost as high as the Littorina saline maximum. The high salinity combined with negative D$_{excess}$ indicates that the marine influence probably is a remnant from the Littorina stage. Moreover, the water chemistry shows that the conditions at the well-screen depth are anaerobic, which can be explained by microbial degradation of organic matter. The tritium concentration is c 1,40 TU (tritium units), which can be classified as a mixture of modern and sub-modern groundwater. The ion composition and the isotope signature show a marine influence, and the water from the well can possibly be classified as relict marine groundwater (Littorina sea water). /Tröjbom et al. 2008/ concluded that the groundwater sampled from well SSM000242 likely is a mixture of ions originating from sea water (modern or relict) and deep saline groundwater.

Hydrochemical data from groundwater monitoring well SSM000035 show an isotopic signature corresponding to the average composition of precipitation, indicating that meteoric recharge is the main source of water to the well, and that the influence of the lake water is negligible.

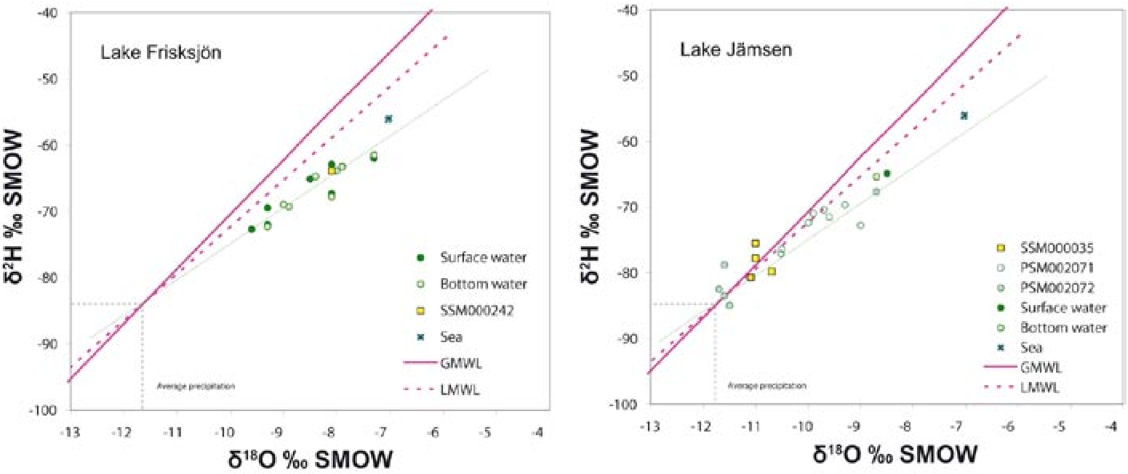


Figure 3-49. *Comparisons of the isotopic signatures (^{2}H and ^{18}O) in lake water and in groundwater monitoring well SSM000242 below Lake Frisksjön (left plot) and SSM000035 at the shore of Lake Jämsen (right plot) /Tröjbom et al. 2008/.*

4 Conceptual and descriptive model of water flow at the Laxemar site II: Quantitative water flow modelling

4.1 Overview of water flow modelling tools used in the site description

A set of quantitative water flow models has been developed and used for modelling of water flow in Laxemar. In the SDM-Site context, CONNECTFLOW /Rhén et al. 2009/ is the primary tool for modelling of groundwater flow in the rock, whereas MIKE SHE /Bosson et al. 2008b/ is the main tool for modelling of groundwater- and surface water flow in the near-surface and surface system. Section 4.1 provides a brief summary of the quantitative water-flow modelling (except MIKE SHE) related to the near-surface and surface system at Laxemar. A more detailed summary of the MIKE SHE SDM-Site Laxemar modelling and the associated results is presented in Section 4.2.

In the Simpevarp 1.2 and Laxemar 1.2 stages, /Werner et al. 2005, 2006, Jarsjö et al. 2006/ report GIS-based flow modelling. /Werner et al. 2005/ use the "Hydrological Modelling" extension of the ArcGIS software, allowing rather simple hydrological models to be developed based on the digital elevation model (DEM) of the modelled area. The modelling results in /Werner et al. 2005/ showed mismatches compared to actual locations of some streams in Laxemar, which show that local effects of land improvement and drainage operations cannot be reproduced using the Laxemar 10-m DEM without modifications.

The PCRaster-POLFLOW approach /Jarsjö et al. 2006, Werner et al. 2006/ provides extended capabilities compared to the GIS-based modelling reported in /Werner et al. 2005/. PCRaster-POLFLOW uses a single language for performing both GIS and process modelling operations, allowing analyses of temporally and spatially varying flow and transport processes within catchments on various spatial-temporal scales. The modelling results show that parameters such as evapotranspiration, precipitation surplus (precipitation minus evapotranspiration) and groundwater recharge may demonstrate relatively large spatial variability across the Laxemar area, due to a spatial precipitation trend combined with spatial variations of topography, QD types and land uses.

/Sokrut et al. 2007/ applied the ECOFLOW distributed hydrological model to the Laxemar area, with the primary objective to assess the ability of the modelling tool, for instance to simulate groundwater- and surface water flow in areas characterised by exposed/shallow rock. The ECOFLOW modelling results were compared with corresponding MIKE SHE /Werner et al. 2005/ and PCRaster-POLFLOW /Jarsjö et al. 2006/ modelling results, focusing on comparisons in terms of the water balance and identification of groundwater recharge-discharge patterns.

In this context, it can also be mentioned that /Karlberg et al. 2006/ used the CoupModel to study carbon and water fluxes in four hypothetical terrestrial boreal ecosystems. The CoupModel is a physically-based, ecosystems modelling package that uses meteorological input data to describe the interaction between biogeochemical and hydrological processes in a soil-plant-atmosphere system. /Karlberg et al. 2006/ modified the hypothetical ecosystems parameterisations and applied the CoupModel to the Laxemar area.

4.2 MIKE SHE modelling

This section provides a summary of the MIKE SHE modelling conducted in support of SDM-Site Laxemar. For a detailed description of the modelling, the reader is referred to /Bosson et al. 2008b/. MIKE SHE is a dynamic, physically based, modelling tool that describes the main processes of the land phase of the hydrological cycle /DHI Software 2007, 2008/. MIKE SHE is used in both the Forsmark /Johansson et al. 2005, Bosson et al. 2008a, Johansson 2008/ and Laxemar-Simpevarp /Werner et al. 2005, 2006, Bosson et al. 2008b/ site-descriptive modelling.

4.2.1 Overview of the modelling tool

The MIKE SHE model structure and associated water-flow processes are shown in Figure 4-1. In the model, precipitation can be either intercepted by vegetation or fall to the ground. The water on the ground surface can infiltrate, evaporate or form overland flow. Once the water has infiltrated into the soil, it enters the unsaturated zone. In the unsaturated zone, it can be either extracted by roots and leave the system as transpiration, or it can percolate down to the saturated zone. MIKE SHE is fully integrated with a 1D channel-flow code, MIKE 11. The exchange of water between the two modelling tools takes place during the whole simulation, i.e. the two programs run simultaneously.

MIKE SHE is developed primarily for modelling of groundwater flow in porous media. However, in the present MIKE SHE modelling the rock is also included, parameterised by data from the CONNECTFLOW modelling /Rhén et al. 2009/. Thus, hydrogeological properties of the rock were imported into the corresponding model elements of the MIKE SHE model.

MIKE SHE consists of the following model components:

- Precipitation (rain or snow).
- Evapotranspiration, including canopy interception, which is calculated according to the method described in /Kristensen and Jensen 1975/.
- Overland flow, calculated by a finite-difference diffusive wave approximation of the Saint-Venant equations adopting the same horisontal model grid as used for the groundwater flow component. Overland flow interacts with streams, the unsaturated zone, and the saturated (groundwater) zone.
- Channel flow, calculated by the MIKE 11 modelling system for river hydraulics. Specifically, MIKE 11 is a dynamic, 1D modelling tool for the design, management and operation of rivers and channel systems. MIKE 11 supports any level of complexity and offers simulation tools that cover the entire range from simple Muskingum routing to high-order dynamic wave formulations of the Saint-Venant equations.
- Water flow in the unsaturated zone is described using a vertical soil profile model that interacts with both overland flow (through ponding) and groundwater flow. In the latter case, the groundwater table acts as the lower boundary of the unsaturated zone. MIKE SHE offers three different modelling approaches for the unsaturated zone; a simple 2-layer root-zone mass balance approach, a gravity flow model, and a full Richards' equation model. In the SDM-Site Laxemar modelling, the last of these options was used.
- Saturated (groundwater) flow, which allows calculation of 3D flow in a heterogeneous aquifer. The groundwater flow conditions can shift between unconfined and confined. The spatial and temporal variations of the dependent variable (the hydraulic head) are described by the 3D Darcy equation and solved numerically by an iterative implicit finite-difference technique.

The specific versions of MIKE SHE used in this project involve software release versions 2007 and 2008. For a detailed description of the processes included in MIKE SHE and MIKE 11, see /Werner et al. 2005, DHI Software 2007, 2008/.

4.2.2 Implementation of the field observation-based conceptual model

Model domain and grid

As shown in Figure 4-2, the SDM-Site Laxemar MIKE SHE model area includes almost the whole SDM-Site Laxemar local model area. The MIKE SHE model area has a size of 34 km^2. In the inland parts of the model area, the model boundaries follow the boundaries of catchment areas or subcatchment areas. Referring to the catchment areas (CA) identified by /Brunberg et al. 2004/ (cf. Figure 3-6), the model area follows the water divides of and comprises CA 3 (stream Sörviksån) and CA 4 (stream Bjurhidebäcken), CA 6 (stream Mederhultsån), CA 7 (stream Kåreviksån and Lake Frisksjön), CA 8 (stream Pistlanbäcken), CA 9 (stream Ekerumsån), CA 11 (Lake Sörå), CA 12 (stream Glostadsbäcken) and CA 21 (stream Äspöbäcken on the island of Äspö). Further, the model area comprises sub-CA 10:2–13 and part of sub-CA 10:1 (stream Laxemarån). Hence, the MIKE SHE model area comprises two (Lake Frisksjön and Lake Sörå) of the six lakes within the catchment areas delineated by /Brunberg et al. 2004/. As can be seen in Figure 4-2, the MIKE SHE model area extends some 1.5 km into the bay of the Baltic, including the island of Äspö. The model area also includes "direct runoff areas" along the coast, i.e. areas that do not include any identified lakes or streams. The model domain extends vertically down to a depth of 600 m.b.s.l.

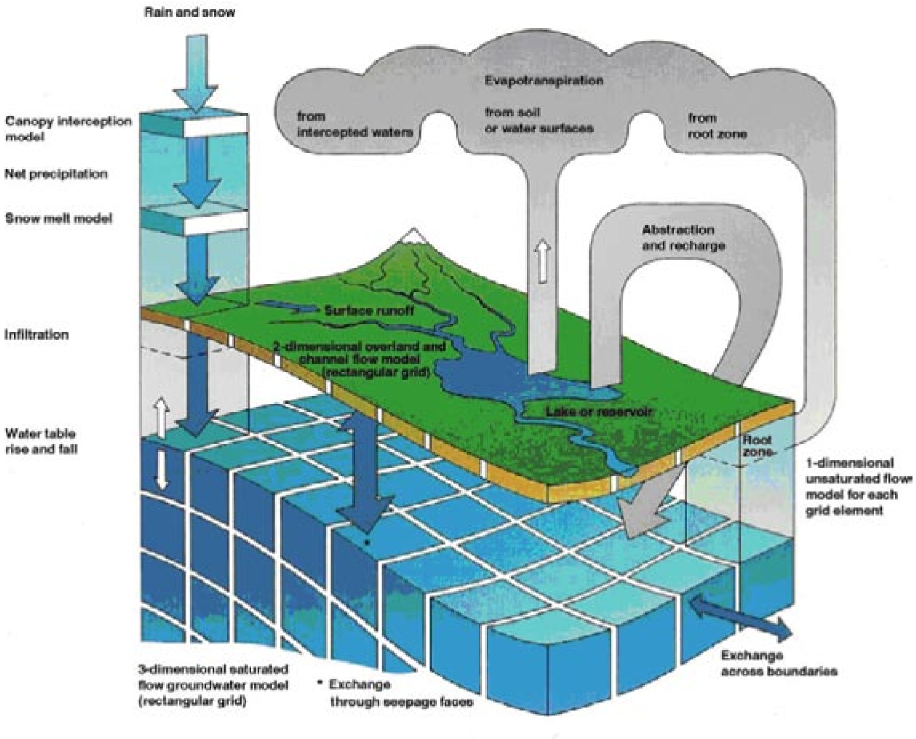


Figure 4-1. *Overview of the model structure and the processes included in MIKE SHE /DHI Software 2007/.*

Figure 4-2. *Overview map showing the extension of the MIKE SHE SDM-Site Laxemar model area (denoted L2.3 in the legend) /Bosson et al. 2008b/. The map also shows the extension of the previous L2.2 MIKE SHE model area /Aneljung et al. 2007/.*

It can be noted that in the Simpevarp 1.2 and Laxemar 1.2 modelling stages /Werner et al. 2005, 2006/, the MIKE SHE model area comprised CA 7 (Simpevarp 1.2) and CA 6–9 (Laxemar 1.2). In the Laxemar 1.2 model version, the model area (horisontal grid-cell size 20 m, total model area 8.9 km^2) was extended to also include coastal land and sea areas, i.e. direct runoff areas and the sea bottom some distance into the adjacent bay of the Baltic.

Within the framework of the so-called open repository modelling /Bosson 2006/, the stream network and the model area was expanded (horisontal grid size 30 m, model area size 18.9 km^2) to also include some sub-CA of CA 10, including part of sub-CA 10:1. It can also be noted that /Bosson 2006/ implemented a code routine that allows plant transpiration also from saturated areas; this option was not available in previous versions of the MIKE SHE code. In the subsequent (intermediate) Laxemar 2.2 modelling stage /Aneljung et al. 2007/, the model area of /Bosson 2006/ was expanded (size 27.2 km^2) to also include CA 12 and some further sub-CA (10:1, 10:8–9 and 10:12–13).

In the SDM-Site Laxemar MIKE SHE modelling, a horisontal spatial resolution of 40 m is used in the whole model area for all flow components, i.e. the saturated zone, the unsaturated zone including the evapotranspiration component, and overland flow. As described further below, the unsaturated zone (in which flow is assumed to be purely 1D) is handled in a semi-distributed manner. Input data on the geometrical and hydrogeologial properties of the QD were given on a 20 m-grid. To handle this, spatial averaging (arithmetic average of four data points) was used to convert 20 m-grids to 40-m grids. The corresponding properties for the rock were available on a 40-m grid, and no spatial averaging was hence required /Bosson et al. 2008b/.

In MIKE SHE, "geological layers" and "computational layers" can be separated. The latter need to be continuous throughout the model domain (as is common in finite-difference models), whereas the thickness of geological layers can be zero. Hence, it is possible to take into account a geological layer that exists only in part(s) of the model domain. One should hence note that hydrogeological properties are defined for the geological layers, whereas initial and boundary conditions are defined for the computational layers. The resulting hydrogeological properties for the computational layers are based on averages of corresponding cells in the geological layers /DHI Software 2007/. The calculation layers in the rock follow the geological layers according to the delivery from the CONNECTFLOW modelling team /Bosson et al. 2008b/.

Boundary conditions, initial conditions and time steps

As described in Section 3.5.1, the identified surface-water divides /Brunberg et al. 2004/ can be assumed to coincide with the water divides for groundwater flow in the QD. This implies that in the inland parts of the MIKE SHE model area, groundwater divides are assumed to coincide with surface-water divides. Accordingly, a no-flow boundary condition is adopted for the external boundaries in these parts. In the offshore parts of the model area, the sea is represented in the uppermost calculation layer. Specifically, a time-varying head boundary condition is assigned in the part of the uppermost calculation layer where the sea is located, for which sea-level monitoring data are used to define the temporal variability (cf. Figure 3-31). Large volumes of overland water can lead to numerical instabilities of the MIKE SHE model. Therefore, the sea is handled as a "geological layer" containing material with a high hydraulic conductivity /Bosson et al. 2008b/.

At the top boundary of the model, meteorological conditions are assigned in terms of precipitation and potential evapotranspiration. In order to mimic the observed spatial trend of the precipitation /Werner et al. 2008/, the precipitation is uniformly distributed in space within each of 3 zones. The actual evapotranspiration is calculated by MIKE SHE during the simulation, using potential evapotranspiration, air temperature data and all sorts of properties of the system as input. A no-flow boundary is used for the bottom boundary at 600 m.b.s.l. It should be noted that a no-flow or a constant-head boundary was set in the rock at 150 m.b.s.l. in previous model stages up to Laxemar 2.2 /Werner et al. 2005, 2006, Bosson 2006, Aneljung et al. 2007/.

The MIKE SHE model was calibrated using input and monitoring data for the period October 10, 2003–December 31, 2006. Moreover, the period January 1–December 31, 2007 was chosen for model testing /Bosson et al. 2008b/. In MIKE SHE, a maximum time step is defined for each model compartment; the time steps may be reduced during the course of simulation. In the present case, the adopted maximum time steps vary between 5 s (MIKE 11) and 3 h (saturated zone) /Bosson et al. 2008b/.

Geometrical and hydraulic properties of hydrological objects and hydrogeological flow domains

Stream network and lakes

The MIKE 11 stream network communicates laterally with the overland flow and saturated zone components of MIKE SHE. Lakes are not geometrically specified in MIKE 11, but are “created” during the simulation by ponding of water in topographical depressions through the communication between MIKE 11 and the overland flow component in MIKE SHE. In the present modelling, and also in the previous Laxemar 2.2 stage /Aneljung et al. 2007/, this communication is handled by a so called “two-way overbank spilling option”.

The total length of the MIKE 11 stream network within the MIKE SHE model area is approximately 67 km. This network is divided into 243 calculation nodes for flow and 334 nodes for head. This yields an average length of c 270 m between nodes for flow calculations and c 200 m between nodes for head calculations. Surveyed cross-sections /Strömgren et al. 2006/ are available at the locations of most head calculation nodes.

The unsaturated zone

In the MIKE SHE Laxemar modelling, an automatic routine selects a limited number of grid cells for simulation of water flow in the unsaturated zone in order to reduce the computational time. The vertical model discretisation of the unsaturated zone (see Table 4-1) is the same for all vertical profiles, ranging between one or a few centimetres in the upper part of the profile, and one to a few decimetres at a depth of c 1 m, i.e. where the groundwater table typically is encountered /Werner et al. 2008/.

The saturated zone

The geometry of the geological layers representing the regolith in the MIKE SHE model is based on the regolith depth and stratigraphy model (RDM) developed by /Nyman et al. 2008/, see Figure 3-1. Moreover, the starting point for assignment of hydrogeological properties (hydraulic conductivity, porosity and specific storage coefficient) to these layers is the data evaluation presented by /Werner et al. 2008/.

The hydrogeological properties of the rock were obtained from the CONNECTFLOW modelling team /Rhén et al 2009/. Due to parallel MIKE SHE and CONNECTFLOW modelling activities, two interim rock models and a “final” rock model have been used during the MIKE SHE modelling process. Specifically, the first two rock models (delivered in March and May, 2008) were based Laxemar 1.2 data combined with updated HCD properties, and an uncalibrated Laxemar 2.3 model, respectively, whereas the third rock model (delivered in September, 2008) was based on a “first-tier” calibrated Laxemar 2.3 model.

The modelling results presented in /Bosson et al. 2008b/, which are summarised in this report, are based on the first (March, 2008) and third (September, 2008) rock models; the second rock model (May, 2008) was an intermediate model that was used to a limited extent within the MIKE SHE SDM-Site Laxemar modelling. Moreover, the third rock model (September, 2008) was delivered in three variants, based on some further CONNECTFLOW model calibration tests. Based on MIKE SHE model calibration /Bosson et al. 2008b/, one of these three variants was chosen as

Table 4-1. Vertical discretisation of the unsaturated zone in MIKE SHE.

From depth (m)	To depth (m)	Cell height (m)	Number of cells
0	0.1	0.01	10
0.1	0.3	0.02	10
0.3	0.8	0.05	10
0.8	1.8	0.1	10
1.8	4	0.2	11
4	20	0.5	32

basis for further modelling work (see Section 4.2.3). It should be noted that the final SDM-Site rock model /Rhén et al. 2009/ was finalised subsequent to the conclusion of the SDM-Site MIKE SHE modelling. /Bosson et al. 2008b/ handled this by means of extended sensitivity analyses (see Section 4.2.6) concerning properties and features in the rock, and including analyses of the influence of dolerite dykes and groundwater inflow to the Äspö Hard Rock Laboratory.

4.2.3 Model calibration and sensitivity analyses

This section provides a summary of the calibration and sensitivity analyses performed as part of the MIKE SHE SDM-Site Laxemar modelling. For a more detailed description, see /Bosson et al. 2008b/. The overall objective with the MIKE SHE model calibration is to obtain a “base case” model that can be used for subsequent analyses and to provide support to the site descriptive modelling and other applications such as environmental impact and safety assessments. The sensitivity analyses, performed as part of the calibration process and/or as separate activities, provide important input regarding the overall confidence of the base case model.

The MIKE SHE pre-modelling exercises in the intermediate Laxemar 2.2 stage /Aneljung et al. 2007/ provided some important insights into steps to be taken for calibration purposes during the MIKE SHE SDM-Site Laxemar modelling. For instance, during the pre-modelling /Aneljung et al. 2007/ noted that the MIKE SHE model calculated too small stream flows and that the MIKE 11 stream network should be extended. /Aneljung et al. 2007/ tested to adjust some vegetation parameters in order to reduce the calculated evapotranspiration, which however resulted in generally too high calculated groundwater levels in the QD.

As mentioned in Section 4.2.2, primarily the first (March, 2008) and third (September, 2008) of the totally three delivered rock models were used as a basis for the MIKE SHE modelling summarised here.

The MIKE SHE SDM-Site Laxemar model calibration process included the following overall steps:

- ***Calibration step 1:*** Sensitivity analyses and parameter adjustments focussing on comparisons between model-calculated and measured stream discharges and lake-water levels.
- ***Calibration step 2:*** Sensitivity analyses and parameter adjustments focussing on comparisons between model-calculated and measured (undisturbed) groundwater levels in the QD.
- ***Calibration step 3:*** Sensitivity analyses and parameter adjustments focussing on comparisons between model-calculated and measured (undisturbed) groundwater levels in the rock, and results of so called interference tests (i.e. disturbed groundwater levels) in the rock.

The following sections summarise the main actions and associated findings from each of these three overall calibration steps. As mentioned in Section 4.2.2, the model calibration period was October 10, 2003–December 31, 2006, whereas the model was tested using monitoring data for the period January 1–December 31, 2007.

The MIKE SHE model calibration and testing take into account the subset of discharge and lake-water level gauging stations, groundwater monitoring wells, and percussion boreholes located within the MIKE SHE model area (see Figure 4-3). For an overview of all discharge- and lake-water level gauging stations, groundwater monitoring wells, and percussion boreholes installed and drilled as part of the site investigations in Laxemar 2002–2007, see Sections 2.2.1–3 and /Werner et al. 2008/. The data used for the MIKE SHE model calibration and testing include the following:

- Stream discharges measured at discharge-gauging stations PSM000347 (stream Kåreviksån), -348 (stream Kåreviksån, downstream the outlet from Lake Frisksjön), -364 (stream Laxemarån) and -365 (stream Ekerumsån).
- Lake level in Lake Frisksjön (gauging station PSM000348).
- Groundwater levels in the QD, measured in 33 groundwater monitoring wells.
- Groundwater levels in the rock, measured in 39 borehole sections in 25 percussion boreholes.
- Groundwater-level drawdown in 11 percussion borehole sections, measured in connection to so-called interference tests.

Figure 4-3. *Overview map showing the locations of the discharge-gauging stations, the surface-water level station in Lake Frisksjön, and the groundwater monitoring wells and percussion boreholes utilised for MIKE SHE model calibration and testing /Bosson et al. 2008b/.*

Calibration step 1: Stream discharges and lake-water levels

Except for model tests involving adjustment of the MIKE 11 representation of the Lake Frisksjön outlet (see below), the first rock model (delivered in March, 2008) was used as a basis for calibration step 1. As a first step of the initial model calibration, some tests were performed regarding the numerical stability of the model. These tests resulted in adjustments of time steps and numerical control parameters, e.g. the maximum number of iterations and the maximum head change between iterations.

In accordance with the calibration methodology suggested by /Aneljung et al. 2007/, the first step of the model calibration process focused on comparisons between model-calculated and measured stream discharges. The first action was to extend the MIKE 11 stream network, due to the larger model area compared to the MIKE SHE model developed and tested by /Aneljung et al. 2007/. Additional stream branches were also defined within the MIKE SHE model area, based on field checks of actual stream locations and characteristics (cf. Section 3.3.3).

/Bosson et al. 2008b/ reduced the potential evapotranspiration (PET), added a surface rock layer, and included near-surface drain features in the model in order to handle a problem that was encountered also during the corresponding SDM-Site Forsmark exercises /Bosson et al. 2008a/; too slow calculated stream discharge responses to precipitation/snowmelt events, as well as calculated stream discharges ("base flow") also during periods with no stream discharge according to measurements. Specifically, the original values in the PET data set /Werner et al. 2008/ were reduced by 15%, and near-surface drains were added in two types of areas; high-altitude areas characterised by shallow/exposed rock, and agricultural areas located in valleys.

The near-surface drains (defined in the form of drainage depths) introduced in the high-altitude areas may represent a high-conductive upper rock and thin QD. In valleys, the near-surface drains (defined in the form of drainage depths and time constants) may represent the (partly unknown) ditches and drains that have been constructed as part of land improvement and drainage operations (see Section 3.3.3). Based on tests of different variants of drainage depths and drainage time constants, the drainage depth was set to 0.35 m in the high-altitude areas and 1 m in the valleys /Bosson et al. 2008b/. In addition, the so-called Manning number, which in this case controls the flow resistance in the overland flow module of MIKE SHE, was reduced; a lower Manning number yields a higher flow resistance.

Based on the findings by /Aneljung et al, 2007/, /Bosson et al. 2008b/ tested to reduce the saturated conductivity (K_s) and the specific yield (S_y) of the unsaturated zone to 1/10 and 1/4, respectively. It was found that these adjustments provided a better fit to measured streams discharges. In addition, many other parameters referring to the evapotranspiration module of MIKE SHE (vegetation and the unsaturated zone) were reset to the values defined by /Bosson 2006/.

/Bosson et al. 2008b/ noted difficulties in matching model-calculated and measured lake-water levels in Lake Frisksjön. As described in /Werner et al. 2008/, there is a large boulder located in the stream Kåreviksån, a small distance downstream from the lake (see Figure 4-4). /Bosson et al. 2008b/ included the boulder in MIKE 11, and it was found that this action improved the match. Note that this exercise was based on the second rock model (delivered in May, 2008).

Figure 4-4. *Photograph of the boulder located in the stream Kåreviksån, downstream from the Lake Frisksjön outlet /Bosson et al. 2008b/.*

Calibration step 2: Groundwater levels in the QD

Following the methodology proposed by /Aneljung et al. 2007/, the second model calibration step involves comparisons between model-calculated and measured groundwater levels in the QD.

The interaction between groundwater (MIKE SHE) and surface water (MIKE 11) is controlled by a so called leakage coefficient. Based on the first rock model (delivered in March, 2008), /Bosson et al. 2008b/ tested the influence of this coefficient and found that it generally had small influence on model-calculated groundwater levels, except for some groundwater monitoring wells located in the immediate vicinity of streams. Based on these findings, the leakage coefficient was increased by a factor of 100 compared to the leakage coefficient used by /Aneljung et al. 2007/.

Based on the first rock model (delivered in March, 2008), /Bosson et al. 2008b/ tested the influence of increasing the horisontal hydraulic conductivity in layers Z1, Z2 and Z6 by factors of 5 and 10. They also tested the influence of increasing the horisontal hydraulic conductivity of model cells in contact with the MIKE 11 stream network only. It was found that the influence on the model-calculated groundwater levels in the QD generally was small, and no changes were made of the original parameter setup (see /Werner et al. 2008/. A better fit to measurements was noted for some groundwater monitoring wells, but this was not considered enough to motivate general parameter changes.

It was found that the best fit to the data was obtained keeping the parameterisation of /Werner et al. 2008/ intact, except for a reduction of the specific yield in the unsaturated-zone component of MIKE SHE. Moreover, as mentioned above, surface drains were applied in all inland parts of the model area with exposed rock (according to the QD map /Sohlenius and Hedenström 2008/), and also in all agricultural areas (according to the Real Estate Map).

Based on the third rock model (delivered in September, 2008), /Bosson et al. 2008b/ tested the influence of reducing the horisontal (K_h) and the vertical hydraulic conductivity (K_v) of the upper 200 m of the rock. K_h and K_v were reduced by a factor of 10, either one of them (and the other kept unchanged) or both at the same time. The results showed different effects for different percussion boreholes. However, the "isotropic" reduction case ($K_h/10$ and $K_v/10$) gave the best overall improvement in terms of the match between model-calculated and measured groundwater levels in the QD. /Bosson et al. 2008b/ also tested the influence of reducing K_h and K_v only in the upper 80 m of the rock. The results showed small differences compared to the case when K_h and K_v were reduced in the upper 200 m. In order to make as small adjustments as possible relative to the delivered rock model, it was decided that the hydraulic conductivity reductions should be restricted to the upper 80 m of the rock.

Calibration step 3: Groundwater levels and interference tests in the rock

In line with the methodology proposed by /Aneljung et al. 2007/, the third model calibration step involved comparisons between model-calculated and measured groundwater levels in the rock. Based on the third rock model delivered in September, 2008, /Bosson et al. 2008b/ tested the MIKE SHE model performance by comparison with the observed groundwater-level drawdown during so-called interference tests. Specifically, the considered tests involved pumping in percussion boreholes HLX14 and -33; for further information on the HLX33 pumping test, see /Werner et al. 2008/.

Based on calibration step 2 (see above) only variants involving reductions of the vertical hydraulic conductivity (K_v) in the upper 80 m of the rock were tested. Moreover, at that stage of the CONNECTFLOW modelling process, it was considered that too large reduction of K_v was not realistic /Bosson et al. 2008b/. Accordingly, the model tests performed by /Bosson et al. 2008b/ included reductions of K_v to $K_v/10$ and $K_v/5$, of which the variant $K_v/5$ was found to provide a sufficiently improved match to the observed groundwater-level drawdown. In addition, a good fit could be attained by adjusting the spatially variable specific storage coefficients (S_s) of the rock to a constant value of $S_s = 10^{-8}\ m^{-1}$ for the whole rock mass.

4.2.4 Performance of the MIKE SHE SDM-Site Laxemar base case model

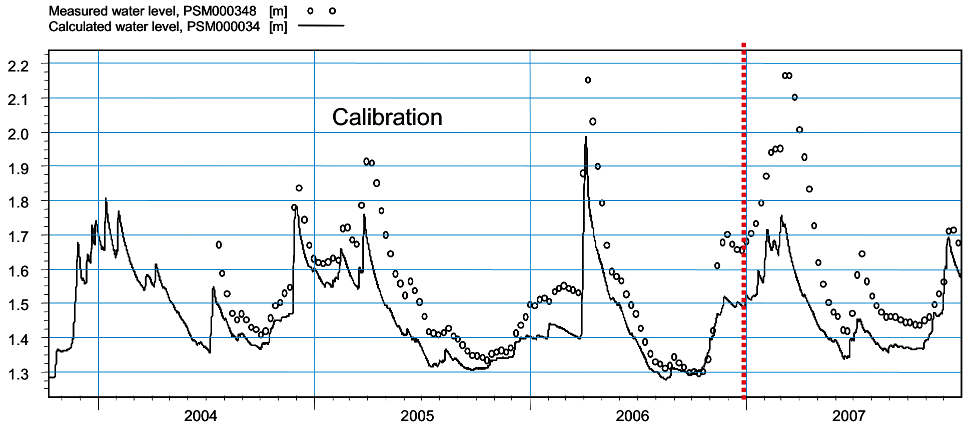
This section summarises the performance of the MIKE SHE SDM-Site Laxemar base case model, in terms of comparisons between model-calculated and measured surface-water levels and discharges, and groundwater levels in QD and rock. In summary, the MIKE SHE model calibration and sensitivity analyses (see Section 4.2.3) resulted in the addition of the following main features and most important parameter adjustments:

- Activation of near-surface drains in high-altitude areas characterised by shallow/exposed rock, and in agricultural areas in valleys and other low-altitude areas.
- Reduction of the specific yield (S_y) in the unsaturated zone to 1/4 relative to the data-based parameterisation presented in /Werner et al. 2008/.
- Reduction of the vertical hydraulic conductivity (K_v) by a factor of 5 in the upper 80 m of the rock relative to the third rock model, which was delivered from HydroNet in September, 2008. In addition, the specific storage coefficient (S_s) of the rock was assigned a constant value of $S_s = 10^{-8}\ m^{-1}$, replacing the spatially variable S_s-values delivered from HydroNet.

Surface-water levels and surface-water discharges at gauging stations

As mentioned previously, the MIKE SHE model was calibrated using monitoring data from one lake-level gauging station (PSM000348 at the Lake Frisksjön outlet) and three discharge-gauging stations located within the MIKE SHE model area; PSM000347 in the stream Kåreviksån upstream of Lake Frisksjön, PSM000364 in the stream Laxemarån, and PSM000365 in the stream Ekerumsån. The discharge data from the natural critical section at PSM000348 were not used. The reason is that the data from this station likely are erroneous and associated with relatively large uncertainty, possibly due to the large boulder located in the stream (see Figure 4-4).

Figure 4-5 shows a time-series plot of the model-calculated and measured lake-water level at the Lake Frisksjön outlet (gauging station PSM000348). According to Figure 4-5, the lake-level variations calculated by the MIKE 11 model demonstrate a close resemblance to the measured lake level. However, except for some short periods the model-calculated lake level is below the measured lake level (on average c 0.1 m below). The difference between the calculated and the measured lake level is relatively large during periods with high lake levels (e.g. during winter and spring 2007). One possible explanation for this difference may be the boulder located downstream from the lake outlet (cf. Figure 4.4 in Section 4.2.3). This boulder is represented in a simplified manner in the MIKE 11 model, and may influence the lake level in a manner that cannot be fully reproduced by the model /Bosson et al. 2008b/.



ME=0.11405
MAE=0.114626
RMSE=0.149898
STDres=0.0972725
R(Correlation)=0.909894
R2(Nash_Sutcliffe)=0.398421

Figure 4-5. *Time series plot of the model-calculated and the measured lake level in Lake Frisksjön (gauging station PSM000348). The vertical red line indicates the end of the model calibration period /Bosson et al. 2008b/.*

Figures 4-6 to 4-13 compare model-calculated (MIKE 11) and measured stream discharges at the four discharge-gauging stations (see above). Data are shown in terms of time-series plots of daily average discharges and accumulated stream discharges. As can be seen in these plots, the MIKE 11 model yields a proper representation of the transient stream discharges, characterised by relatively long periods with little or no discharge interrupted by short high-discharge periods. However, the model does not reproduce the annual maximum discharge periods, occurring in connection to intense snowmelt during the spring (primarily the spring of 2006).

The plots of accumulated stream discharges show that there is some discrepancy between the model-calculated and measured data. A more detailed examination of the time-series plots informs that the discrepancy mainly emanates from the spring period 2006 (cf. above), i.e. intense snowmelt that is not properly represented in the model. According to /Bosson et al. 2008b/, the four considered discharge-gauging stations have a model-calculated accumulated discharge that on average is c 10% less than the measured accumulated stream discharge for the period April 1–May 15, 2006. Considering the whole period (October 10, 2003–December 31, 2007), the difference between model-calculated and measured accumulated stream discharges is –23% for discharge-gauging station PSM000347 (i.e. the calculated accumulated discharge is 23% less than the measured), 8% for station PSM000348, –9% for station PSM000364, and –8% for station PSM000365 /Bosson et al. 2008b/. For a time series co-plot of the measured lake-water level in Lake Frisksjön, groundwater level in the QD below the lake, and stream discharges into and out from the lake, see Figure 3-42 in Section 3.5.3.

Table 4-2 compares model-calculated and measured specific discharges ($L \cdot s^{-1} \cdot km^{-2}$) for the four discharge-gauging stations, separated into the calibration period (up to Dec. 31, 2006) and the test period (year 2007) /Bosson et al. 2008b/. Due to the low quality of the measured discharge data from station PSM000348 /Werner et al. 2008/, average values excluding the PSM000348 data are also shown.

For the whole calibration period and test period, the average model-calculated specific discharge for the four stations is 4.66 $L \cdot s^{-1} \cdot km^{-2}$ (corresponding to 147 $mm \cdot y^{-1}$). Excluding the PSM000348 station, the average is 5.44 $L \cdot s^{-1} \cdot km^{-2}$ (172 $mm \cdot y^{-1}$). Moreover, the average model-calculated specific discharge is 5.44/6.01 = 90% of the average measured specific discharge (excluding PSM000348). As can be seen in Table 4-2, and also can be noted from measurements at the totally nine discharge stations in the Laxemar area /Werner el al. 2008/, the specific discharge demonstrates relatively large variations between different time periods and gauging stations. The largest specific discharge is noted for station PSM000364, installed in the stream Laxemarån and with the largest catchment area size.

The best fit between model calculations and measurements (93% and 97%, respectively, in terms of the ratio between model-calculated and measured specific discharge) is noted for stations PSM000364 and -365, installed in the stream Laxemarån and Ekerumsån, respectively. In this context, it should be noted that the western MIKE SHE model boundary crosses the Laxemarån stream. To handle this, an assigned stream discharge is used in MIKE 11 at the western boundary to calculate the “incoming” discharge in the Laxemarån stream.

An interesting observation can be made concerning gauging stations PSM000347 and PSM000348 installed in the stream Kåreviksån, upstream and downstream from Lake Frisksjön, respectively. A comparison between these two stations show large differences in terms of the measured specific discharge /Werner et al. 2008/, whereas there is only a very small difference between the stations in terms of the model-calculated specific discharge (see Table 4-2). This observation emphasises that measured discharge data from station PSM000348 are associated with lower quality compared to other gauging stations in the Laxemar area /Werner et al. 2008/.

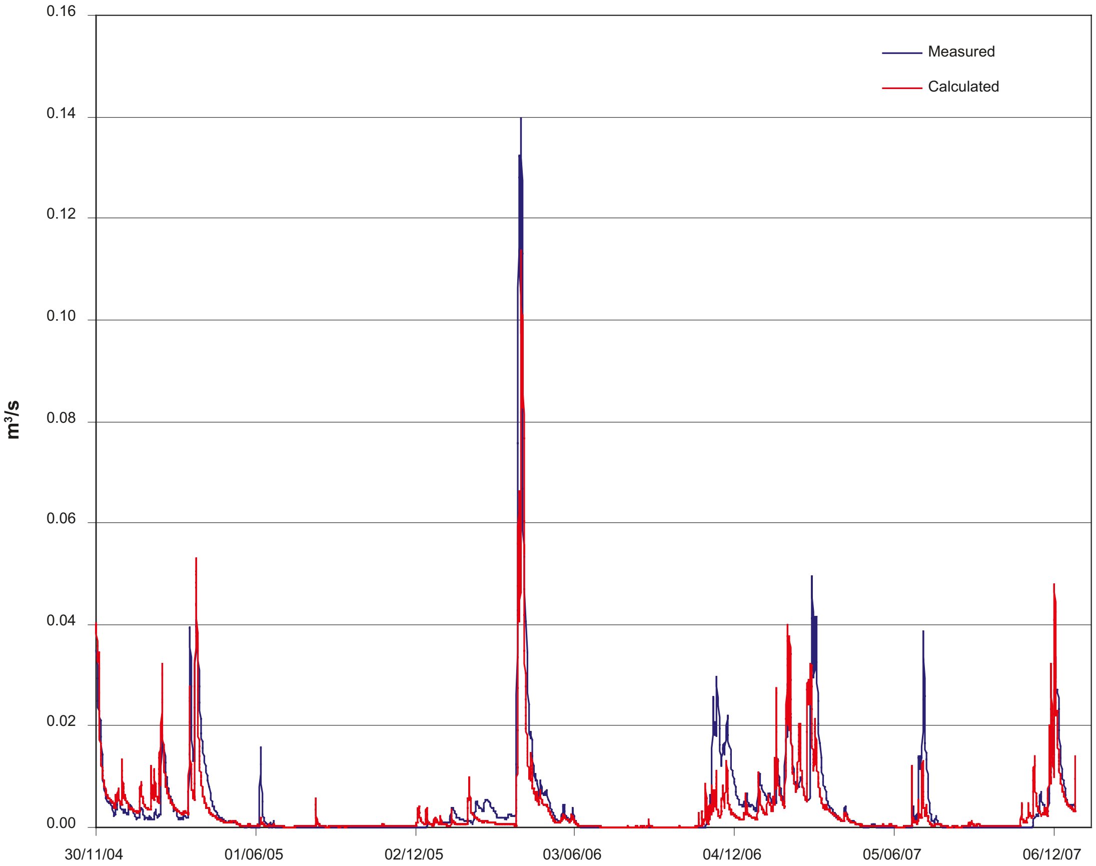


Figure 4-6. *Time series plot of the model-calculated and measured stream discharge at gauging station PSM000347 in the stream Kåreviksån, upstream from Lake Frisksjön.*

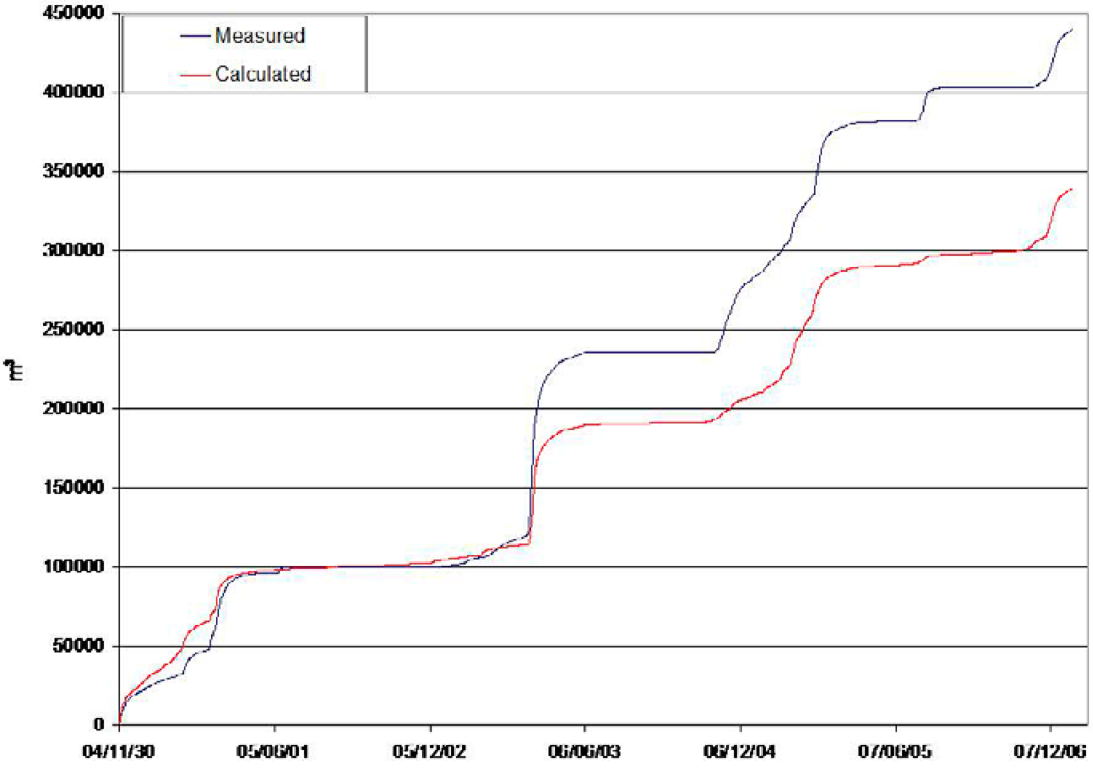


Figure 4-7. *Time series plot of the model-calculated and measured accumulated stream discharge at gauging station PSM000347 in the stream Kåreviksån, upstream from Lake Frisksjön.*

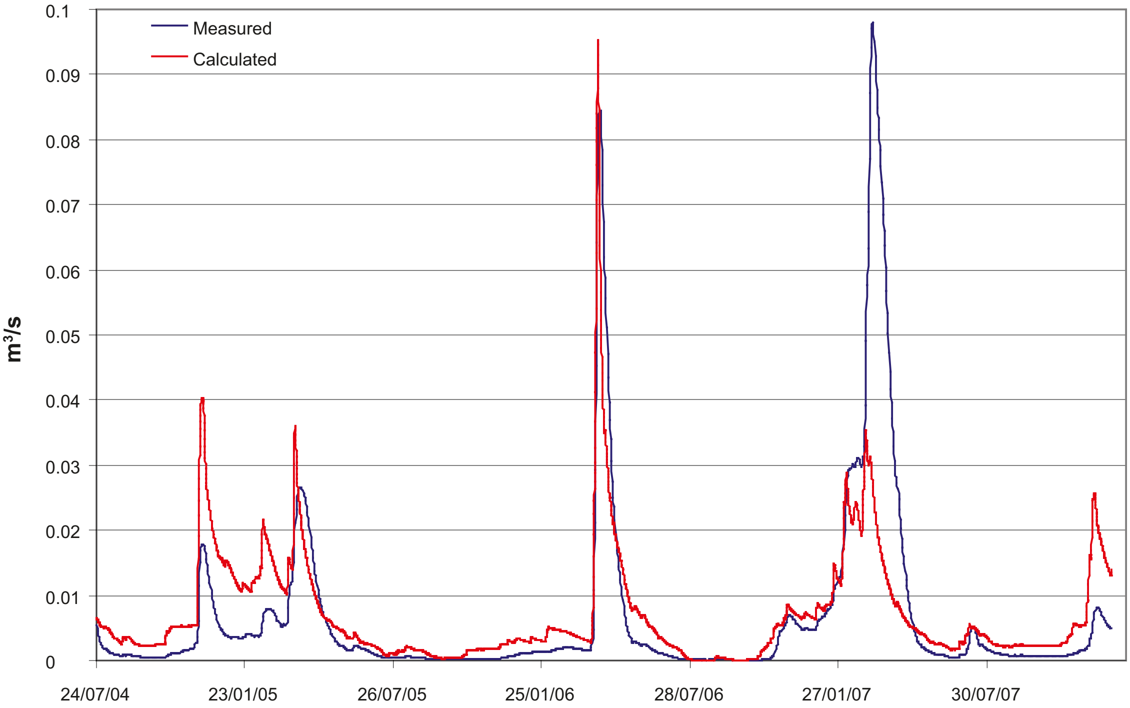


Figure 4-8. *Time series plot of the model-calculated and measured stream discharge at gauging station PSM000348 in the stream Kåreviksån, downstream from Lake Frisksjön.*

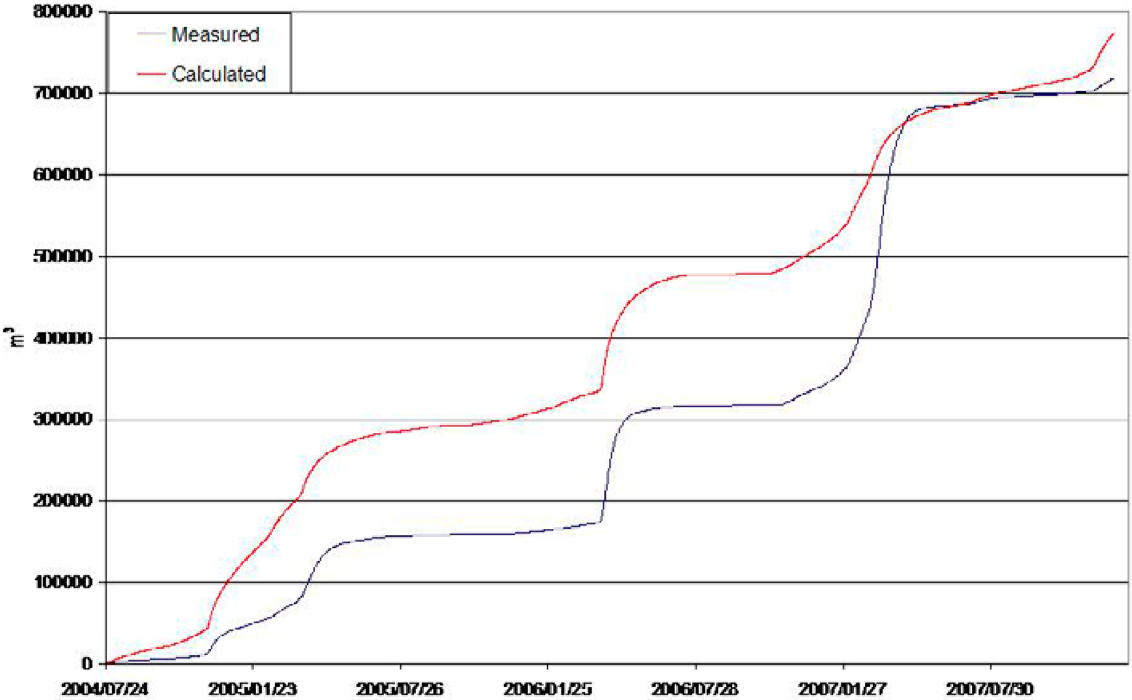


Figure 4-9. *Time series plot of the model-calculated and measured accumulated stream discharge at gauging station PSM000348 in the stream Kåreviksån, downstream from Lake Frisksjön.*

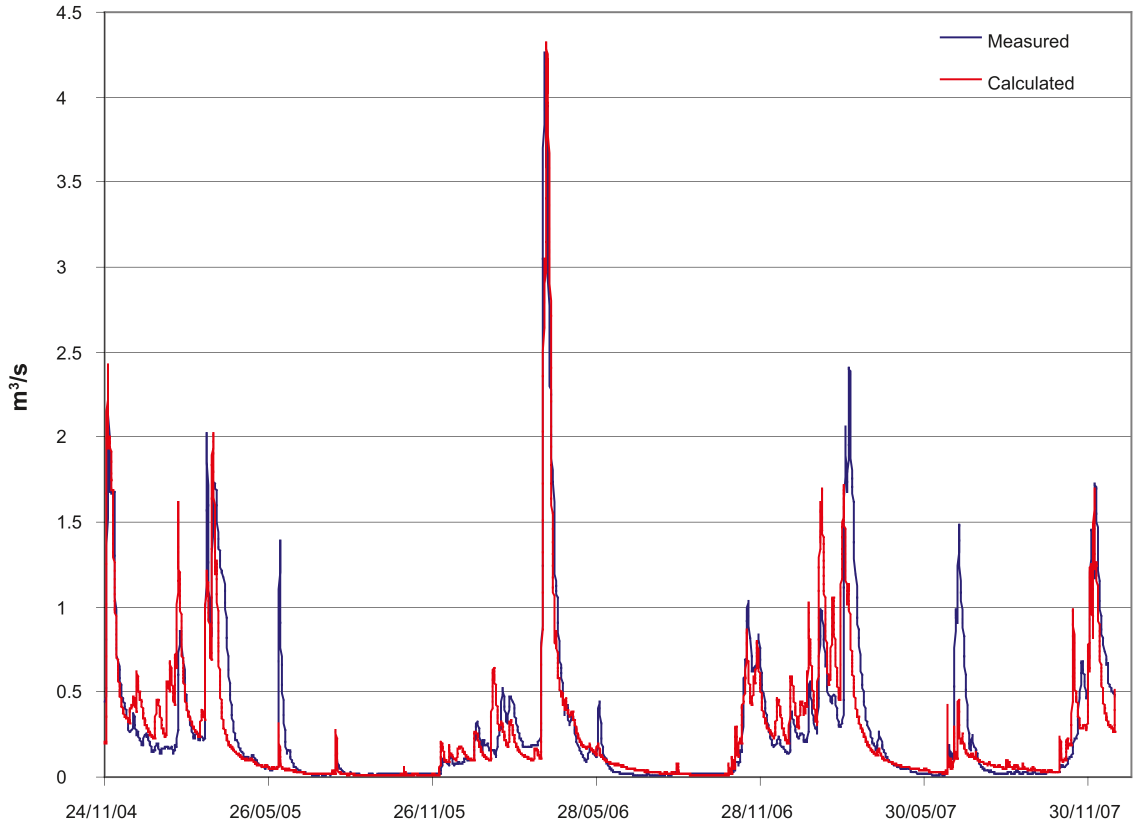


Figure 4-10. *Time series plot of the model-calculated and measured stream discharge at gauging station PSM000364 in the stream Laxemarån.*

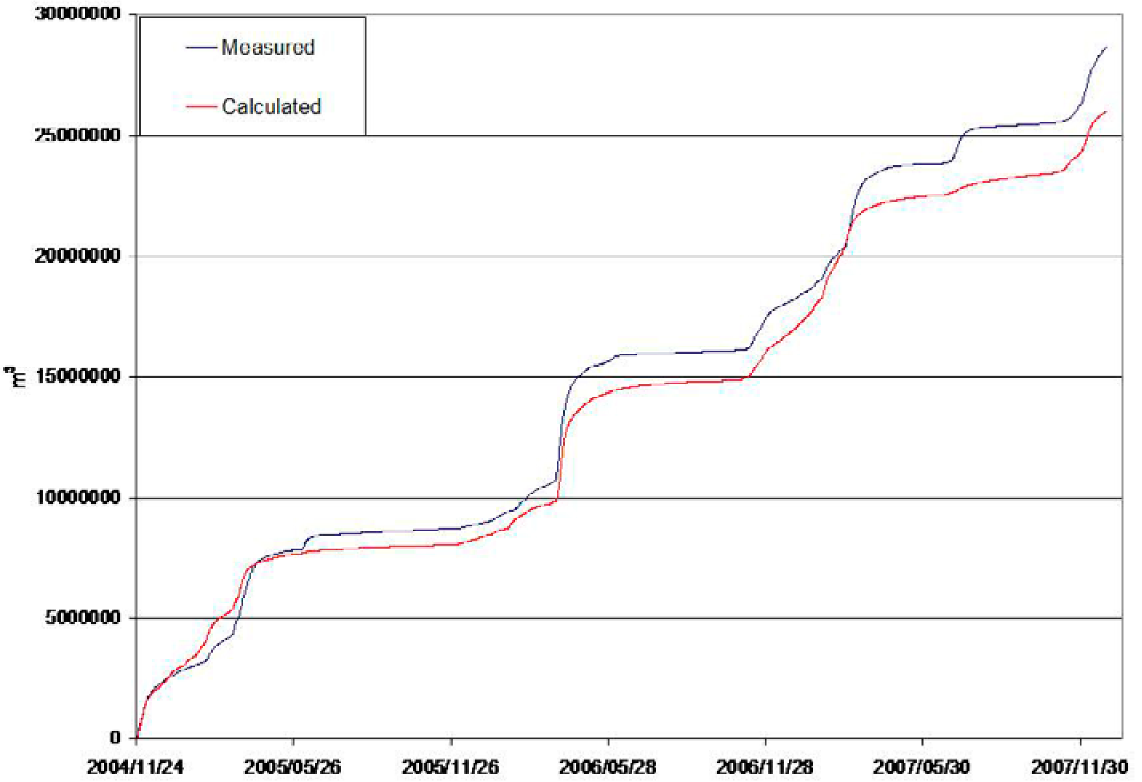


Figure 4-11. *Time series plot of the model-calculated and measured accumulated stream discharge at gauging station PSM000364 in the stream Laxemarån.*

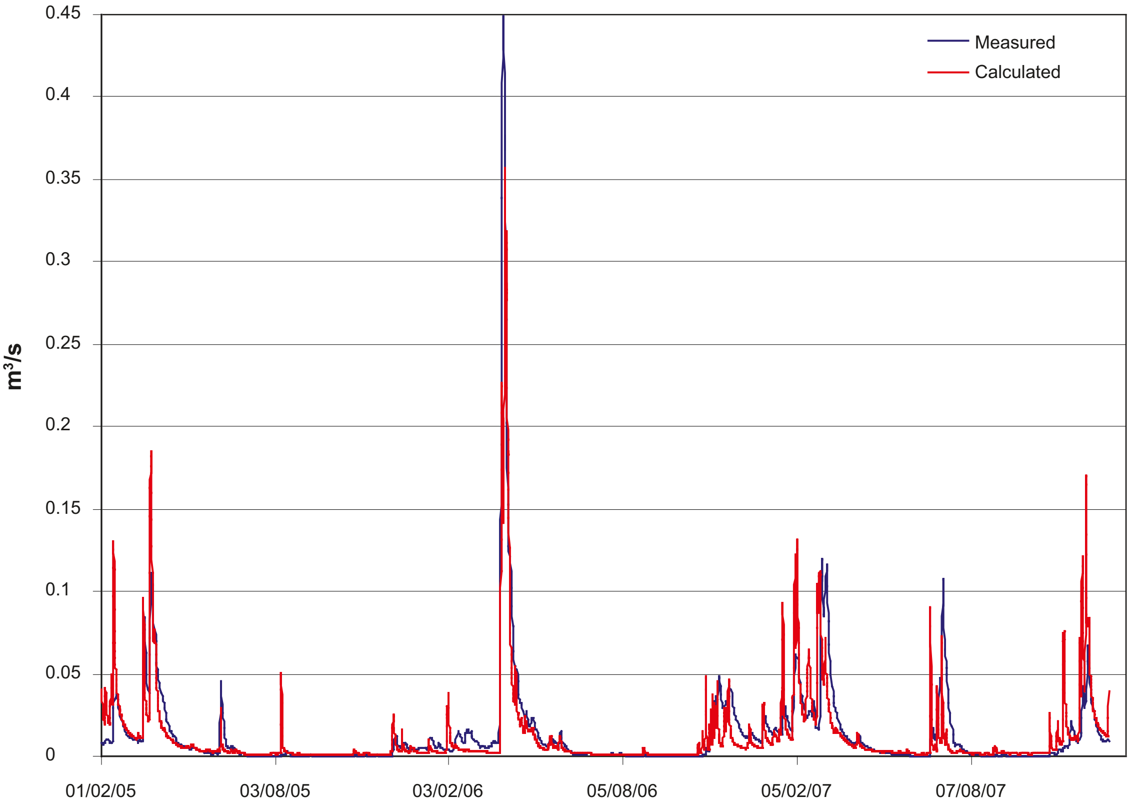


***Figure 4-12.** Time series plot of the model-calculated and measured stream discharge at gauging station PSM000365 in the stream Ekerumsån.*

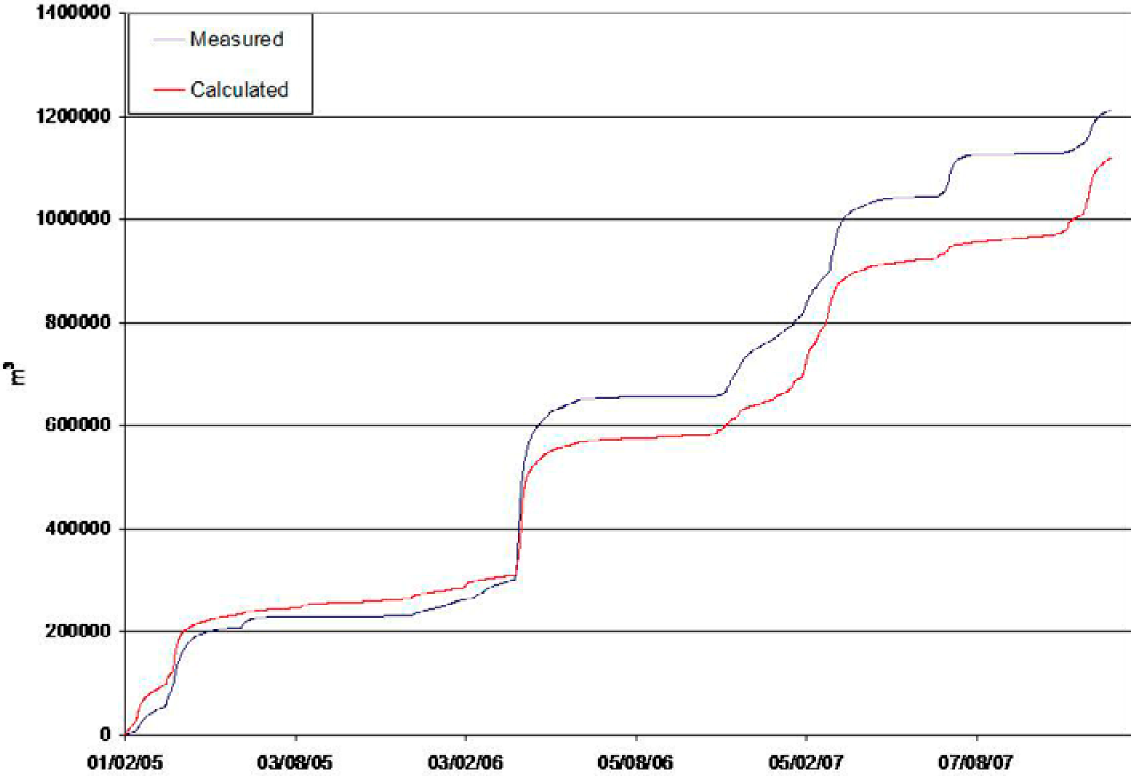


***Figure 4-13.** Time series plot of the model-calculated and measured accumulated stream discharge at gauging station PSM000365 in the stream Ekerumsån.*

Table 4-2. Comparison between model-calculated and measured specific discharges (L·s⁻¹·km⁻²) for the four discharge-gauging stations located within the MIKE SHE model area (see Figure 2-4 in Section 2.2.2 for their locations) /Bosson et al. 2008b/.

	Calibration period (up to Dec. 31, 2006)		Test period (year 2007)	
Gauging station	**Calculated**	**Measured**	**Calculated**	**Measured**
PSM000347	3.62	4.80	4.45	5.29
PSM000348	3.61	2.36	4.41	6.36
PSM000364	6.46	6.43	7.17	8.30
PSM000365	4.68	5.33	6.23	5.92
Average (excl. PSM000348)	4.59 (4.92)	4.73 (5.52)	5.57 (5.95)	6.47 (6.50)

Groundwater levels in groundwater monitoring wells and percussion boreholes

The scattergram in Figure 4-14 illustrates the fit between model-calculated (horisontal axis) and measured (vertical axis) average groundwater levels in groundwater monitoring wells (SSM; red dots) and percussion boreholes (HLX; blue dots) for the period October 10, 2003–December 31, 2007. As can be seen in the figure, the MIKE SHE base case model yields a relatively close match between model-calculated and measured groundwater levels. The fit is somewhat better for the groundwater monitoring wells, whereas the discrepancy is larger in terms of groundwater levels in the rock. Specifically, the base case model generally underestimates groundwater levels in the rock.

Tables 4-3 and 4-4 summarise model-fit statistics for the 33 groundwater monitoring wells and the 25 percussion boreholes from which monitoring data have been obtained for calibrating the MIKE SHE model. The statistics are calculated for the period October 10, 2003–December 31, 2007, and are shown in terms of the mean error (ME) and the mean absolute error (MAE). ME for a specific well or borehole (section) is the sum of the differences between measurements and calculations,

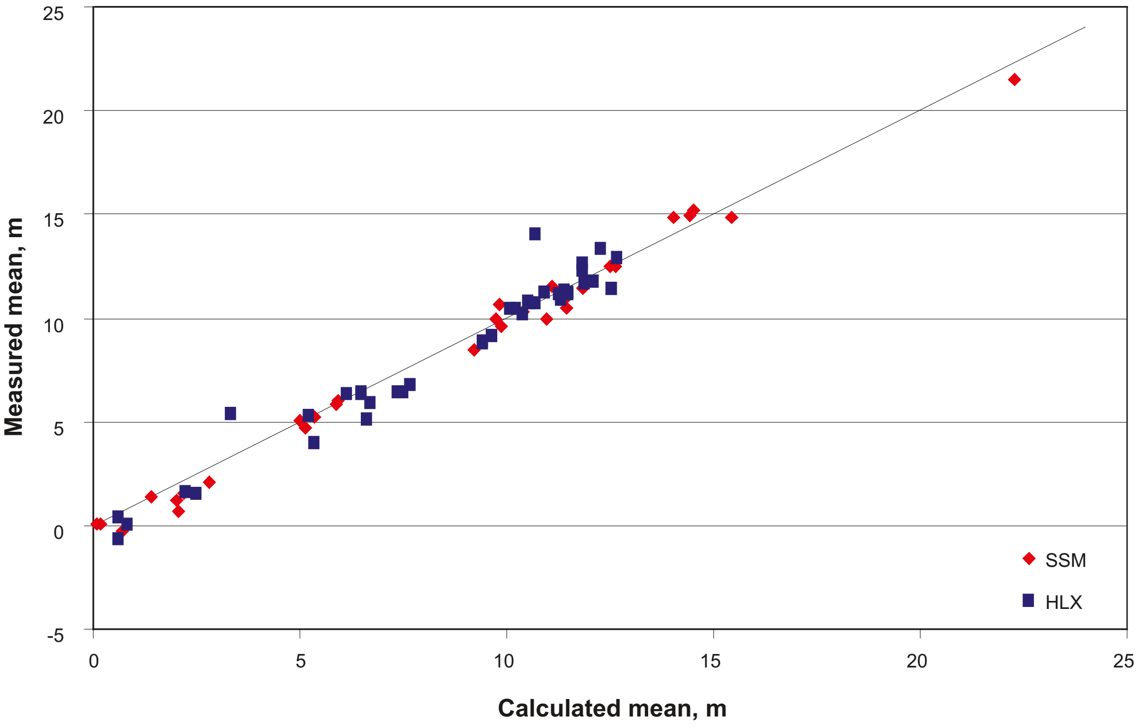


Figure 4-14. Scattergram illustrating the relation between model-calculated (horisontal axis) and measured (vertical axis) average groundwater levels in groundwater monitoring wells ("SSM") and percussion boreholes ("HLX"). The averages are calculated for the period October 10, 2003–December 31, 2007.

divided by the number of observations. Moreover, MAE is obtained as the sum of the absolute values of these differences, divided by the number of observations. Hence, a positive ME for a specific well or borehole section implies that on average, the model-calculated groundwater level is below the measured groundwater level.

As shown at the bottom of Table 4-3, the average of all mean absolute errors (MAE) for the groundwater monitoring wells is 0.55 m, whereas the average of all mean errors (ME) is 0.17 m. The low MAE means that the temporal variations of the measured groundwater levels can be considered to be properly represented by the model, whereas a small positive ME implies that on average, model-calculated groundwater levels in the QD are somewhat lower than measured groundwater levels. According to /Bosson et al. 2008b/, most of the groundwater monitoring wells demonstrating the largest discrepancies between model-calculated and measured groundwater levels are installed in slopes. For these wells, the discrepancies can be explained by that the 40-m grid resolution is too coarse to resolve short-term dynamics and groundwater gradients.

Table 4-3. Comparison of model-calculated and measured groundwater levels for 33 groundwater monitoring wells /Bosson et al. 2008b/ located within the MIKE SHE model area (for locations of the wells, see Figure 2-6 in Section 2.2.3). MAE and ME are short for mean absolute error and mean error, respectively. The statistics refer to the period October 10, 2003–December 31, 2007. *Corrected monitoring data (cf. /Werner et al. 2008/).

Well ID	MAE (m)	ME (m)
SSM000011	0.66	–0.58
SSM000017	0.70	0.66
SSM000019	0.34	0.09
SSM000021	0.22	–0.18
SSM000030	0.10	0.00
SSM000031	0.27	0.27
SSM000032	0.33	–0.33
SSM000033	0.65	0.37
SSM000034	0.47	–0.45
SSM000037*	0.04	–0.02
SSM000039	0.37	–0.19
SSM000041*	0.13	–0.12
SSM000042	0.29	0.28
SSM000210	0.49	–0.18
SSM000213	1.16	1.16
SSM000219	1.36	1.36
SSM000220	0.85	0.77
SSM000221	0.88	0.81
SSM000222	0.14	–0.03
SSM000223	0.14	–0.04
SSM000224	0.21	0.19
SSM000225	0.22	0.20
SSM000226	0.83	0.74
SSM000227	0.53	0.44
SSM000228	0.22	0.18
SSM000229	0.84	0.79
SSM000230	1.08	–1.08
SSM000237	0.98	0.98
SSM000239	0.14	–0.14
SSM000240	0.04	0.02
SSM000242	0.43	–0.43
SSM000249	0.73	–0.64
SSM000250	1.50	1.50
Average	0.55	0.17

Table 4-4 summarises the corresponding statistics for the percussion boreholes. As shown in the table, most boreholes are divided into sections by means of packers. These sections are numbered from the borehole bottom and upwards. For instance, HLX11.1 and HLX11.2 denote the lower and upper section, respectively, in percussion borehole HLX11, which hence has two borehole sections. Note that open boreholes without packers (e.g. HLX02) contain a single section, denoted by .1 (i.e. HLX02.1).

The average of all mean absolute errors for the combined calibration and test periods is 0.78 m, whereas the average of all mean errors is 0.27 m. A positive ME implies that on average, model-calculated groundwater levels in the rock are below measured groundwater levels. For approximately half of the percussion borehole sections the mean absolute error is equal to or smaller than 0.5 m. For the other borehole sections, the mean absolute error is on the order of 1 m; 15% of the boreholes demonstrate mean absolute errors larger than 1 m.

Table 4-4. Comparison of model-calculated and measured groundwater levels in 39 borehole sections in 25 percussion boreholes /Bosson et al. 2008b/ located within the MIKE SHE model area (for the locations of the boreholes, see Figure 2-8 in Section 2.2.3). MAE and ME are short for mean absolute error and mean error, respectively. The statistics refer to the period October 10, 2003–December 31, 2007.

Borehole/section ID	MAE (m)	ME (m)
HLX01.1	0.44	–0.23
HLX02.1	2.66	2.66
HLX06.1	1.07	0.83
HLX07.1	0.56	–0.05
HLX08.1	0.63	–0.63
HLX09.1	1.03	–1.03
HLX09.2	0.33	0.02
HLX11.1	0.38	–0.06
HLX11.2	0.39	–0.13
HLX13.1	1.17	1.17
HLX14.1	0.79	0.79
HLX15.1	0.65	0.65
HLX18.1	0.67	–0.67
HLX18.2	0.41	–0.41
HLX21.1	0.38	0.26
HLX21.2	0.35	0.26
HLX22.1	0.69	0.65
HLX22.2	1.10	–1.09
HLX23.1	0.83	0.81
HLX23.2	0.45	0.25
HLX24.1	0.72	0.66
HLX24.2	0.74	0.74
HLX25.1	0.52	0.08
HLX25.2	0.49	–0.11
HLX26.1	1.08	–1.08
HLX27.1	0.46	–0.43
HLX27.2	0.52	–0.51
HLX28.1	3.45	3.45
HLX30.1	0.42	–0.18
HLX30.2	0.38	–0.16
HLX31.1	0.40	–0.18
HLX31.1	0.47	0.23
HLX31.2	0.37	0.36
HLX33.1	0.62	0.58
HLX33.2	0.43	0.39
HLX34.1	1.80	1.80
HLX35.1	1.43	1.21
HLX35.2	0.56	–0.44
HLX36.1	0.38	0.20
Average	0.78	0.27

4.2.5 Interpretation of flow modelling results

This section summarises and discusses the MIKE SHE modelling results calculated using meteorological and sea-level data for the time period October 10, 2003–December 31, 2007.

Water balance

Figure 4-15 presents the MIKE SHE-calculated annual average water balance for the time period October 1, 2004–October 1, 2007, corresponding to three so-called hydrological years /Bosson et al. 2008b/. For the same time period, Figure 4-16 shows the calculated annual average water balance for each calculation layer in the saturated zone of MIKE SHE. Note that the modelling results in these figures are calculated for the terrestrial part of the model area.

For the considered 3-year period, the annual average (and area-averaged) precipitation was 608 mm, whereas the calculated annual average of the (actual) evapotranspiration was 425 mm, which is the sum of evaporation from different land and open water surfaces and transpiration from vegetation. The largest single evapotranspiration component is transpiration from vegetation (on average 202 mm·y^{-1}). The calculated evaporation from soil is on average 88 mm·y^{-1} and evaporation from ponded areas 5 mm·y^{-1}. On average, interception by leaves is quantified to 124 mm·y^{-1} and evapotranspiration from "wet" areas 6 mm·y^{-1}. The model-calculated annual average specific discharge is 170 mm·y^{-1} (including direct runoff to the sea and runoff to the sea from the saturated zone), corresponding to c 5.4 L·s^{-1}·km^{-2}.

The model-calculated specific discharge is in agreement with the measured site-average specific discharge for the years 2005–2007 (165 mm·y^{-1}) and within the interval of the estimated long-term average of 150–180 mm·y^{-1} /Larsson-McCann et al. 2002, Werner et al. 2008/. It should be noted that there are relatively large inter-annual water balance differences. For instance, considering a different but partly overlapping 3-year period (October 15, 2003–October 15, 2006), the MIKE SHE-calculated annual average specific discharge is 199 mm·y^{-1}.

In Figure 4-15, one can note that there is relatively large interaction between the overland and saturated zone model components. The underlying reason for this is the near-surface drains that are defined in the model in high-altitude areas and agricultural areas located in valleys and other low-altitude areas (see Section 4.2.3). In the MIKE SHE model, these drains act to transfer water either to streams (MIKE 11) or to local topographical lows, which in the latter case may lead to the formation of ponded areas. In MIKE SHE, this phenomenon is handled as flow from the saturated zone component to the overland flow component. The ponded water is subsequently transfered to the unsaturated or saturated zone components.

According to Figure 4-16, the net annual area-averaged groundwater recharge from the unsaturated zone to the uppermost calculation layer representing the QD is 226 mm, whereas the area-averaged groundwater recharge to the rock is 35 mm. The net annual average groundwater recharge from the QD to the rock is 7 mm (35 minus 28 mm). It can also be noted that the vertical groundwater flow further down in the rock is relatively small. For instance, at 150 m.b.s.l. the vertical flow is 10 mm downwards and 9 mm upwards, which hence implies a very small downward net flow.

Groundwater table and vertical hydraulic gradients

The overview map in Figure 4-17 shows model-calculated average depths to the groundwater table in metres below the ground surface (m.b.g.s.) for the period October 1, 2004–October 1, 2007 /Bosson et al. 2008b/. The results show that the groundwater table generally mimics the topography, i.e. the (average) elevation of the groundwater table is related to the ground-surface elevation. On average, the model-calculated groundwater table is located close to the ground surface in low-lying areas (e.g. valleys) and located at larger depths in higher-elevated areas. For the considered period, the spatially averaged depth to the groundwater table (i.e. the average of the average depths shown in Figure 4-17) is c 3 m.b.g.s. which is somewhat deeper than the temporal and spatial average calculated from available groundwater-level measurements in the QD /Werner et al. 2008/. However, as noted in /Werner et al. 2008/, few groundwater monitoring wells are installed in high-elevated areas, which may lead to an underestimation of average groundwater table depths in the measured data.

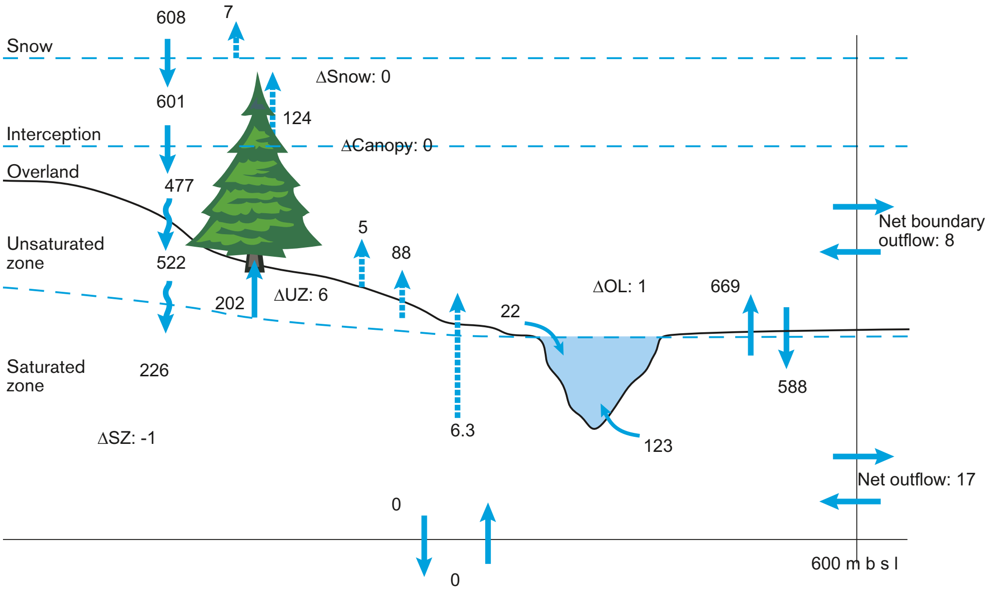


***Figure 4-15.** Model-calculated annual average water balance (mm) for the time period October 1, 2003–Oct. 1, 2007 /Bosson et al. 2008b/. Storage changes (ΔUZ, ΔSZ, ΔOL, and so forth) are also given in mm·y^{-1}.*

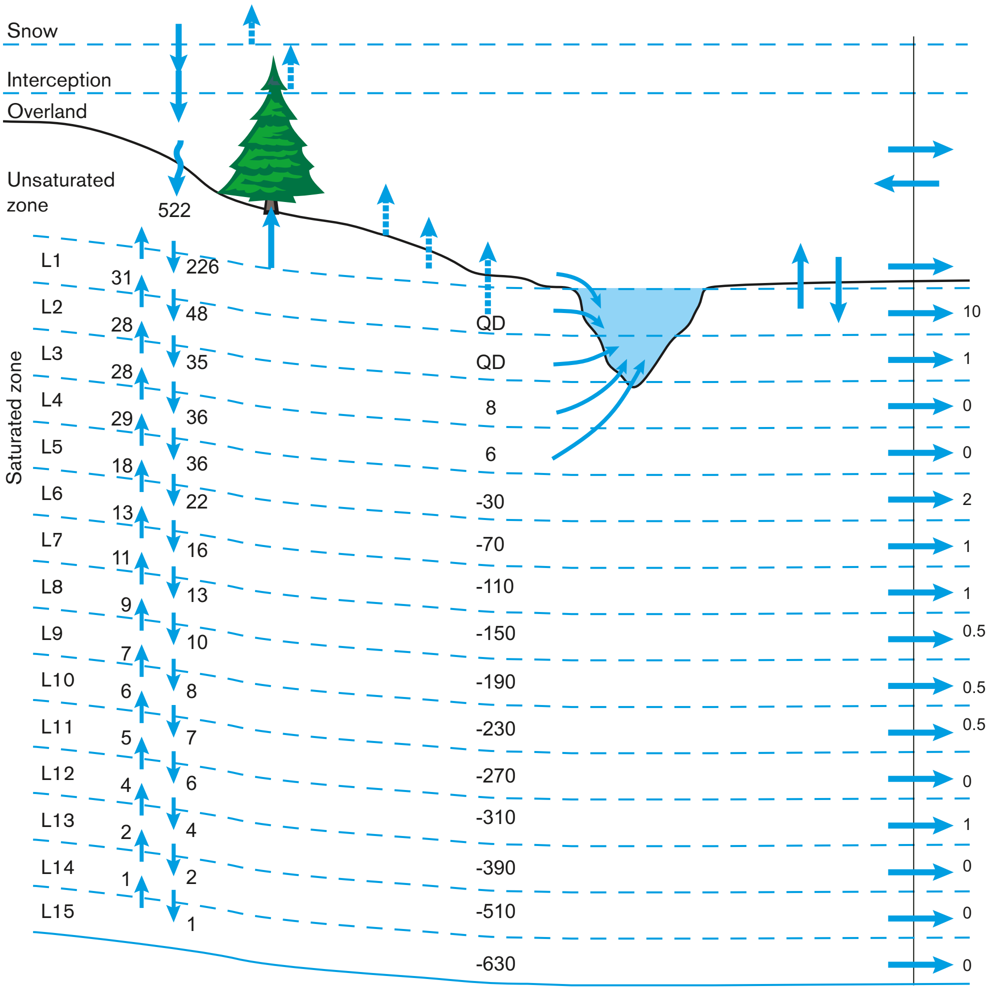


***Figure 4-16.** Model-calculated annual water balance for each layer in the saturated zone in the terrestrial parts of the model area, including quantification of vertical flow components /Bosson et al. 2008b/. The average level (m.a.s.l.) of the lower boundary of each calculation layer is shown in the middle of the figure.*

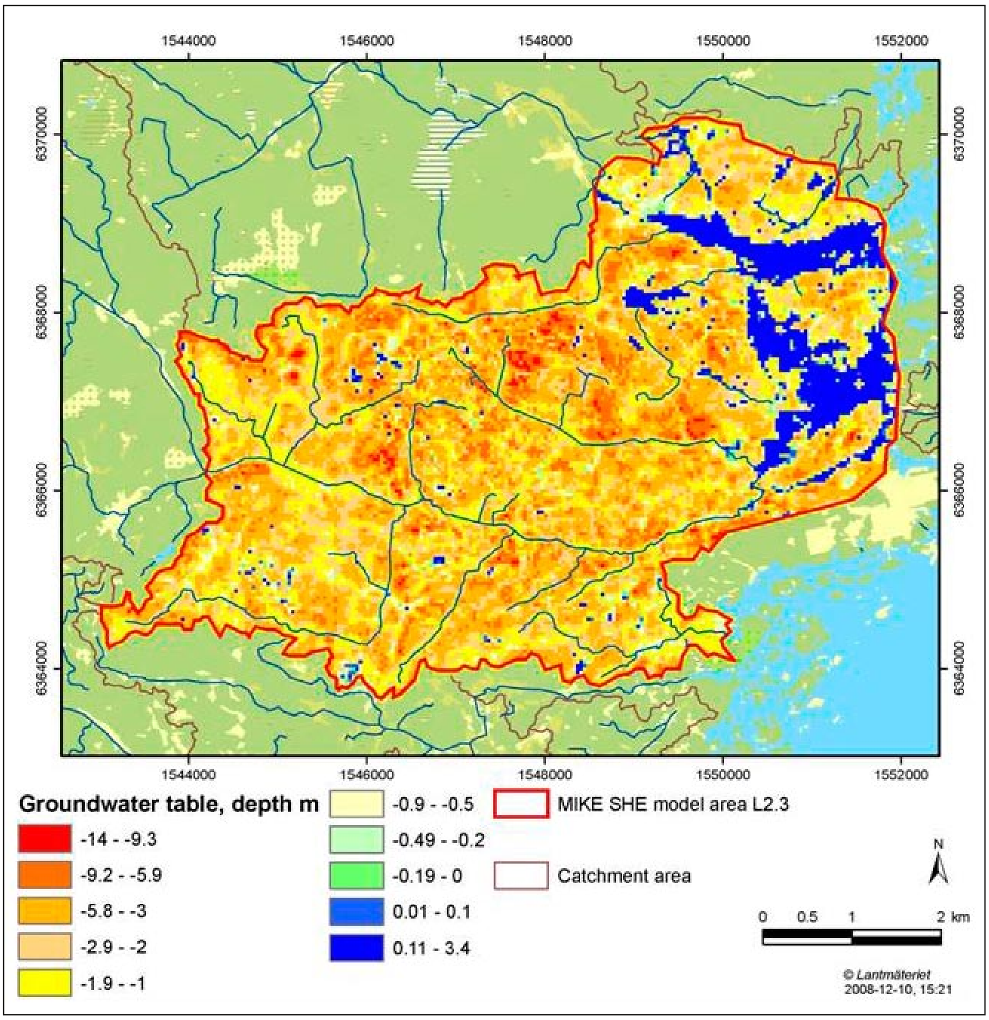


***Figure 4-17.** Overview map of temporally averaged model-calculated depths to the groundwater table for the period October 1, 2004–October 1, 2007. Areas with ponded water (streams, lakes, wetlands and the sea) are shown in blue /Bosson et al. 2008b/.*

According to the MIKE SHE calculations /Bosson et al. 2008b/, the largest temporally averaged groundwater table depth is c 14 m.b.g.s. whereas the corresponding maximum is c 4 m.b.g.s. based on groundwater-level measurements /Werner et al. 2008/. According to the MIKE SHE calculations, the model-calculated temporally averaged depth to the groundwater table is less than 3 m.b.g.s. in the largest part of the model area; the temporal average is larger than 5 m.b.g.s. in 15% of the model area, whereas the corresponding fraction is less than 0.5% for depths larger than 10 m.b.g.s.

The blue areas in Figure 4-17 represent ponded areas, i.e. areas where the model-calculated hydraulic head in the uppermost calculation layer is located above the ground surface (or lake/sea bottom). Hence, these areas represent surface waters, i.e. streams, lakes, wetlands and the sea. "Positive depths" to the groundwater table can therefore be interpreted in terms of surface-water depths. According to /Bosson et al. 2008b/, model-calculated ponded areas generally coincide with field-checked surface waters (e.g. lakes and wetlands).

Figures 4-18 and 4-19 show the model-calculated temporally averaged distribution of vertical hydraulic head differences; near the ground surface (Figure 4-18) and at an elevation of c 50 m.b.s.l. in the rock (Figure 4-19). In Figure 4-18, groundwater recharge and discharge areas are identified by the temporally averaged difference of the hydraulic head between the two uppermost calculation layers (i.e. in the QD) for the period January 1, 2004–December 31, 2006. Specifically, areas with a higher hydraulic head in the top calculation layer compared to the underlying layer for the considered period are defined as groundwater recharge areas; the opposite applies for groundwater discharge areas. In Figure 4-19, vertical hydraulic head differences are calculated as the temporally

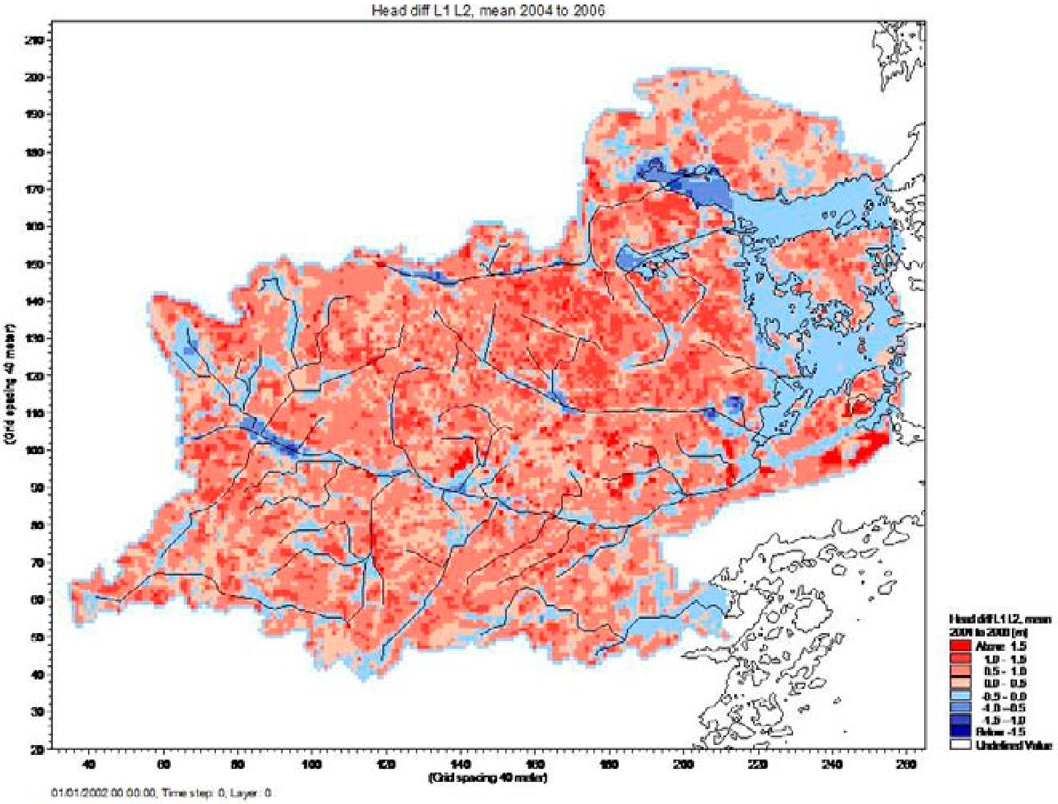


Figure 4-18. *Model-calculated distribution of near-surface groundwater recharge and discharge areas. These areas are identified based on temporally averaged hydraulic-head differences between the two uppermost calculation layers of the model, for the period 2004–2006 /Bosson et al. 2008b/. Streams and the shoreline are indicated by black solid lines.*

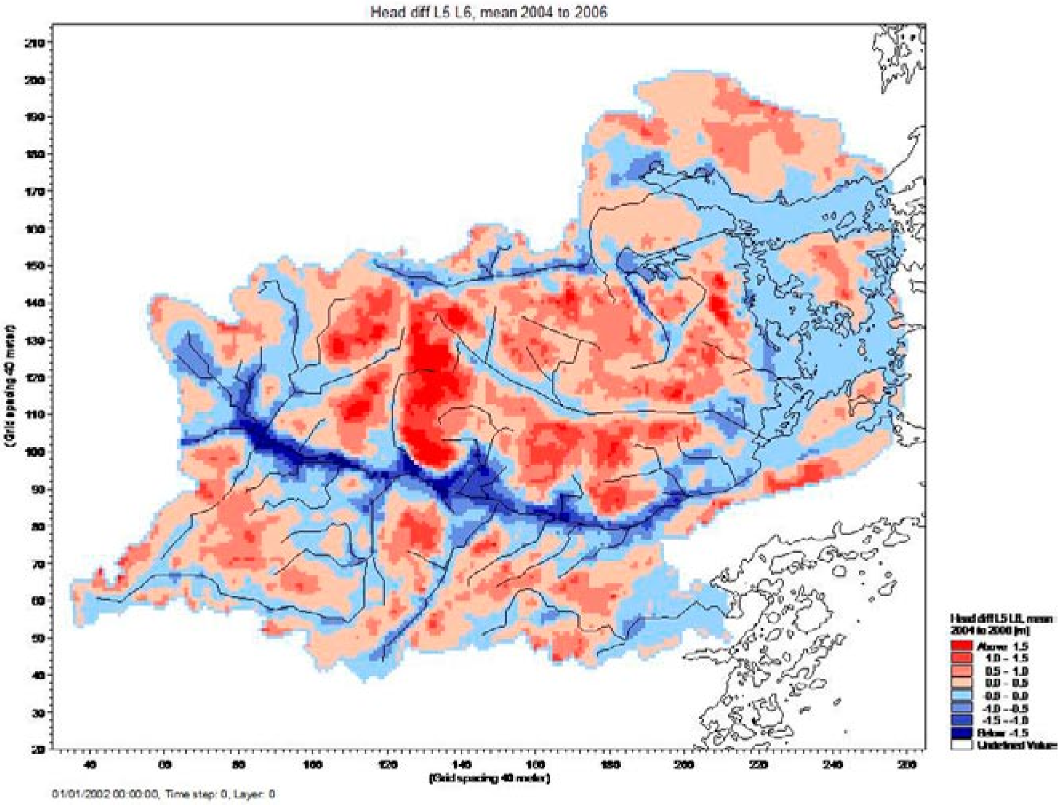


Figure 4-19. *Model-calculated distribution of areas with downward (red) and upward (blue) hydraulic head gradients between elevations 30 and 70 m.b.s.l. in the rock. These areas are identified based on temporally averaged hydraulic-head differences between calculation layers 5 and 6 of the model, for the period 2004–2006 /Bosson et al. 2008b/. Streams and the shoreline are indicated by black solid lines.*

averaged difference of the hydraulic head between calculation layers 5 and 6 of the model for the same period; layers 5 and 6 are located at elevations of c 30 and 70 m.b.s.l. respectively. Note that streams and the shoreline are indicated by black solid lines in both figures.

According to Figure 4-18, the near-surface groundwater flow system is dominated by groundwater recharge areas, occupying c 70% of the MIKE SHE model area /Bosson et al. 2008b/. Close to the ground surface, model-calculated groundwater discharge areas (hence occupying c 30% of the MIKE SHE model area) are located to low-lying areas such as stream valleys, Lake Frisksjön and the sea bays near the coast. As indicated in Figure 4-19, approximately half (55%) of the MIKE SHE model area has downward head gradients between 30 and 70 m.b.s.l. of the rock. In particular, one can note that there are head-gradient conditions for upward groundwater flow at this depth interval in the rock in larger (wider) areas below the stream valleys, compared to the smaller (thinner) areas with upward head gradients near the ground surface (cf. Figure 4-18). The most pronounced downward head gradients at the considered depth in the rock (Figure 4-19) are located in high-altitude areas along water divides (i.e. the highest elevations in the MIKE SHE model area), whereas groundwater recharge-discharge conditions near the ground surface (Figure 4-18) are more influenced by the local topography.

/Bosson et al. 2008b/ used the MIKE SHE Laxemar model to analyse the influence of temporally variable hydro-meteorological conditions on the distribution of areas with downward and upward head gradients near the ground surface and in the upper part of the rock (30–70 m.b.s.l.). Specifically, hydraulic head differences corresponding to Figures 4-18 and 4-19 were calculated during a dry period and a wet period; two fortnight periods of the year 2006 were chosen to represent the dry (July 5–20) and the wet conditions (April 1–15). During the dry period, the accumulated precipitation was less than 1 mm at both the Äspö and Plittorp meteorological stations, whereas the accumulated precipitation was c 30 mm at both stations during the wet period. In addition, there was a (calculated) accumulated snowmelt of c 95 mm during the wet period (cf. /Werner et al. 2008/).

The results indicate that the overall near-surface groundwater recharge-discharge pattern is relatively stable during the year (for details, see /Bosson et al. 2008b/). For the analysed wet and dry periods, the relative change (compared to the average situation) of the sizes of areas with downward and upward head gradients is on the order of 1–7% near the ground surface. The results show a larger size of near-surface recharge areas during wet periods, as compared to both dry periods and the average situation, whereas the size of discharge areas is larger during a dry period. The same applies to the head-gradient conditions in the considered depth interval in the rock. However, according to the MIKE SHE modelling results, the influence (in relative terms) of wet and dry periods is more pronounced compared to the QD.

Infiltration and groundwater recharge

As described in Sections 3.4.1 and 3.5.2, precipitation and snowmelt are considered to be the dominant sources of groundwater recharge. Such recharge takes place in high-altitude areas of Laxemar, dominated by shallow/exposed rock. According to Section 3.4.1, groundwater recharge also takes place within the "hummocky moraine" and "glaciofluvial deposits" type areas, characterised by smaller-scale topography and eskers, respectively.

As outlined in Section 3.5.2, the high-altitude areas containing shallow/exposed rock are difficult to parameterise in conceptual models and also to represent properly in quantitative water flow models. Conceptually, unsaturated (Hortonian) overland flow may appear on outcropping rock, but likely over short distances (say, less than 10 m) before precipitation or snowmelt reaches open fractures or other cavities in the surface rock or a contact between rock and QD. In the MIKE SHE modelling, near-surface drains are activated in the high-altitude areas (cf. Section 4.2.3). Results of the MIKE SHE modelling indicate that in areas with shallow/exposed rock, on the order of 10% of the annual precipitation forms groundwater in the rock. Hence, on an annual basis, the largest part of the precipitation that falls in areas with shallow/exposed rock flows towards low-altitude areas in the form of surface/near-surface water flow.

Sub-flow systems and discharge

As mentioned in Sections 3.4.1 and 3.5.3, groundwater discharge is conceptually thought to take place in low-altitude areas, corresponding to the "valley" type areas (Section 3.4.1). The characteristics of the hydrogeological flow domains QD and rock (see Section 3.4.1) imply that one can identify two main sub-flow systems for groundwater flow in the discharge areas: One system located to the upper part of the rock and the QD, which overlies a larger-scale flow system primarily associated with deformation zones (of different orientations) in the rock. Conceptually, most groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper (say, 10 m) of the rock. Groundwater flow in deeper parts of the rock primarily occurs in deformation zones, and the associated groundwater discharge takes place at locations where these zones outcrop in valleys; groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones.

In order to illustrate the concepts of sub-flow systems and groundwater discharge in Laxemar, Figures 4-21 and 4-22 show MIKE SHE-calculated hydraulic heads and groundwater flow directions in vertical cross sections (see overview map in Figure 4-20). Specifically, Figure 4-21 shows model-calculated heads and flow directions in a c 400 m long N-S section across the Laxemarån stream valley, in the vicinity of percussion borehole HLX15. Moreover, Figure 4-22 shows corresponding modelling results for a c 6.5 km long W-E section along the stream valley. The upper plots in these two figures show results for a point in time (April 8, 2006) representing wet conditions, whereas the lower plots represent dry conditions (July 13, 2006).

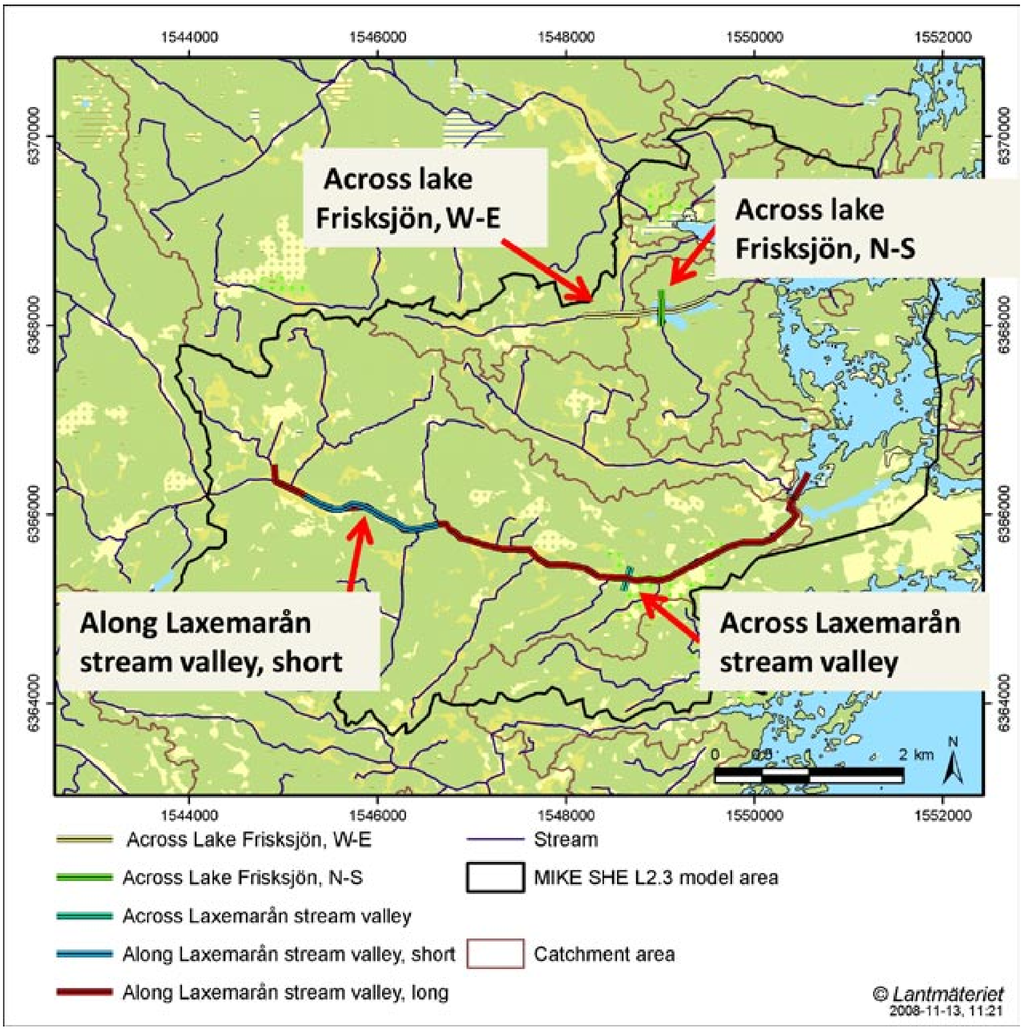


Figure 4-20. *Overview map showing the geographical extensions of the sections in Figures 4-21 to 4-23 (across the Laxemarån stream valley, the long section along the Laxemarån stream valley, and the W-E section across Lake Frisksjön).*

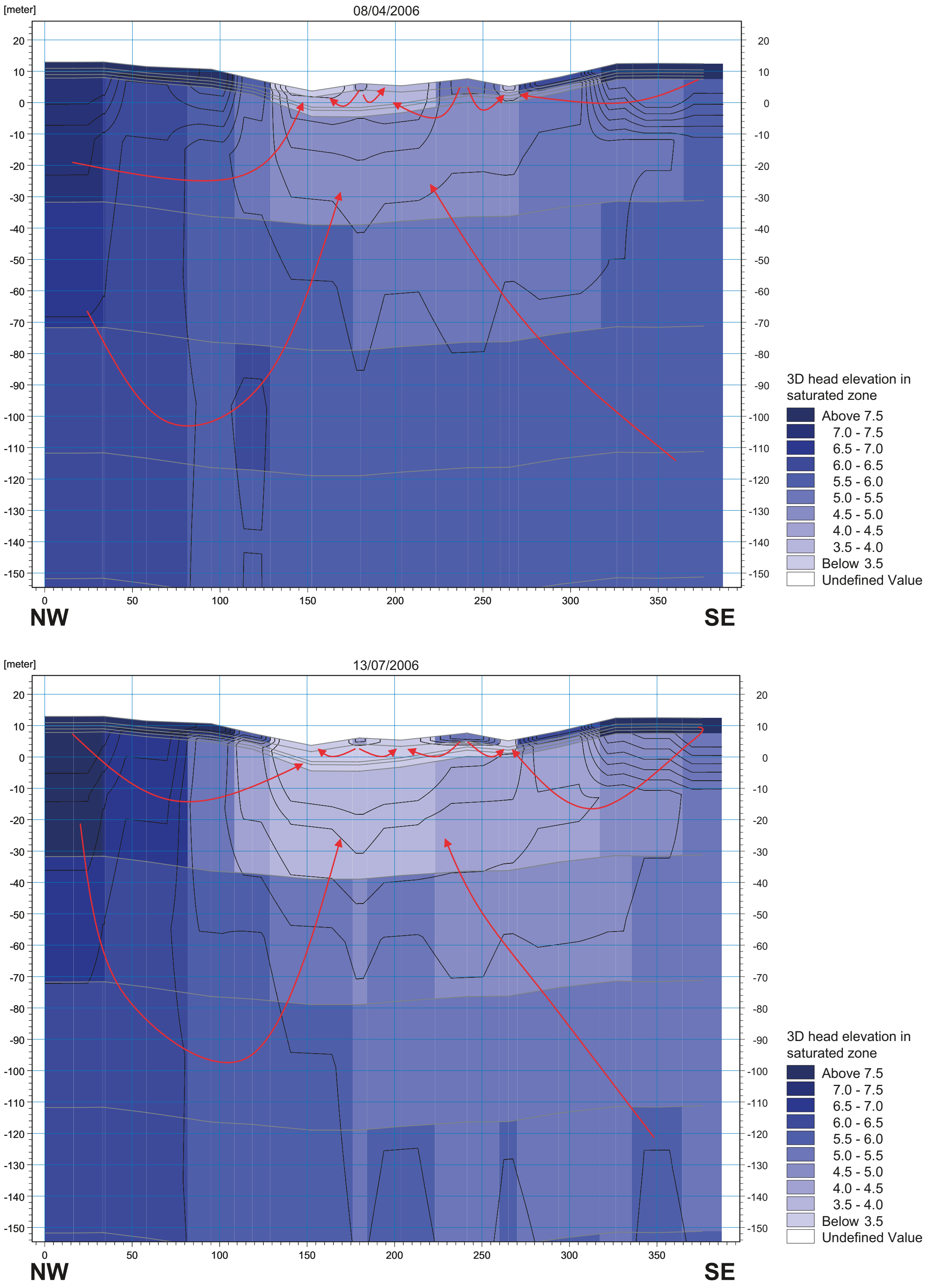


Figure 4-21. *MIKE SHE-calculated hydraulic heads (m.a.s.l.) and groundwater flow directions (red arrows) in a c 400 m long N-S section across the Laxemarån stream valley, in the vicinity of percussion borehole HLX15. The geographical extension of the section is shown in Figure 4-20. The plots show hydraulic heads down to c 150 m.b.s.l. representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006) /Bosson et al. 2008b/.*

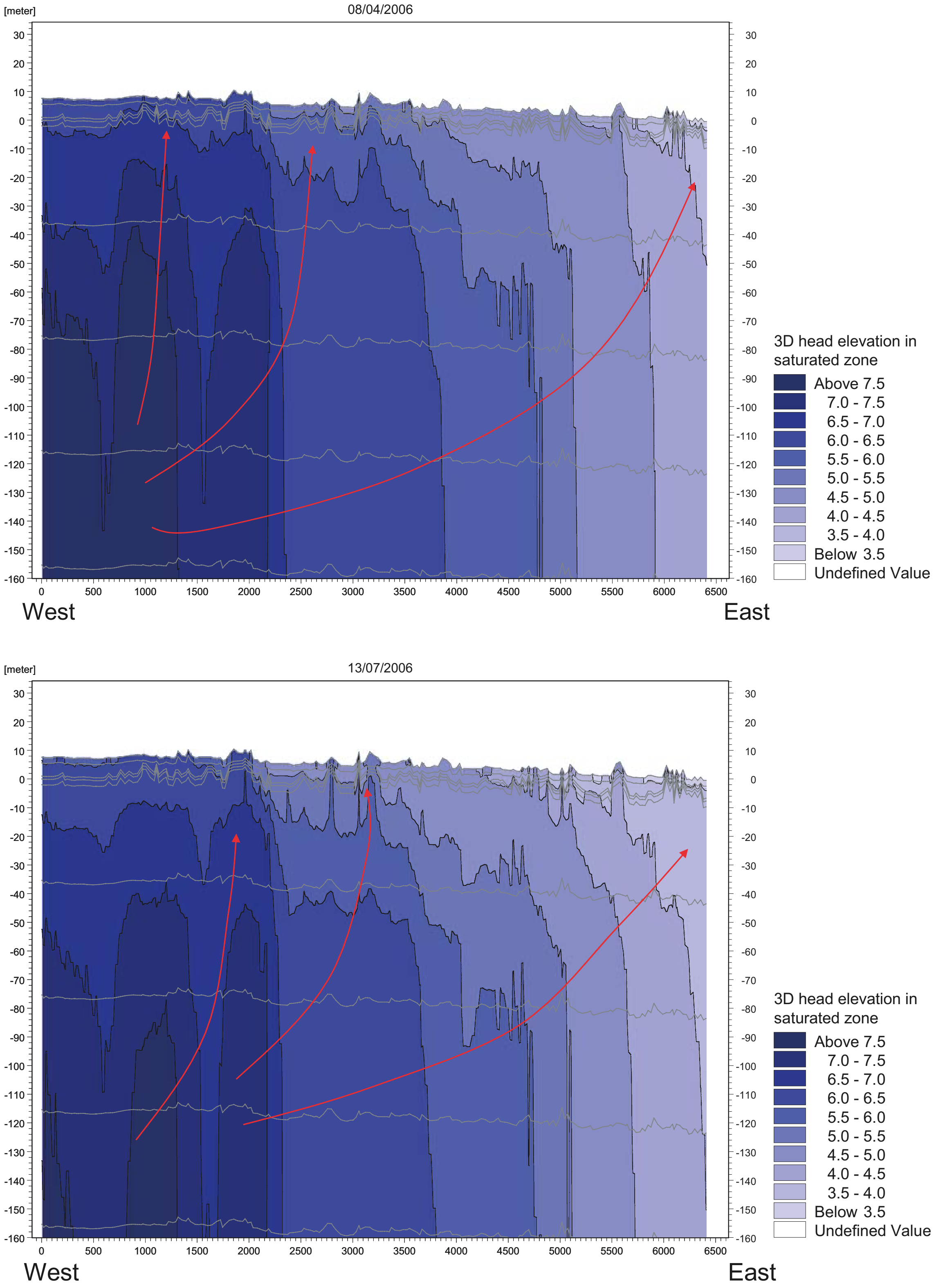


Figure 4-22. ***MIKE SHE-calculated hydraulic heads (m.a.s.l.) and groundwater flow directions (red arrows) in a c 6.5 km long W-E section along the Laxemarån stream valley. The geographical extension of the section (the long section) is shown in Figure 4-20. The plots show hydraulic heads down to 160 m.b.s.l. representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006) /Bosson et al. 2008b/.***

In the across-valley section (Figure 4-21), groundwater flow is mainly directed from the higher-altitude areas towards the valley bottom, acting as a "drain" for groundwater flow in the rock. The local topography has a larger influence on groundwater-flow patterns closer to the ground surface. This can be seen in Figure 4-21 in the form of near-surface groundwater flow systems with more local-scale recharge-discharge patterns. A comparison between the upper and lower plots indicates that there generally are higher hydraulic heads in the stream valleys during wet periods (upper plot) than during dry periods (lower plot).

According to the along-valley modelling results (Figure 4-22), there is a regional W-E head gradient (i.e. from inland areas towards the sea). Moreover, head gradients along the profile are also directed from the rock to the QD. There seem to be small flow-pattern differences between wet and dry periods. Interestingly, the modelling results indicate that the local topography has an impact also on the hydraulic heads in the rock. For instance, in the eastern part of Figure 4-22, one can observe that even relatively small local highs yield an increase in the hydraulic head in the rock, and the opposite for local depressions.

One can also observe that the influence of the sea boundary is less farther from the coast, which implies that there is more pronounced groundwater discharge from the rock towards the ground surface in the inland part of the section. As was also noted in the across-valley section (Figure 4-21), the local topography has a larger influence on groundwater-flow patterns closer to the ground surface. Hence, the MIKE SHE modelling results indicate that there may be near-surface groundwater flow systems with more local-scale recharge-discharge patterns along the large valleys in Laxemar.

Interaction between lake water and groundwater in the underlying QD and rock is illustrated in Figure 4-23, showing MIKE SHE-calculated hydraulic heads and groundwater flow directions in a c 1.4 km long W-E section across Lake Frisksjön (see overview map in Figure 4-20). The upper plot shows results for a point in time (April 8, 2006) representing wet conditions, whereas the lower plot represents dry conditions (Jul. 13, 2006).

The across-lake hydraulic heads and groundwater flow directions resemble the across-valley case (Figure 4-21). Along the profile, groundwater flow is mainly directed from the higher-altitude areas towards the lake, which acts as a "drain" for groundwater flow in the rock. Compared to the Laxemarån stream-valley bottom, the lake represents a relatively large drain, influencing groundwater flow both in the rock and the QD. One can also note that there are small hydraulic-head gradients in the QD below the central parts of lake, which support the conclusion drawn from measurements, i.e. that interaction between lake water and groundwater in the underlying QD is limited to near-shore areas. In the lower plot, one can note that hydraulic heads in the QD below the lake decrease during dry periods.

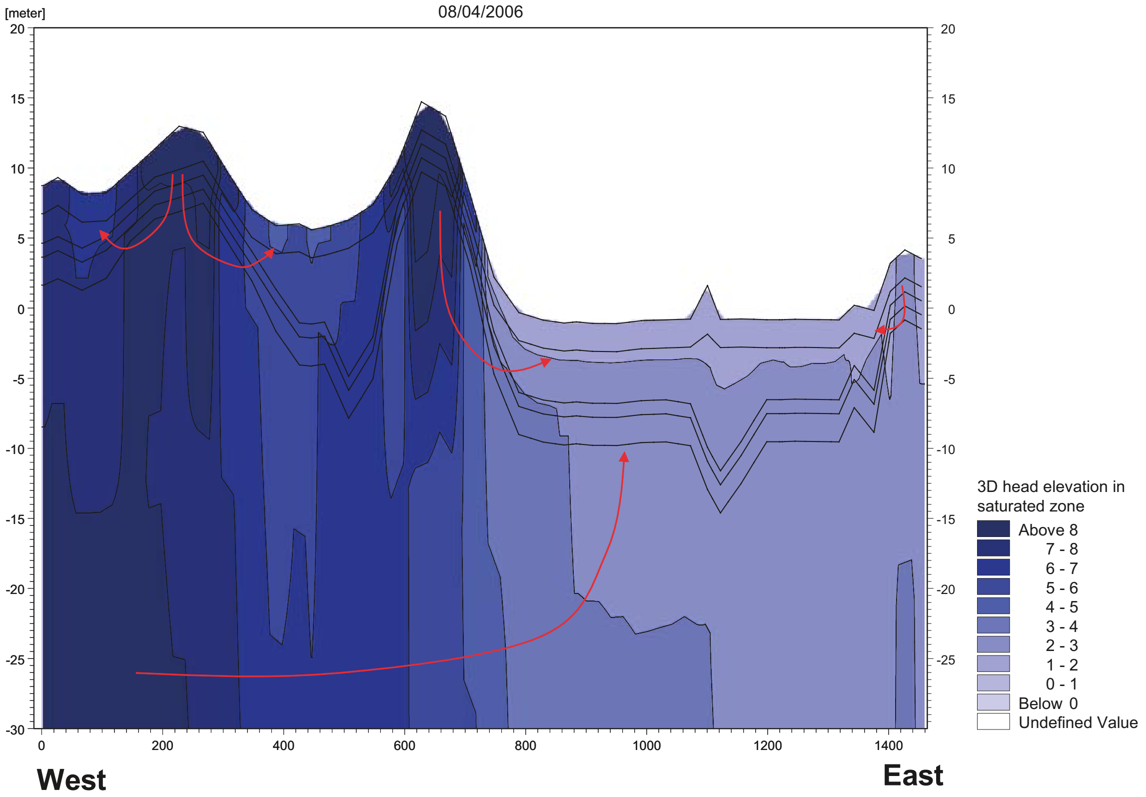
4.2.6 Influence of properties and features in the rock

Chapter 4 is concluded by presenting the main findings from three MIKE SHE sensitivity studies /Bosson et al. 2008b/, concerning the influence from the following properties and features in the rock:

- The influence of less conductive upper and deep rock.
- The influence of groundwater inflow to the Äspö Hard Rock Laboratory.
- The influence of dolerite dykes.

Less conductive upper and deep rock

During the latter part of the MIKE SHE modelling process, there were indications that the underlying hydrogeological model of the rock partially was too permeable and therefore required an update /Bosson et al. 2008b/. Instead of implementing an updated rock-model update per se in MIKE SHE, further sensitivity analyses were performed using the calibrated MIKE SHE model, based on the third rock model (i.e. the model delivered in September, 2008). The objectives with these further tests were to investigate the influence of a less conductive rock within different depth intervals, in order to assess potential consequences of not implementing the updated rock model. For purposes of the tests, "upper rock" was defined as the rock in the depth interval 0–80 metres below the upper rock surface, whereas "deep rock" was defined as the rock below 80 m. A variety of sensitivity cases were tested in MIKE SHE, involving reductions to 1/10 and 1/50 of the hydraulic conductivity (K) of the upper and deep rock, both in the horisontal (K_h) and vertical (K_v) directions.



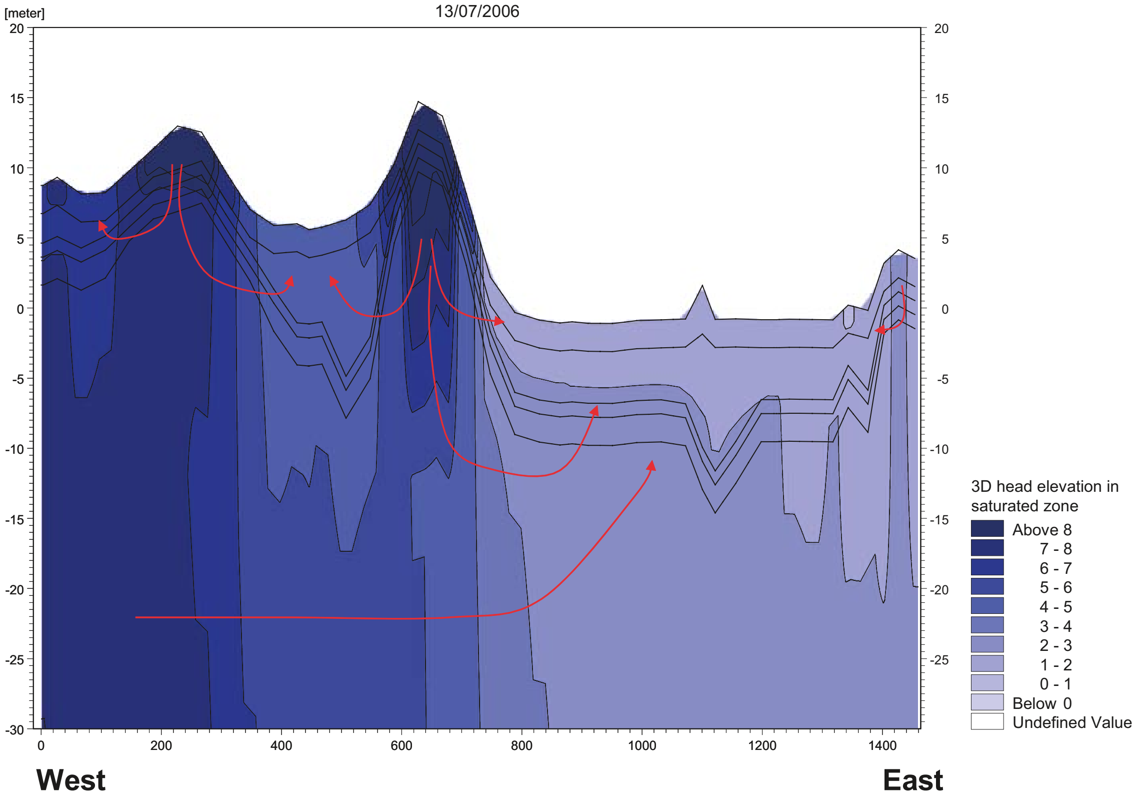


Figure 4-23. *MIKE SHE-calculated hydraulic heads (m.a.s.l.) and groundwater flow directions (red arrows) in a c 1.4 km long W-E section across Lake Frisksjön. The geographical extension of the section is shown in Figure 4-20. The plots show hydraulic heads down to c 150 m.b.s.l. representing wet conditions (upper plot; April 8, 2006) and dry conditions (lower plot; July 13, 2006) /Bosson et al. 2008b/.*

In accordance with the results of the sensitivity analyses reported above (cf. Section 4.2.3), the results show that a reduction of the hydraulic conductivity of the rock yields an increase of the model-calculated stream discharges and thereby a generally better fit to measurements. Hence, these results indicate that a less conductive rock would not lead to a negative influence on the surface hydrology part of the MIKE SHE model. However, different influences of different sensitivity cases for the considered discharge-gauging stations indicate that a hydraulic-conductivity reduction of the rock preferably is done with different magnitudes in different parts of the rock-model volume. One can also note that the influence of a less conductive rock is relatively small for the model-calculated discharge at discharge-gauging station PSM000364, installed in the stream Laxemarån. The underlying reason for this insensitivity is, as mentionded previously, that the western MIKE SHE model boundary crosses the stream, at which location the stream discharge in Laxemarån is assigned.

Generally, there is a small influence of a less conductive rock on the groundwater levels at the locations of the groundwater monitoring wells within the MIKE SHE model area. Considering all wells, a less conductive rock leads to reduced mean (absolute) errors (ME and MAE). However, as was also observed for discharge-gauging stations (see above), the results show that a hydraulic-conductivity reduction of the rock preferably should be done with different magnitudes in different parts of the rock-model volume. Considering point water heads in the rock, the sensitivity analysis demonstrates small overall differences between the tested sensitivity cases. However, the differences between the cases are larger for the individual boreholes.

In summary, the investigation indicates that an updated, less conductive hydrogeological model of the rock likely would yield relatively small but positive effects in terms of the quantitative description of the water-flow conditions in the near-surface and surface system. Based on the results of the sensitivity analyses, the underlying rock model utilised to develop the calibrated MIKE SHE model is considered acceptable for the purposes of the site descriptive modelling. However, due to the at the time not finalised hydrogeological model development regarding the rock, it was decided not to perform MIKE SHE transport calculations (e.g. particle tracking) in the SDM-Site Laxemar context. Such transport calculations were done within the framework of SDM-Site Forsmark (see /Bosson et al. 2008a, Johansson 2008/).

Groundwater inflow to the Äspö Hard Rock Laboratory

The current groundwater inflow to the underground Äspö Hard Rock Laboratory (Äspö HRL), located below the island of Äspö, is c 1,100 L·min^{-1} or less than 20 L·s^{-1} /Hartley et al. 2007/. In order to investigate the potential influence of this inflow on the groundwater flow conditions in the Laxemar area, and thereby assess whether this feature is important for the near-surface and surface water flow modelling, the inflow to the Äspö HRL was implemented in MIKE SHE /Bosson et al. 2008b/, based on the third rock model (delivered in September, 2008). The implementation was made in a simplified manner, by introducing a number of wells in the rock below the island of Äspö. These wells were assigned at the locations of all tunnel sections with a measured inflow above 20 L·min^{-1}, which implies that totally c 85% of the total inflow was represented in the MIKE SHE model. The locations of the wells are projected onto the ground surface (green square symbols) in Figures 4-24 and 4-25.

The MIKE SHE modelling results show that the groundwater inflow to the Äspö HRL has small effects on the groundwater levels at the locations of the groundwater monitoring wells within the MIKE SHE model area. However, the inflow causes a drawdown in the rock in the near-coastal areas of Laxemar. Specifically, the MIKE SHE model calculates a drawdown in percussion boreholes HLX08 and -09. It can be mentioned that /Rhén et al. 2009/ used the CONNECTFLOW model to study the influence of the Äspö HRL groundwater inflow. They report results that are similar to those presented here. Specifically, the CONNECTFLOW model could reproduce the actual drawdown, according to an assessment by /Hartley et al. 2007/, provided that low-permeable QD cover the whole bottom of the sea bays around the island of Äspö. Otherwise, the CONNECFLOW model calculated groundwater recharge through the sea bottom that underestimated the (assessed) actual influence of the Äspö HRL inflow.

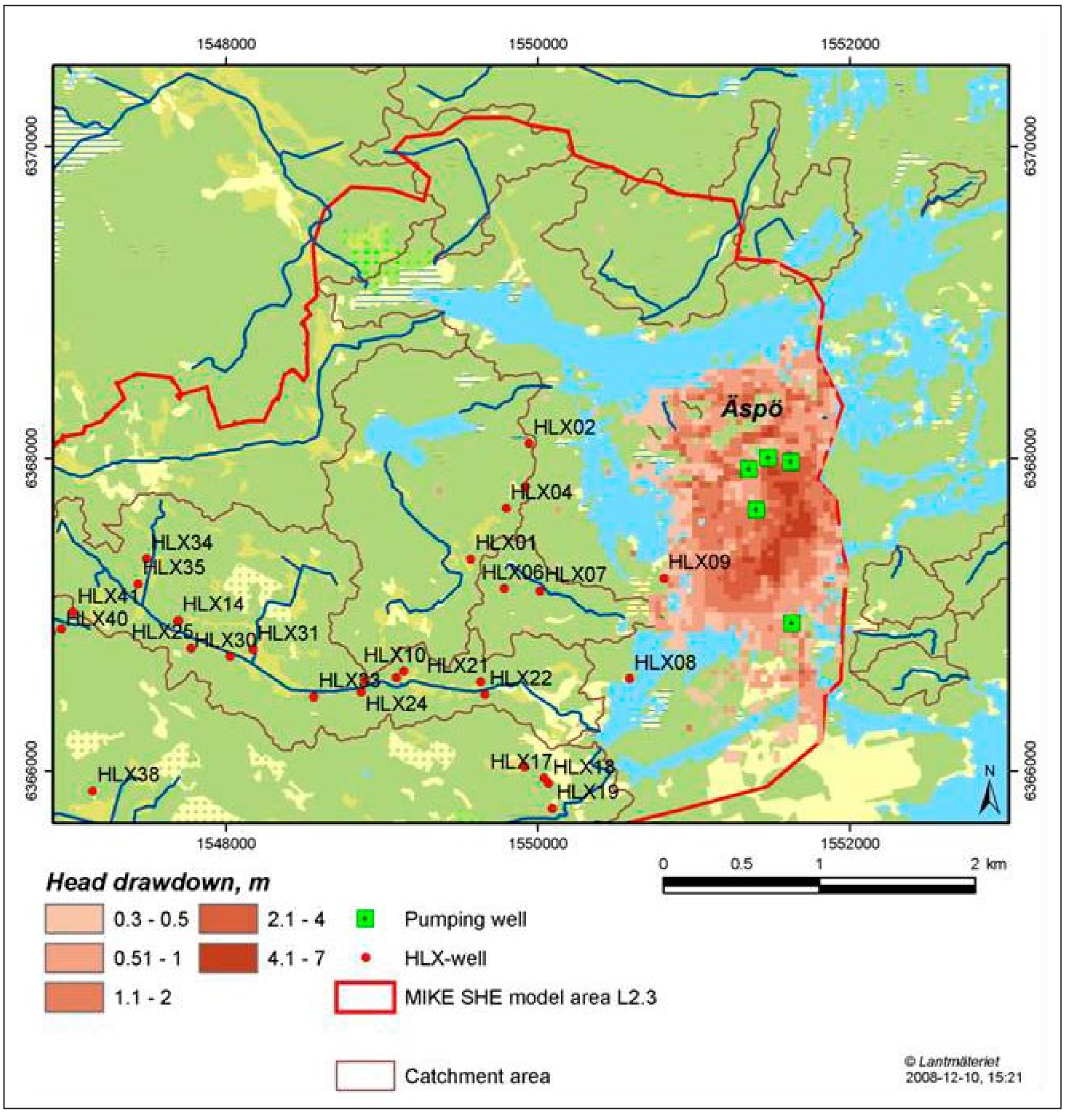


Figure 4-24. *Model-calculated point water head drawdown at 10 m.b.s.l. in the rock, with groundwater inflow to the Äspö HRL /Bosson et al. 2008b/.*

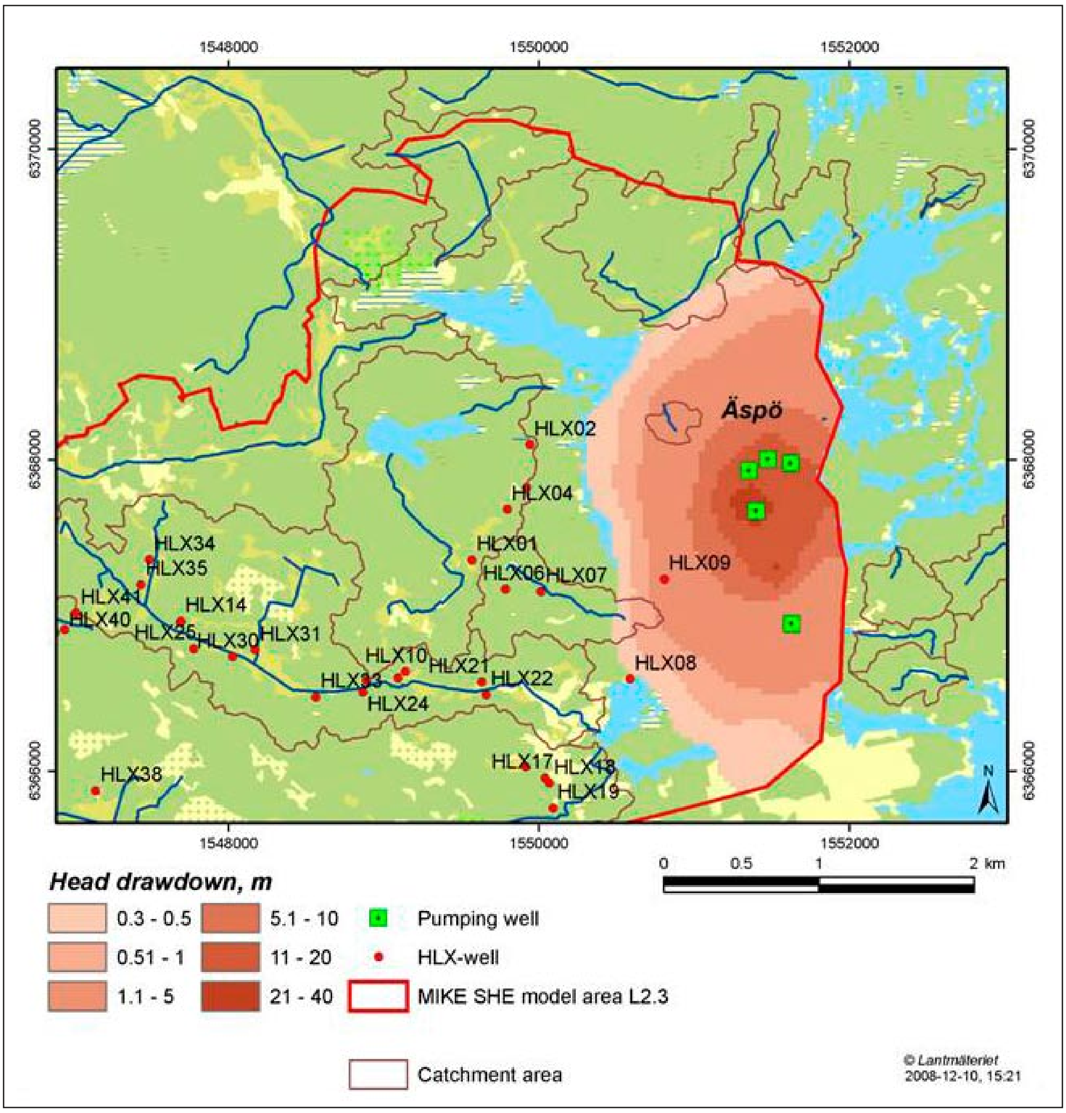


Figure 4-25. *Model-calculated point water head drawdown at 110 m.b.s.l. in the rock, with groundwater inflow to the Äspö HRL /Bosson et al. 2008b/.*

Figures 4-24 and 4-25 provide illustrations of the MIKE SHE-calculated "influence area" at two levels in the rock, 10 m.b.s.l. (Figure 4-24) and 110 m.b.s.l. (Figure 4-25). In these figures, the head drawdown at a certain location and level is defined as the time-averaged point water head without the Äspö HRL groundwater inflow minus the corresponding head with the inflow present. As can be seen in these figures, the influence area is restricted to the island of Äspö and the surrounding sea and near-shore areas. Specifically, the influence area is larger deeper in the rock (110 m.b.s.l.) compared to closer to the ground surface. This observation supports the conclusion that the inflow has small effects on groundwater levels in wells installed within the MIKE SHE model area. It should be noted that none of the groundwater monitoring wells or percussion boreholes on the island of Äspö have been used to calibrate or test the MIKE SHE model.

Dolerite dykes

As mentioned in Section 3.2.5, a number of north-south trending subvertical dolerite dykes have been observed in some boreholes in the rock in the Laxemar area. Conceptually, these dykes may partially act as barriers for groundwater flow in the rock, since they likely have a very low transversal hydraulic conductivity. On the other hand, the longitudinal hydraulic conductivity may be substantially higher. Their influence on the groundwater flow within the MIKE SHE model area was investigated by /Bosson et al. 2008b/. The three considered dykes are those handled deterministically in the hydrogeological modelling of the rock (Figure 4-26, cf. Figure 3-5 in Section 3.2.5). Based on the third rock model (delivered in September, 2008), these dykes were represented in MIKE SHE using the so-called "Sheet piling module", combined with a high east-west flow resistance and a low flow resistance in the north-south direction.

The MIKE SHE modelling results show that the dykes have small or negligible effects on the groundwater levels at the locations of the groundwater monitoring wells located in the MIKE SHE model area. However, the results indicate that there is some influence on the groundwater flow conditions in the rock. Specifically, with the dolerite dykes present, the mean absolute error (MAE) is reduced for 9 percussion borehole sections, whereas the corresponding error in fact increases for 12 sections.

Due to the observed small effects on the groundwater flow conditions in the QD, the dykes are not included in the MIKE SHE SDM-Site Laxemar base case model /Bosson et al. 2008b/. However, as noted by /Bosson et al. 2008b/, the dykes may have to be included for other modelling purposes, e.g. calculation of groundwater flow paths in the rock.

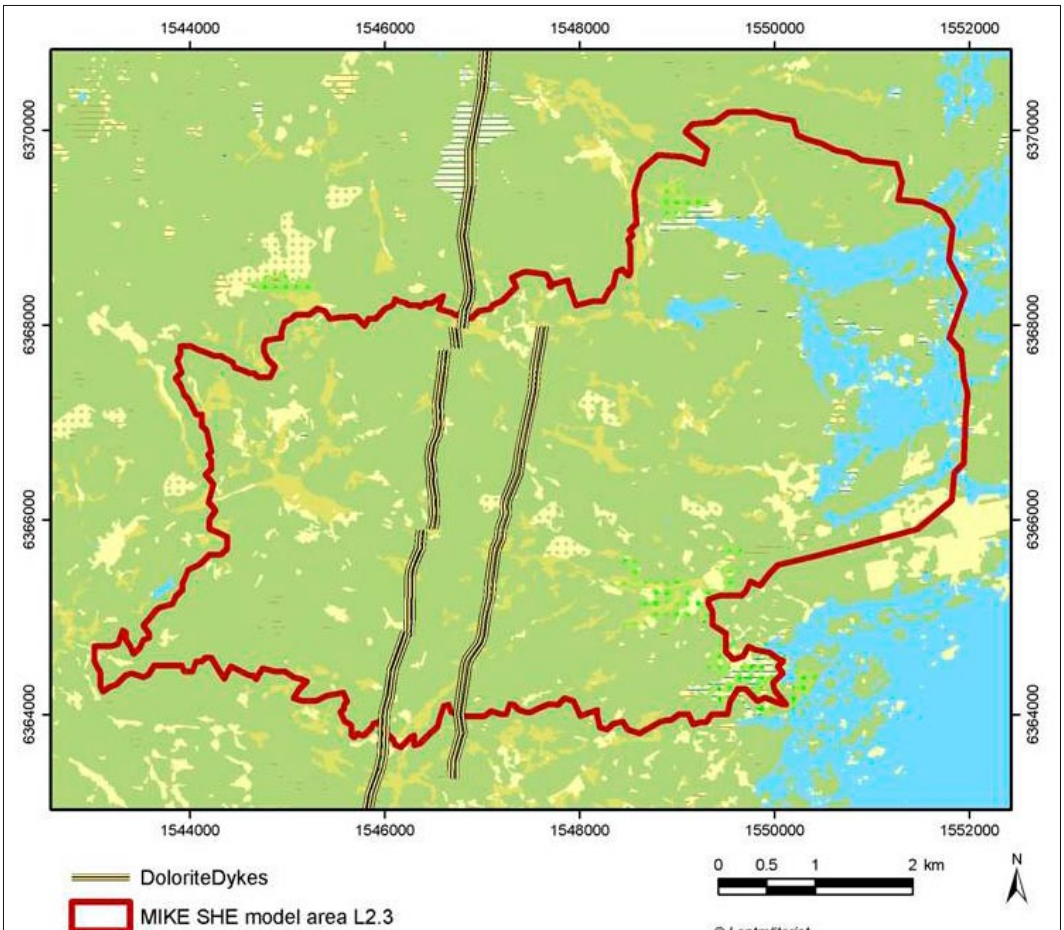


Figure 4-26. Dolerite dykes crossing the MIKE SHE model area /Bosson et al. 2008b/. The E-W flow resistance across the dykes is set high.

5 Resulting site description

5.1 Summary of the site description

5.1.1 Physiographic setting

The Laxemar-Simpevarp area (Laxemar) in south-eastern Sweden is located on the coast of the Baltic Sea, close to the Oskarshamn nuclear power plant in the municipality of Oskarshamn. The topography of the Laxemar area is characterised by relatively distinct valleys, surrounded by higher-altitude areas dominated by exposed/shallow rock. The south-western and central parts of the Laxemar-Simpevarp regional model area are characterised by hummocky moraine and thereby a smaller-scale topography. Almost the whole area is located below 50 m.a.s.l. and the entire area is located below the highest coastline.

The main lakes in the regional model area are Lake Jämsen (0.24 km^2), Lake Frisksjön (0.13 km^2), Lake Sörå (0.10 km^2), Lake Plittorpsgöl (0.03 km^2), Lake Fjällgöl (0.03 km^2) and Lake Grangöl (no size data). These relatively small lakes are shallow, with average depths in the range 1–4 m and maximum depths in the range 2–11 m. All lakes are located above sea level, which implies that no sea-water intrusion takes place. Wetlands cover totally c 3% of the delineated catchment areas.

Most streams in the area are affected by land improvement and drainage operations. The flow in the streams demonstrates large seasonal variability. Of the monitored streams, there is flow throughout the year in the streams Laxemarån, Kåreviksån downstream from Lake Friskjön and Kärrviksån. The stream Ekerumsån is dry during dry summers, whereas the other monitored small streams are dry during approximately half of the year.

The precipitation demonstrates a near-coastal gradient, with less precipitation on the coast compared to areas further inland. During the period 2005–2007, the annual average precipitation was c 580 mm on Äspö and c 620 mm in Plittorp, whereas the potential evapotranspiration was approximately 540 and 530 mm·y^{-1}, respectively. Based on the available site investigation data, the site-average water balance for the years 2005–2007 can hence be estimated as P = 600 mm·y^{-1}, ET (actual evapotranspiration) = 435 mm·y^{-1} and R (specific discharge) = 165 mm·y^{-1} (or approximately 5.2 L·s^{-1}·km^{-2}). The specific discharge is within the interval of the regional long-term average of 150–180 mm·y^{-1}, estimated by /Larsson-McCann et al. 2002/ prior to the site investigations.

According to the conceptual description of the regolith, sandy-gravelly till is overlying the rock in more or less the whole regional model area, also in most areas with exposed/shallow rock (which may have a QD depth of up to c 0.5 m). The exceptions are some of the exposed/shallow rock areas, in which organic soil and a relatively thin vegetation layer is directly overlying the rock. The sandy-gravelly till is characterised by a relatively high hydraulic conductivity, approximately 4·10^{-5} m·s^{-1}. Furthermore, there are indications that the hydraulic conductivity of the QD overlying the rock in the deepest parts of the large valleys is about one order of magnitude higher than that of till in other parts of the area. Permeameter tests on till indicate an anisotropic hydraulic conductivity, with an horisontal hydraulic conductivity being on the order of 15–30 times the vertical one. However, this result should be used with caution since permeameter tests are conducted on relatively small QD samples. Generic data are used to support the estimates of the hydrogeological properties for QD types other than till.

5.1.2 Boundary conditions

The meteorological conditions constitute the upper (top) boundary condition of the hydrological and hydrogeological system. Water is naturally added to this system by rainfall and snowmelt, and abstracted by evaporation and transpiration. As indicated above, the precipitation demonstrates a near-coastal gradient, with less precipitation at the coast compared to areas further inland. For temporal and spatial averages of the water balance components, see Section 5.1.1.

For hydro-meteorological conditions typical for Sweden, snow accumulation during winter, snowmelt in spring and seasonally variable potential evapotranspiration imply that the actual "source term" for groundwater recharge and surface runoff demonstrates strong seasonal variations. Evaluation of site investigation data shows that even on an annual basis, snowmelt represents an important source term.

Groundwater levels in the QD are of potential interest as a basis for setting the upper boundary conditions in hydrogeological models. The observed strong correlation between groundwater levels in the QD and ground-surface elevations implies that the 3D "groundwater surface" in the QD generally follows that of the ground surface. It can therefore be assumed that the identified surface-water divides /Brunberg et al. 2004/ coincide with the water divides for groundwater flow in the QD.

5.1.3 Infiltration and groundwater recharge

Groundwater recharge mainly takes place in high-altitude areas of Laxemar, dominated by shallow/exposed rock. Groundwater recharge also takes place within "hummocky moraine" and "glaciofluvial deposits" type areas, characterised by smaller-scale topography and eskers, respectively. Precipitation and snowmelt are considered to be the dominant sources of groundwater recharge; groundwater-level monitoring in the QD near the shore of Lake Jämsen and in the QD below Lake Frisksjön indicates that interaction between lake water and groundwater in the underlying QD is limited to near-shore areas. In particular, the monitoring data indicate that near-shore areas of Lake Jämsen act as groundwater recharge areas during dry summer periods, whereas there is almost no vertical hydraulic gradient between Lake Frisksjön and the underlying QD.

The infiltration capacity of the QD in Laxemar generally exceeds the rainfall and snowmelt intensity. However, the high-altitude areas containing shallow/exposed rock are difficult to parameterise in conceptual models and also to represent properly in quantitative water flow models. Conceptually, unsaturated (Hortonian) overland flow may appear on outcropping rock, but likely over short distances (say, less than 10 m) before precipitation or snowmelt reaches open fractures or other cavities in the surface rock or a contact between rock and QD. In the MIKE SHE quantitative water flow modelling, near-surface drains are activated in the high-altitude areas. Results of the MIKE SHE modelling indicate that in areas with shallow/exposed rock, on the order of 10% of the annual precipitation forms groundwater in the rock. Hence, these results indicate that on an annual basis, the largest part of the precipitation that falls in areas with shallow/exposed rock flows towards low-altitude areas in the form of surface/near-surface water flow.

5.1.4 Sub-flow systems and discharge

Groundwater discharge mainly takes place in low-altitude areas. The characteristics of the hydrogeological flow domains QD and rock imply that one can identify two main sub-flow systems for groundwater flow in the discharge areas: One system located to the upper part of the rock and the QD, which overlies a larger-scale flow system primarily associated with deformation zones (of different orientations) in the rock. According to the conceptual model of the rock and the QD, most groundwater flow towards the discharge areas in the valleys takes place in the QD and in the upper part (say, 10 m) of the rock. Groundwater flow in the deeper parts of the rock primarily occurs in a system of connected deformation zones, and the associated groundwater discharge takes place at locations where this system connects to zones that outcrop in the valleys. Groundwater discharge from the deep rock is less likely in areas where there are no outcropping deformation zones.

According to the MIKE SHE modelling results, the near-surface groundwater flow system is dominated by groundwater recharge areas, occupying c 70% of the MIKE SHE model area. The groundwater discharge areas, hence occupying c 30% of the model area, are located to low-lying areas such as stream valleys, Lake Frisksjön and the sea bays near the coast. MIKE SHE-analyses of seasonal variations show that the overall near-surface groundwater recharge-discharge pattern is relatively stable during the year.

Except for some minor wetlands, the surface waters (lakes, streams and wetlands) are located to the low-altitude areas. These surface waters are mainly underlain by glacial and post-glacial sediments. Specifically, the general bottom-up QD stratigraphy below surface waters is till and glacial clay, overlain by postglacial sediments (sand/gravel, gyttja clay/clay gyttja, overlain by fen peat and bog peat in the wetlands). However, some parts of the streams pass through areas where there are no layers of glacial clay or postglacial sediments, which is also the case for some near-shore areas of the lakes. The local conditions for surface water-groundwater interaction are also influenced by land improvement and drainage operations, which for instance imply that water flows in subsurface pipes along parts of the valleys.

In the large valleys of Laxemar, groundwater discharge from the upper rock-QD part of the groundwater flow system to the surface (surface waters) is hence strongly influenced by the geometry and the hydrogeological properties of the QD overlying the till. Moreover, there is also an influence on this process of the hydrogeological properties of the upper rock (including the deformation zones) and the high-conductive QD overlying the rock in the valleys. The large valleys in Laxemar are hence characterised by groundwater discharge to the surface, as well as more horisontal groundwater flow along the valley in the upper rock-QD system; groundwater discharge to the surface is facilitated in areas where there are no layers of glacial clay or postglacial sediments above the till.

Joint evaluations of monitoring data on stream discharges and groundwater levels in the QD in the vicinity of the streams, indicate that there is an (unconfined) groundwater level "threshold" for initiation of discharge, likely related to the local drainage depth (i.e. the depth to the bottom of the stream). Moreover, as mentioned above, monitoring of lake-water levels and groundwater levels near and below lakes indicates that interaction between lake water and groundwater in the underlying QD is limited to near-shore areas.

According to the MIKE SHE modelling, the net annual area-averaged groundwater recharge from the unsaturated zone to the uppermost calculation layer representing the QD is 226 mm, whereas the annual area-averaged groundwater recharge to the rock is 35 mm. The net annual average groundwater recharge from the Quaternary deposits to the rock is 7 mm. It can also be noted that the vertical groundwater flow further down in the rock is relatively small. For instance, at 150 m.b.s.l. the vertical flow is 10 mm downwards and 9 mm upwards, which hence implies a very small downward net flow.

5.2 Summary of uncertainties

Joint evaluations of meteorological data, surface-water level and discharge data, and groundwater level/point water head data have led to an improved understanding of hydrology and near-surface hydrogeology in Laxemar. The presented conceptual model conveys the current understanding of the hydrological and hydrogeological driving forces and the overall water-flow patterns, as well as knowledge gaps in terms of properties and detailed process descriptions. Specifically, there are some uncertainties associated with the data used for modelling of hydrology and near-surface hydrogeology. Examples of such uncertainties include non-standard design and natural sections at some of the surface-discharge gauging stations. This is handled by excluding the uncertain data when developing the conceptual model description (water balances) and calibration of quantitative water flow models (MIKE SHE).

There are generally a larger amount of detailed field investigations performed in the central parts of the Laxemar local model area, and also on Hålö, the island of Ävrö and the Simpevarp peninsula. There are hence less detailed underlying descriptions available for other areas, for which descriptions primarily are based on remote sensing studies.

Characteristic for Laxemar are the large areas with exposed/shallow rock. Such areas are difficult to parameterise in conceptual models and also to represent properly in quantitative water flow models. There are relatively few monitoring data (including hydrogeological monitoring data) from the high-altitude areas that can be used to describe the processes of infiltration and groundwater recharge. This bias also concerns the MIKE SHE modelling, since the hydrogeological and hydrological (surface-water discharges) calibration data set primarily includes monitoring data from low-lying areas.

Another characteristic for Laxemar is the large anthropogenic influence. Of particular interest for hydrology and near-surface hydrogeology is the fact that many areas are affected by land improvement and drainage operations. This has been taken into account by field checks and implementation of ditches in the MIKE SHE model. Moreover, "disturbances" due to the ongoing site investigations have been handled by analysing and removing data for periods with disturbed groundwater levels and point water heads from the data set used for conceptual model development and quantitative model calibration.

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