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Abstract

The Swedish Nuclear Fuel and Waste Management Company (SKB) has performed site investigations at two potential sites for a final repository for spent nuclear fuel. This report presents results of water flow modelling of the Laxemar area. The modelling reported in this document is focused on the near-surface groundwater, i.e. groundwater in Quaternary deposits and shallow rock, and surface water systems, and was performed using the MIKE SHE tool. The main objective of the modelling was to provide input to the radionuclide transport and dose calculations that were carried out as a part of the comparison between the Laxemar and Forsmark sites.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) har genomfört platsundersökningar inom två potentiella områden för lokalisering av ett slutförvar för använt kärnbränsle. Denna rapport presenterar resultat av vattenflödesmodelleringar av Laxemarområdet. Modelleringen som redovisas i denna rapport är fokuserad på det ytnära grundvattnet, dvs grundvattnet i jordlagren och i den övre delen av berget, och ytvattensystemet. Den har utförts med modellverktyget MIKE SHE. Huvudsyftet med modelleringen var att generera indata till de transport- och dosberäkningar som utgjorde en del av underlaget för jämförelsen mellan Laxemar och Forsmark i valet av plats för det planerade kärnbränsleförvaret.

Contents

1 Introduction

1.1 Background

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Within SKB's program for the management of spent nuclear fuel, an interim storage facility and a transportation system are in operation today (2011). SKB has performed site investigations at two different locations in Sweden, referred to as the Forsmark and Laxemar areas, with the objective of siting a final repository for the spent fuel. In June 2009, a decision was made to focus on the Forsmark site. This decision was based on a large amount of evidence suggesting Forsmark to be more suitable for a spent fuel repository than Laxemar; a comparative analysis supporting the site selection is presented in SKB (2010a).

Data from the site investigations have been used in a variety of modelling activities; the results are presented and utilised within the frameworks of Site Descriptive Models (SDM), Safety Assessment (SA), and Environmental Impact Assessment (EIA). The SDM provides a description of the present conditions at the site, which is used as a basis for developing models intended to describe the future conditions in the model volume considered within the SA. In March 2011, SKB submitted a licence application for building and operating a repository for spent fuel at Forsmark. The safety assessment included in this licence application is referred to as SR-Site.

The main purposes of the SR-Site safety assessment (SKB 2011) are to assess the safety of a potential KBS-3 repository at Forsmark in order to support the license application, and to provide feedback to the design development and the SKB research and development programme. For the dose and risk assessments within the safety assessment, a radionuclide transport and dose model for the biosphere (presented in detail in Andersson (2010)) has been developed on the basis of a comprehensive site investigation programme. This model is designed to handle important processes for different sites, using site-specific data.

The biosphere radionuclide model has been applied in the dose assessments for Forsmark using the methodologies described in the biosphere synthesis report (SKB 2010b) based on site specific landscape development described in the landscape modelling report (Lindborg 2010), site specific parameters described in the ecosystems reports (Andersson 2010, Aquilonius 2010, Löfgren 2010) and radionuclide transport and dose calculations (Avila et al. 2010).

A comprehensive site investigation and site descriptive modelling programme has also been carried out for the Laxemar site (SKB 2009). However, only limited biosphere assessments focusing on long-term safety have been carried out, with the aim of obtaining an estimate of the possible impact of differences between the Forsmark and Laxemar sites in terms of radiological consequences of a potential release to the biosphere from a future repository.

This report presents model results of numerical flow and transport modelling of surface water and near-surface groundwater at the Laxemar site for present and future conditions. Different locations of the shoreline representing different present and future site conditions are considered in the modelling. The modelling is performed using the modelling tool MIKE SHE and is based on the previous SDM-Site Laxemar MIKE SHE model (Bosson et al. 2009). The results are used as an input to the radionuclide transport and dose calculations of Laxemar described in SKB (2010a), where preliminary landscape dose conversion factors (LDF) are presented and compared with the corresponding SR-Site results for Forsmark.

1.2 Objective and scope

The general objectives of the SR-Site modelling and the specific objectives of the SR-Site biosphere modelling are presented in SKB (2011) and SKB (2010b), respectively. The present report is a background report describing the numerical modelling of surface hydrology and near-surface hydrogeology at Laxemar for present and future conditions. In line with the limited scope of the Laxemar biosphere studies related to long-term safety, this report contains only a subset of the analyses presented in the corresponding Forsmark report (Bosson et al. 2010).

Formally, the modelling presented in this report is not a part of the SR-Site project, but has been performed as a separate task in order to provide input data to calculations made to underpin the comparative analysis of the Laxemar and Forsmark sites. However, the modelling has been performed during the SR-Site stage (in parallel with the SR-Site work) and with a methodology similar to that used in the corresponding SR-Site modelling of Forsmark. Therefore, the calculations and results presented herein are referred to as "SR-Site" whenever compared to results from site descriptive modelling, usually referred to as "SDM-Site", and field data.

Within the site descriptive hydrological modelling presented in Bosson et al. (2009), only the present conditions at the site were described and analysed. The present work aims to describe future hydrological conditions at the site taking shoreline displacement into consideration. The water fluxes within and between different ecosystems are of great importance when describing the different ecosystems at landscape level. They constitute the driving force in the radionuclide transport and dose model, and results from the descriptive and numerical hydrological modelling are used as input to the radionuclide model, as described in detail for Forsmark in Bosson et al. (2010), Andersson (2010) and Avila et al. (2010).

The objectives of the modelling reported in this document are the following:

1 With the SDM-Site model as a starting point, update the MIKE SHE model and perform model simulations of present and future model areas.
2 Evaluate the performance of the updated MIKE SHE water flow model by investigating its ability to reproduce groundwater levels, surface water discharges and surface water levels measured at the site.
3 Present a modelling methodology and results relevant for the assessment of future conditions at the site.
4 Describe the flow modelling results that were delivered to the radionuclide transport and dose modelling.

1.3 Setting

The Laxemar area is located approximately 230 km south of Stockholm, in eastern Småland within the municipality of Oskarshamn. Figure 1-1 shows the regional model area and the local model area of the final site-descriptive model, SDM-Site Laxemar. Also some lakes and other objects of importance for the hydrological modelling are shown in the figure.

During the period from 2002 to 2007, site investigations were conducted within a square-shaped area referred to as the Laxemar-Simpevarp regional model area, covering c. 273 km^2 (Figure 1-1). The site investigations were initially focused on the so-called Simpevarp subarea (including the Simpevarp peninsula and the islands of Ävrö and Hålö), and later on the Laxemar subarea (i.e. the inland parts of the area). In the SDM-Site context, a smaller square-shaped area was defined within the regional area, referred to as the Laxemar local model area (Figure 1-1), see SKB (2009) for details. For simplicity and brevity, we often use "Laxemar" or "the Laxemar area" in this report when discussing the area in general (i.e. when not considering a particular model area or similar well-defined entity).

A description of the meteorological, hydrological and hydrogeological conditions in the Laxemar-Simpevarp area is presented in Werner (2009). Söderbäck and Lindborg (2009) give a description of the whole surface and near-surface system, including the most recent models of, e.g. the topography and the Quaternary deposits. The site characteristics and parameters considered in the present work are summarised and described in Chapter 2.

The reference system for elevation used in the Laxemar site descriptive and safety assessment-related modelling, including the present report, is the national RHB70 levelling system (SKB 2009). Depending on the type of data presented, levels are in this report expressed in metres above sea level (m.a.s.l. for short) or metres below sea level (m.b.s.l.) according to RHB70. The X/Y coordinate system used is the national 2.5 gon W 0:-15 RT90 system with X (easting) and Y (northing), the so-called RAK system.

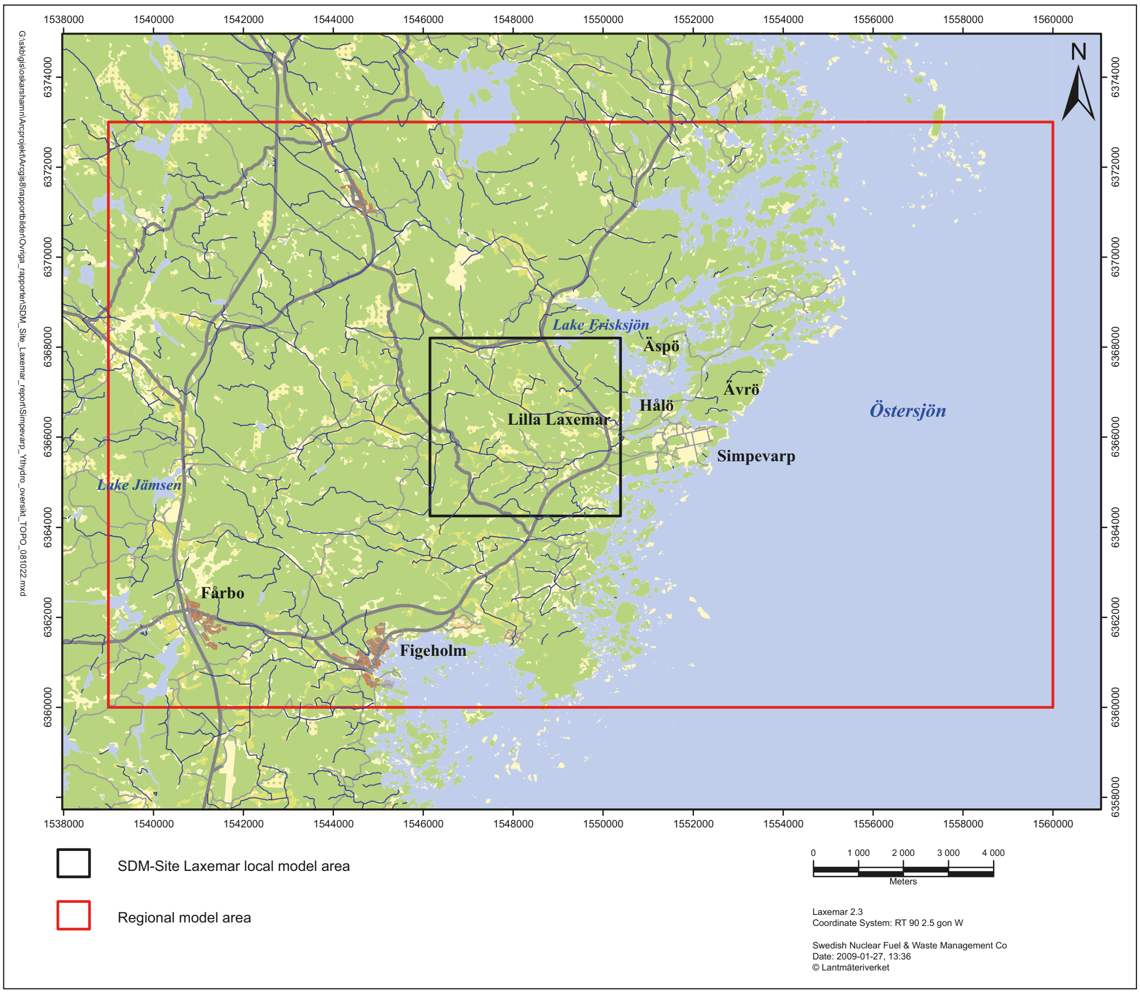

Figure 1-1. *Overview map of the Laxemar-Simpevarp regional model area and the SDM-Site Laxemar local model area (Werner 2009).*

1.4 Related modelling activites

Several modelling activities have provided the various external input data and models required for the present hydrological and hydrogeological numerical modelling. The MIKE SHE SDM-Site model is the starting point for the model development described in this report. Data for the modelling of future conditions are described in Chapter 2, whereas all data used for the SDM-Site modelling are described or referred to in Bosson et al. (2009) and in Werner (2009). This report briefly discusses other modelling activities that consider flow modelling of the integrated bedrock-Quaternary deposits system.

The work described in this report is focused on the surface systems, i.e. the Quaternary deposits and the upper part of the bedrock. The numerical model was developed using the MIKE SHE tool. The ground surface, as obtained from the topographic model of the site, is the upper model boundary and the bottom boundary is placed at 600 m.b.s.l. The modelling activities that provided inputs to the various parts of this work can be summarised as follows:

- The SDM-Site conceptual modelling of the hydrology and near-surface hydrogeology at the Laxemar site (Werner 2009, Werner et al. 2008) provided a basic hydrogeological parameterisation and a hydrological-hydrogeological description that was used in the numerical MIKE SHE SDM-Site modelling (Bosson et al. 2009) upon which the present work is built.
- The SDM-Site Laxemar bedrock hydrogeology modelling performed with the ConnectFlow modelling tool (Rhén et al. 2008, 2009) delivered the hydrogeological properties of the bedrock used in the present MIKE SHE SDM-Site model.

- The SDM-Site Laxemar geological models of the Quaternary deposits (Nyman et al. 2008, Sohlenius and Hedenström 2008) provided the geological-geometrical framework for the stratigraphical description of the Quaternary deposits used in the MIKE SHE SDM-Site model.
- The SR-Site bedrock hydrogeology modelling of the initial temperate period (Joyce et al. 2010) delivered model results used in the identification of the biosphere objects studied in the present work.

The relations between the near-surface and bedrock hydrogeological models are discussed in Söderbäck and Lindborg (2009) and SKB (2009).

1.5 This report

This report provides an integrated presentation of the modelling activities corresponding to objectives 1-4 in Section 1.2. Chapter 2 describes the input data (objective 1). Chapter 3 describes the modelling tool and the numerical flow models of different time periods (objective 3). In Chapter 4, the results from the comparison with the MIKE SHE SDM-Site model are presented (objective 2). Chapter 4 also presents the results for future conditions, where different times in the future are described in terms of different shoreline locations and flow boundary conditions (objective 3). Furthermore, in Chapter 4 the delivery of the MIKE SHE modelling results to the radionuclide transport and dose calculations is summarised (objective 4). Finally, the conclusions and a discussion of the work are presented in Chapter 5.

2 Site hydrology and input data

2.1 Site hydrology

The topography of the Laxemar-Simpevarp 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 Laxemar-Simpevarp regional model area (Figure 1-1) are characterised by hummocky moraine and thereby by 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), see Figure 2-1. Lake Frisksjön is the only natural lake situated inside the MIKE SHE model area (Section 2.2.2). 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 well above sea level, which implies that no sea-water intrusion takes place. Wetlands cover totally c. 3% of the delineated catchment areas (Brunberg et al. 2004). Most streams 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, see Figure 2-1. The stream Ekerumsån is dry during dry summers, whereas the other monitored small streams are dry during approximately half of the year.

Figure 2-1. *Overview map of the Laxemar area showing main lakes and surface water streams.*

As a part of the site-descriptive modelling of the hydrology at Laxemar, four main hydrogeological type areas have been defined, which conform to the subdivision of the Quaternary deposits: High-altitude areas, large and small valleys, glaciofluvial deposits, and hummocky moraine areas. These type areas are mainly used as a framework for description of the overall patterns of groundwater recharge and discharge in the Laxemar area, as further discussed below.

Groundwater levels in the Quaternary deposits are shallow; according to monitoring data, the depth to the groundwater table is on average less than one metre during 50% of the time (Werner et al. 2008). Generally, there is a larger depth to the groundwater table in high-elevation areas compared to low-elevation areas. However, there is a much smaller range of depths to the groundwater table compared to that of the absolute groundwater levels. Hence, there is a close correlation between the ground-surface topography and groundwater levels in the Quaternary deposits, which in turn implies that topography has a strong influence on near-surface patterns of groundwater recharge and discharge.

The conceptualisation of the hydrological-hydrogeological system in Laxemar-Simpevarp for selected local-scale type environments is summarised in this section. More detailed descriptions are given in the background reports for hydrology and near-surface hydrogeology (Werner 2009) and bedrock hydrogeology (Rhén et al. 2009). Figure 2-2 illustrates the overall conceptual model of hydrology and hydrogeology in Laxemar.

The hydraulic conductivity of the rock generally decreases with depth, both in the deterministically described deformation zones and in the rock between these zones. The deformation zones are mostly sub-vertical and typically one order of magnitude more conductive than the surrounding rock. Many deformation zones coincide with and outcrop in valleys. In the background rock between the deformation zones, there is a more pronounced decrease with depth of the intensity of sub-horizontal fractures compared to sub-vertical fractures. As can be seen in Figure 2-2, the deformation zones vary in thickness, and are generally wider closer to the interface between Quaternary deposits and bedrock.

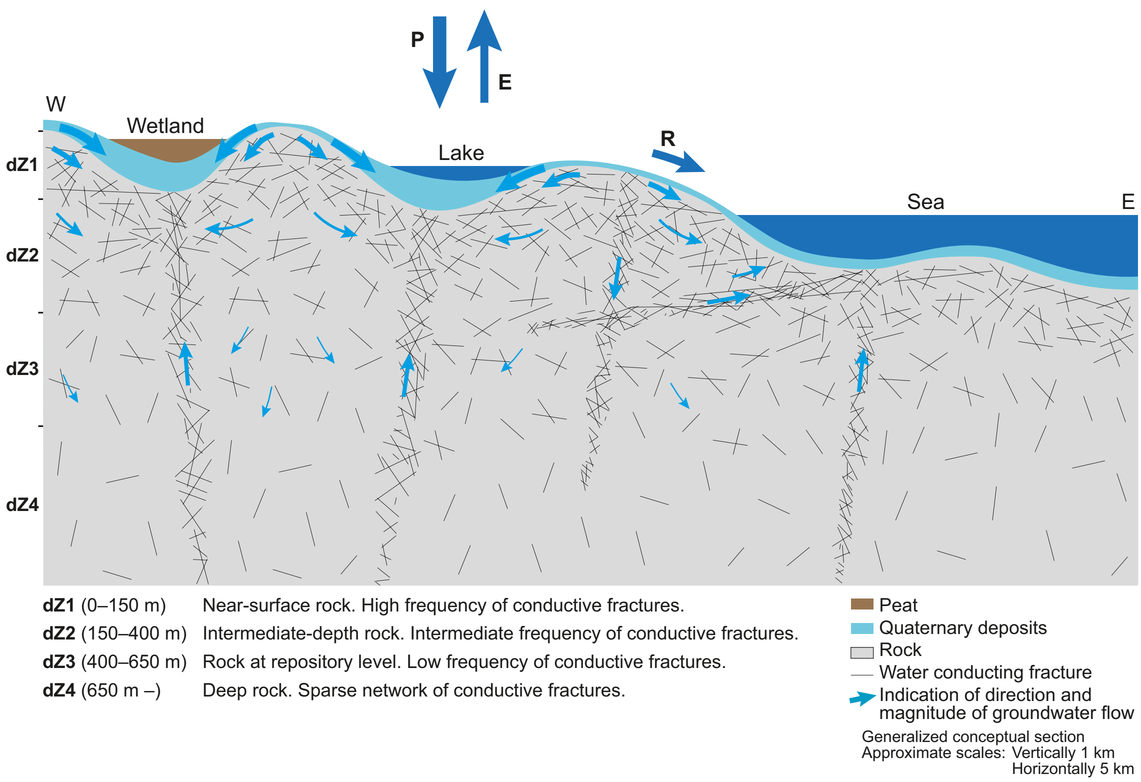

Figure 2-2. *Generalised section illustrating the conceptual model of hydrology and hydrogeology in Laxemar (Werner 2009). Note the different horizontal (5 km) and vertical (1 km) scales, and that the thickness of the Quaternary deposits is exaggerated in the figure. The arrows marked P, E and R indicate precipitation evapotranspiration and runoff, respectively.*

From a conceptual point of view, the bedrock in Laxemar can hydrogeologically be divided and described in terms of the following depth intervals, here denoted dZ1–dZ4 (cf. Figure 2-2):

- 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 and deeper): Deep rock, characterised by a sparse network of conductive fractures.

Except for some minor wetlands, the surface waters (lakes, streams and wetlands) are associated with low-altitude areas. These surface waters are mainly underlain by glacial and post-glacial sediments. Specifically, the general bottom-up regolith 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 the conceptual section in Figure 2-3, groundwater level measurements below lakes indicate that the interactions between surface water in the lakes and groundwater in the underlying Quaternary deposits is limited to near-shore areas.

Some parts of the streams pass through areas where there are no layers of glacial clay and 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 some parts of the streams.

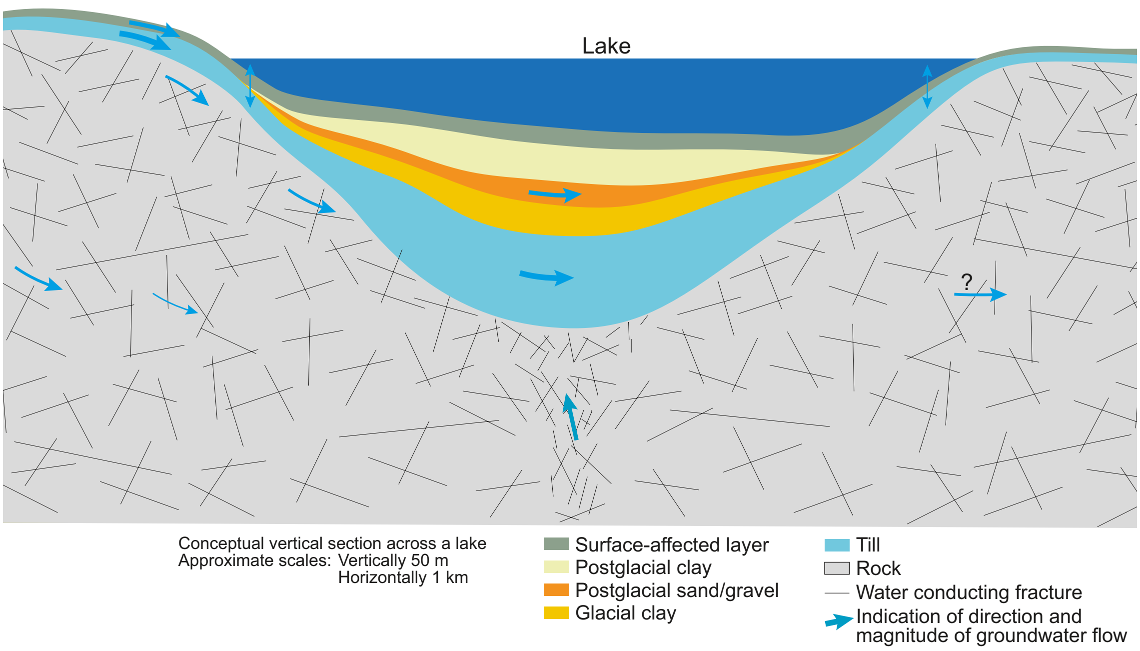

Figure 2-3. *Conceptual vertical section across a lake in Laxemar, illustrating the interaction between surface water in the lakes and groundwater in the underlying Quaternary deposits in near-shore areas (Werner 2009). Note the different horizontal (1 km) and vertical (50 m) scales in the figure. The flow pattern in the bedrock is uncertain; this is marked by a question mark at the arrow indicating the flow direction in the rock.*

2.2 Input data

The input data to the MIKE SHE model include data on topography, land use, vegetation, geology, hydrogeology and meteorology. A detailed description of the model input data that were used for the MIKE SHE SDM-Site modelling can be found in Bosson et al. (2009, Chapter 2). In this section, a brief description of the input data is given. The main focus is on data that differ between the MIKE SHE SR-Site model and the MIKE SHE SDM-Site model.

Section 2.2.1 describes the climatic data used for the different MIKE SHE SR-Site model simulations, whereas Section 2.2.2 describes the input to the surface water system and Section 2.2.3 the vegetation and overland flow parameters. Section 2.2.4 presents the Quaternary deposits data and Section 2.2.5 the input data on the hydraulic properties of the bedrock. A summary of the model updates made for the MIKE SHE SR-Site model in comparison to the MIKE SHE SDM-Site model is given in Chapter 3 (Section 3.6).

2.2.1 Climate data

The MIKE SHE model requires data on temperature, precipitation and potential evapotranspiration. Locally measured data are available for the period from 2003 to 2007. The meteorological input data are taken from meteorological stations at Plittorp and Äspö (see below). The stations and the measurements are described in Werner et al. (2008).

A simulation was made with site specific time series data from the same time period as used in the MIKE SHE SDM-Site simulations. The purpose of the model simulation was to check the performance of the MIKE SHE SR-Site model compared to the MIKE SHE SDM-Site model. In all other model simulations, a selected meteorological year has been used. The selected meteorological year represents a year with a "normal" climate, i.e. an actual year with meteorological conditions as close to mean values as possible. This year has been cycled to cover the entire simulation periods. The selection of the year is further described below.

Meteorological data are available from two stations established by SKB within the regional model area, Plittorp and Äspö, see Figure 2-4. The Äspö station is located close to the sea, while the Plittorp station is an inland station. The registered precipitation differs between the two stations and there is a gradient from the sea towards the inland, i.e. in the east-to-west direction, with a higher precipitation at the inland station Plittorp. To account for the differences, the MIKE SHE model area is divided into three different zones, see Figure 2-4. In zone 1 (to the west) the precipitation is based on the Plittorp station only, in zone 3 (to the east) on the Äspö station only, and in zone 2 (in between) on an average of the two stations. All meteorological data are handled in the same way as the precipitation. More details on the meteorological stations and the handling of meteorological data are found in Werner et al. (2008) and Bosson et al. (2009).

Based on the precipitation data from the Plittorp and Äspö meteorological stations covering the period from 2003 to 2007, average monthly sums were calculated. The monthly sums were then compared to estimated monthly mean values for the reference period 1961–1990 for the same meteorological stations. The estimation of the mean values for the reference period 1961–1990 is explained in Werner et al. (2008, Section 2.2.1). In the same way, the mean yearly precipitation for the reference period was compared to the accumulated yearly precipitation for each year for the observed data.

The year that gave the best fit to mean values for the reference period, both in terms of yearly and monthly values, was then selected to represent a normal year with regard to precipitation. The selected year covers the period August 2004 to July 2005. Table 2-1 and Table 2-2 show the monthly mean values for the selected year as well as the monthly average values for the reference period for both stations. Figure 2-5 shows the precipitation time series for the selected year, Figure 2-6 shows the accumulated precipitation for both Äspö and Plittorp, and Figure 2-7 shows the potential evapotranspiration for the selected year.

***Figure 2-4.** Locations of the two meteorological stations PAS00028, situated on Äspö, and PSM107738 at Plittorp. The figure also illustrates the location of Lake Frisksjön and the division of the model area into three different climate data zones.*

Table 2-1. Average monthly precipitation (mm) for station Äspö for the reference period 1961–1990 and monthly precipitation for the selected year, August 2004–July 2005.

Month	Average monthly sums 1961–1990 (mm)	Monthly precipitation for selected year (mm)
August	53	66
September	55	14
October	45	81
November	49	87
December	50	22
January	49	44
February	35	46
March	32	32
April	38	4
May	39	34
June	44	72
July	64	48
Yearly sum	**553**	**552**

Table 2-2. Average monthly precipitation (mm) for station Plittorp for the reference period 1961–1990 and monthly precipitation for the selected year, August 2004–July 2005.

Month	Average monthly sums 1961–1990 (mm)	Monthly precipitation for selected year (mm)
August	61	71
September	64	16
October	51	90
November	56	84
December	56	22
January	54	54
February	39	70
March	36	32
April	43	5
May	45	35
June	51	93
July	73	47
Yearly sum	**629**	**619**

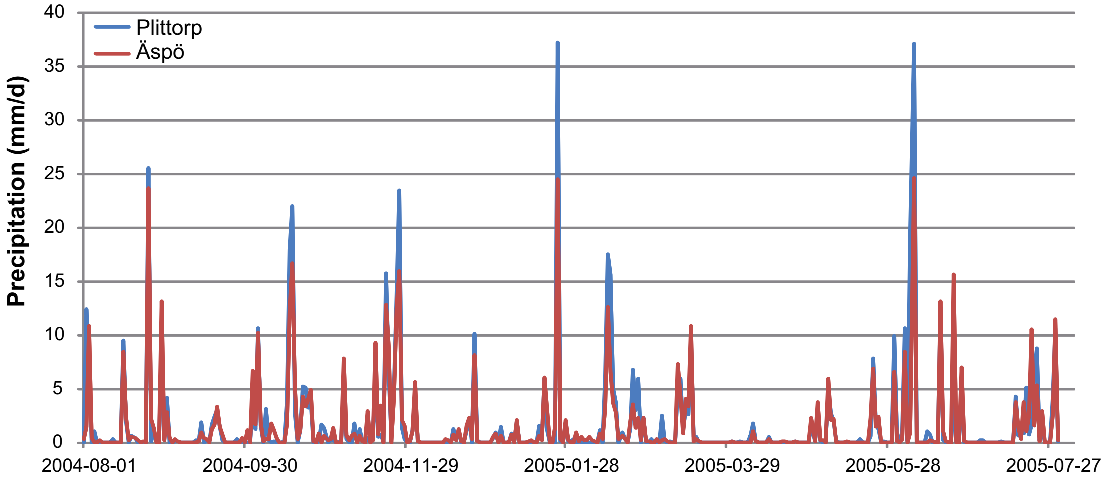

Figure 2-5. *Precipitation for the selected year, August 2004 to July 2005, for the two meteorological stations Plittorp (blue line) and Äspö (red line).*

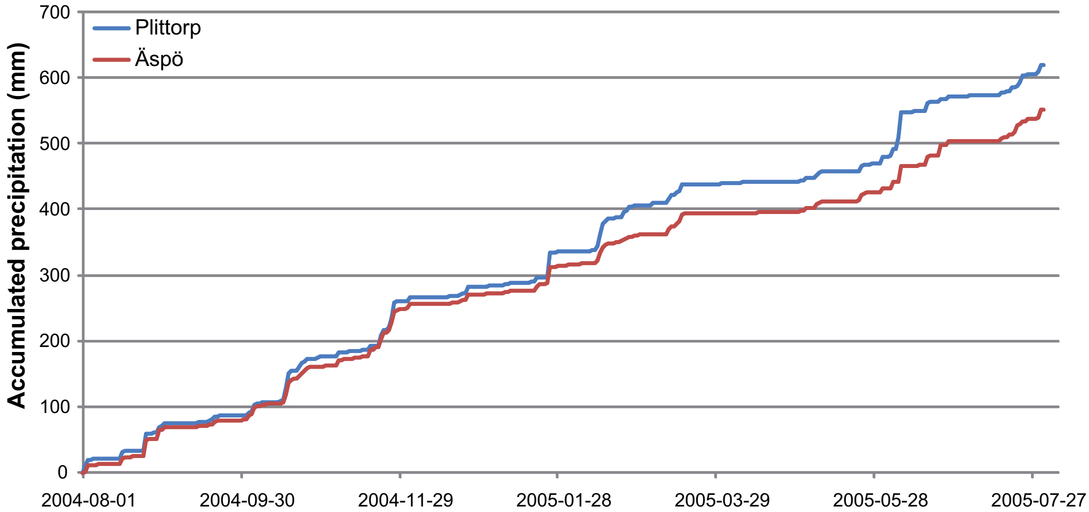

Figure 2-6. *Accumulated precipitation for the selected year, August 2004 to July 2005, for the two meteorological stations Plittorp (blue line) and Äspö (red line).*

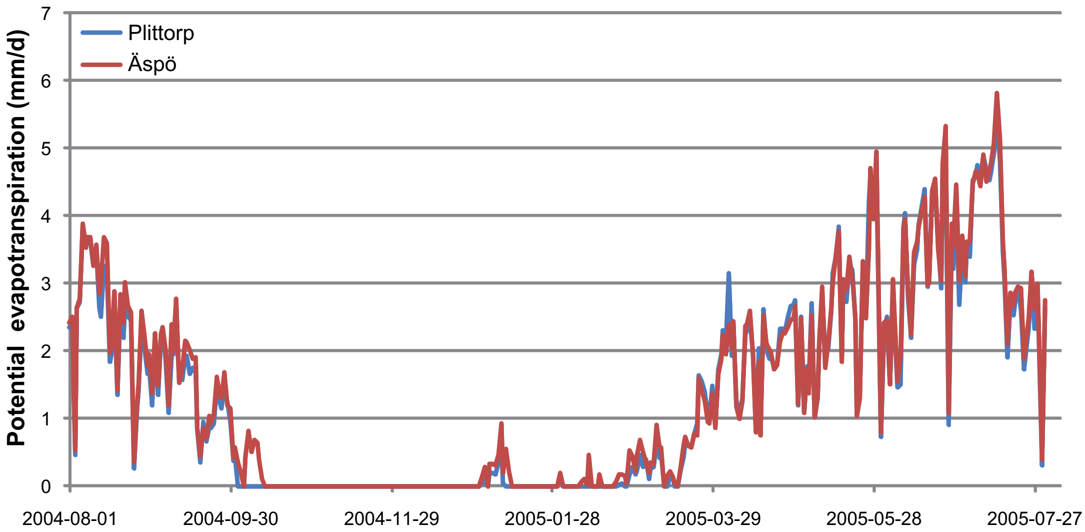

Figure 2-7. *Potential evapotranspiration for the selected year, August 2004 to July 2005, for the two meteorological stations Plittorp (blue line) and Äspö (red line).*

2.2.2 Surface water system

Data on lake thresholds and bathymetry levels, cross sections of the water courses and the extent of the stream network have been used as input to the description of the surface water system in the MIKE SHE stream compartment MIKE 11 (see Chapter 3). There is only one natural lake within the model area, Lake Frisksjön (Lake Sörå, or Söråmagasinet is a man-made reservoir). The lake threshold of Lake Frisksjön is at 1.29 m.a.s.l. The geometrical data for the streams and lake thresholds are described in Bosson (2006).

Within the SR-Site modelling, future cases have been simulated. GIS-modelled streams based on the digital elevation model (DEM) (Strömgren and Brydsten 2008) are used when defining future surface water systems.

The stream Laxemarån crosses the model boundary where it has an upstream catchment area of 24.66 km^2. As in previous model versions, the discharge at the model boundary is described by a time-varying inflow, calculated using the MIKE 11 NAM model. Further details on the MIKE 11 NAM model are found in Aneljung et al. (2007). Figure 2-8 shows the calculated inflow in Laxemarån over the model boundary from the upstream part of the catchment.

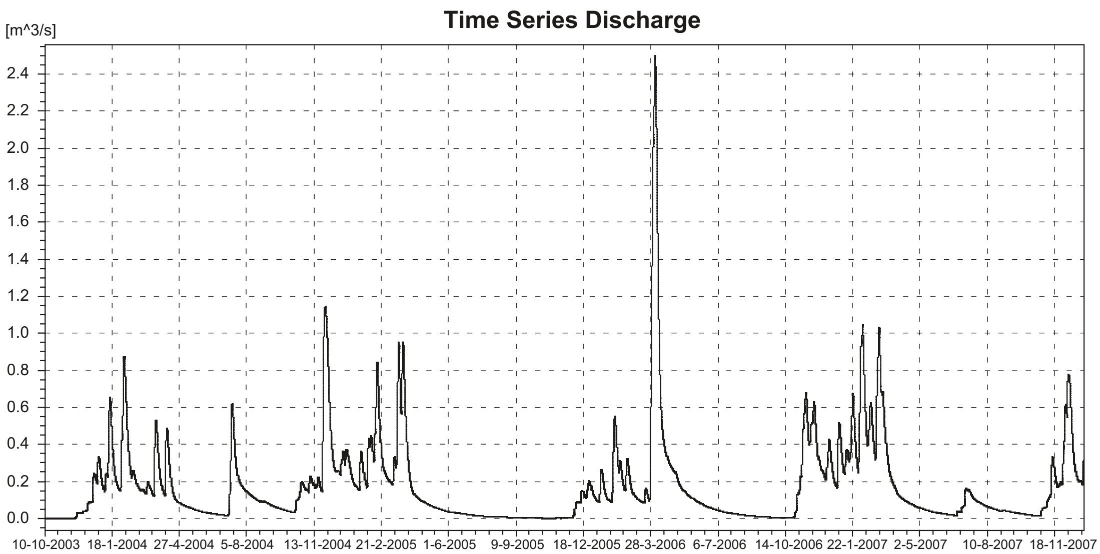

Figure 2-8. *Calculated inflow in the Laxemarån stream at the MIKE SHE model boundary, see Aneljung et al. (2007) for details.*

The bed resistance, which is expressed by the Manning number (M), has not been changed since the version of the MIKE 11 model reported in Aneljung et al. (2007). The Manning number is 10 $m^{1/3}s^{-1}$ in the whole model except from the branches in the drainage area of Ekerumsån and Kärrviksån where the Manning number is set to 5 $m^{1/3}s^{-1}$. The leakage coefficient, which affects the conductance used in the calculation of the water exchange between the stream network and the saturated zone in MIKE SHE, is not changed either; the value is set to $1 \cdot 10^{-4}$ s^{-1}.

2.2.3 Vegetation and overland flow

Vegetation parameters are used to specify vegetation data for the evapotranspiration calculations. The vegetation parameters are time-varying characteristics for each type of vegetation that is specified in the model domain.

The vegetation used in the 2000 AD setup of the MIKE SHE SR-Site model is the same as the vegetation map used in the MIKE SHE SDM-Site model (Bosson et al. 2009). As the sea shoreline is displaced with time, new land areas will appear and the vegetation applied as input to the model is based on the type of Quaternary deposits present in the new area. Areas with bedrock will have the vegetation type Scots pine-dominated forest, clayey areas will be set as arable land, areas with peat will become wetlands, and areas with till or sand will be have the vegetation type needle-leaved forest.

The overland flow module is necessary when using the MIKE 11 model together with MIKE SHE, since the overland flow module provides lateral runoff to the stream network. No changes in the overland flow parameter values were made for the MIKE SHE SR-Site model compared to the MIKE SHE SDM-Site model. For more details on parameter values for overland flow, see Bosson et al. (2009).

2.2.4 Quaternary deposits

The input data describing the Quaternary deposits in the MIKE SHE SR-Site model are based on the same input as the MIKE SHE SDM-Site model, as described in Bosson et al. (2009). Figure 2-9 shows the spatial distribution of the Quaternary deposits in the area. The black line illustrates the MIKE SHE SR-Site model domain.

The applied QD model, i.e. the model describing the Quaternary deposits (QD), describes the present conditions at 2000 AD. No development of the QD model has been performed to accommodate future conditions at 5000 AD and 10,000 AD (QD development was considered in the Forsmark modelling, see Bosson et al. (2010)). The QD model for 2000 AD is applied in all MIKE SHE SR-Site simulation cases.

The types of Quaternary deposits in the unsaturated zone are the same as in the MIKE SHE SDM-Site model and described in Bosson et al. (2009). The same relation between QD types in the saturated zone description and the soil classes in the unsaturated zone is applied and the same methodology is applied when simplifying and reducing the soil classes. However, since the model domain in the MIKE SHE SR-Site model is larger than that in the MIKE SHE SDM-Site model, a few new soil classes are added. Soil classes present only in very small parts of the model area (one or two grid cells, see Section 3.2) are not included in the model.

2.2.5 Bedrock hydrogeology

The bedrock model and the hydraulic properties of the bedrock are the same as described in Bosson et al. (2009). The extent of the bedrock model used in the MIKE SHE SDM-Site model is however limited and does not cover the entire model area of the MIKE SHE SR-Site model. The geological layers have therefore been extrapolated. The extrapolation of the bedrock parameters is made by extrapolating the values at the boundary to the new MIKE SHE SR-Site model boundary. However, this means that there will be less spatial variation in the bedrock parameters in the new areas of the model domain. Figure 2-10 shows the extent of the bedrock in the MIKE SHE SDM-Site model and the areas subjected to extrapolation.

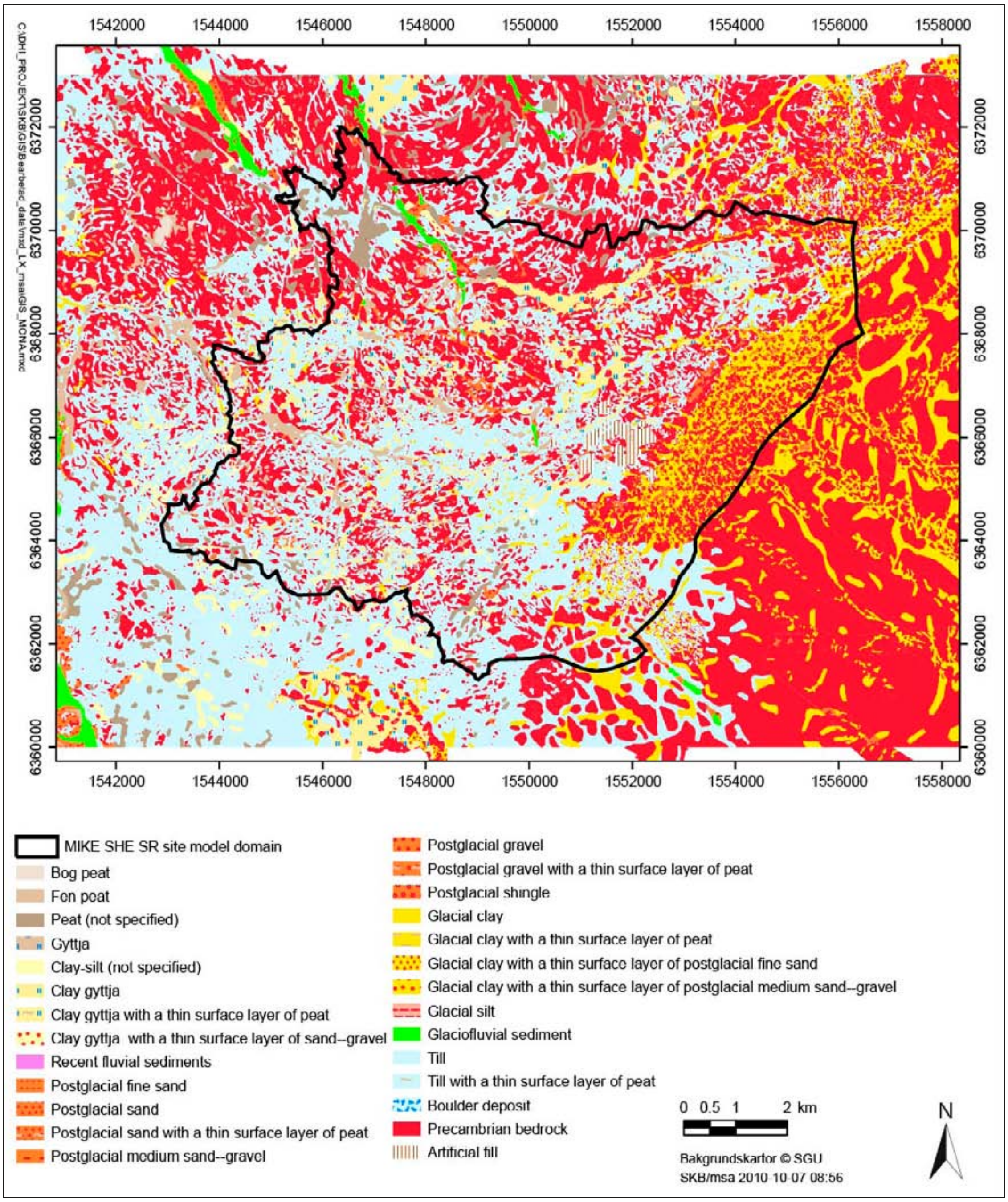

Figure 2-9. *Spatial distribution of Quaternary deposits in the unsaturated zone description. The black line indicates the boundary of the MIKE SHE model area.*

The extrapolation of the bedrock parameters has been made for each geological layer for the horizontal hydraulic conductivity, K_h, the vertical hydraulic conductivity, K_v, the saturated specific yield, S_y, and the specific storage, S_s. The geometric mean values for the horizontal hydraulic conductivity in the layers down to a depth of 200 meters are in the range of $2 \cdot 10^{-7}$ m/s to $3.8 \cdot 10^{-7}$ m/s. For the vertical hydraulic conductivity the values range from $2.8 \cdot 10^{-7}$ m/s to $5.3 \cdot 10^{-7}$ m/s. For both the horizontal and vertical conductivity there is a depth trend such that the hydraulic conductivity is decreasing with depth.

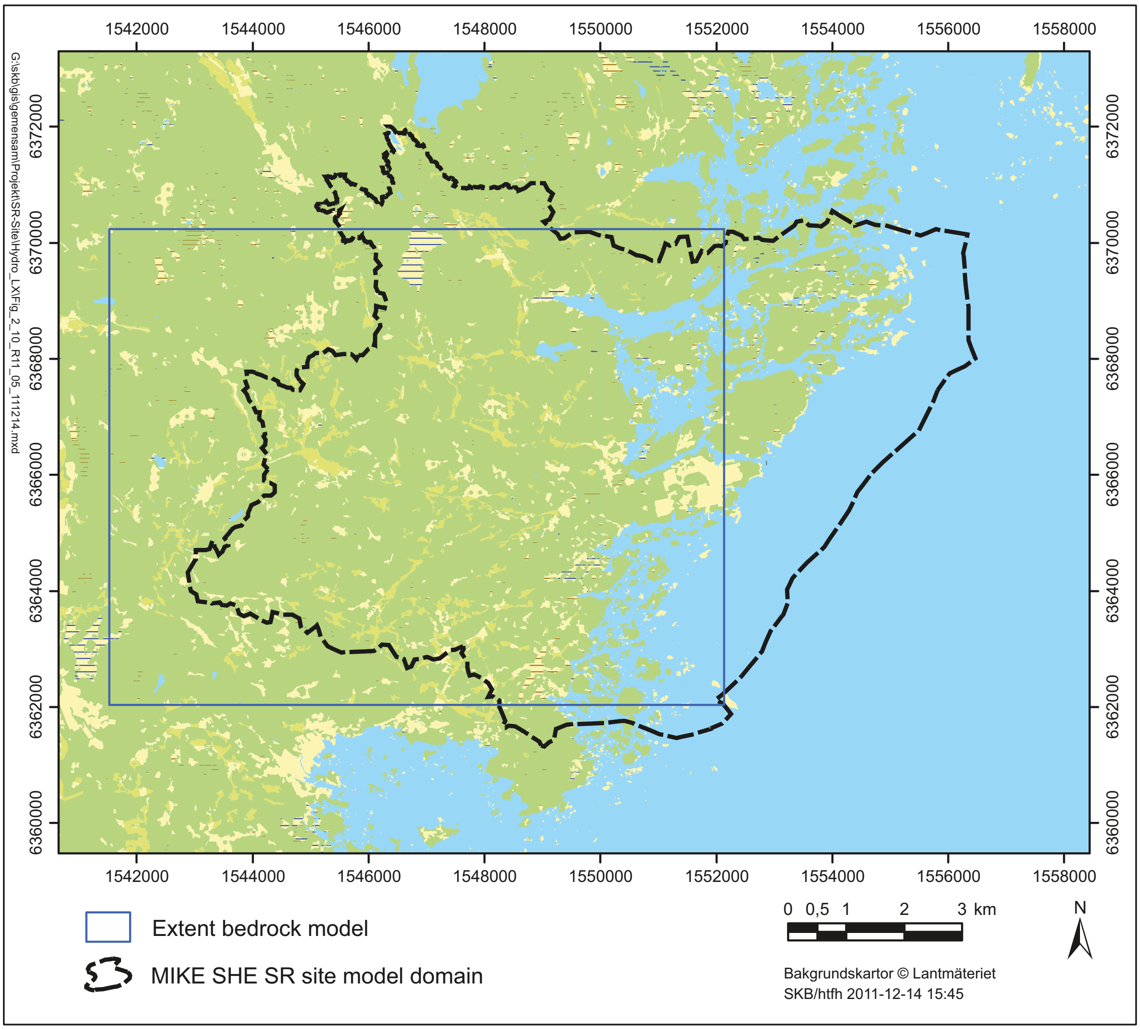

Figure 2-10. *Extent of the SDM-Site bedrock model used in the present work (blue line) and the MIKE SHE SR-Site model area (black line).*

3 Modelling tool and numerical flow model

3.1 The MIKE SHE modelling tool

The modelling tool used in the present analysis is MIKE SHE; the specific code version used in this project is software release version 2009 (DHI Software 2009). MIKE SHE is a dynamic, physically based, modelling tool that describes the main processes in the entire land phase of the hydrological cycle, see Figure 3-1.

MIKE SHE consists of components for precipitation, evapotranspiration, overland flow, channel flow, unsaturated flow, and saturated flow. The precipitation can either be intercepted by leaves or fall to the ground. The water on the ground surface can infiltrate, evaporate or form overland flow. Once the water has infiltrated the soil, it enters the unsaturated zone. In the unsaturated zone, it can either be extracted by roots and leave the system as transpiration, or it can percolate down to the saturated zone.

The water can also be extracted by roots in the saturated zone if the vegetation is classified as hydrophilic. MIKE SHE is fully integrated with a 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. For a detailed description of the processes included in MIKE SHE and MIKE 11, see DHI Software (2009). The first hydrology modelling report produced during the SDM work (Werner et al. 2005) provides a relatively detailed process description in an SKB context.

MIKE SHE may also be used for simulations of solute transport. Solute transport simulations may be performed by either the particle tracking module or the advection-dispersion module. In both cases, the three-dimensional flow field calculated by the MIKE SHE water movement module described above is the basis for the transport simulations.

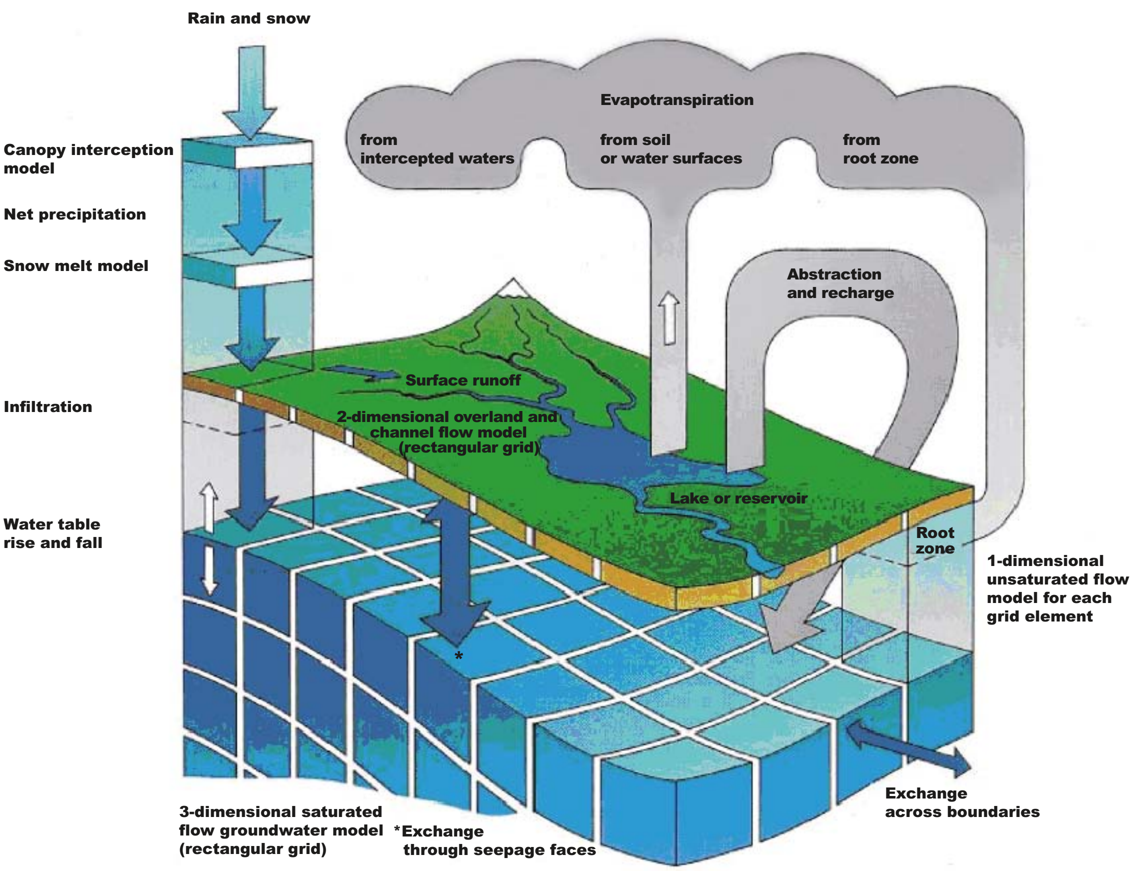

Figure 3-1. *Overview of the model structure and the processes included in MIKE SHE (DHI Software 2009).*

Particle tracking is in the MIKE SHE model system per definition modelled as purely advective transport, without dispersion or diffusion effects. This means that the substance is moved with the Darcy flow vectors, and nothing else. In particle tracking simulations, hypothetical inert particles or "water parcels" are traced as they are transported by the groundwater flow field in the model volume. The resulting flow paths provide important information as such; they connect the selected starting points with groundwater discharge points or other exit points on the model boundaries. Furthermore, travel or residence times along the flow paths can be calculated. For more details on solute transport simulations with the MIKE SHE model, see DHI Software (2009).

3.2 Model domain and grid

In the MIKE SHE SDM-Site model for Laxemar, see Bosson et al. (2009), the model area was approximately 34 km^2 and the horizontal computational grid cell size was 40 m by 40 m. In the MIKE SHE SR-Site model, the model area was extended in the north-western part, as well as in the southern part, and along the shoreline in the east. Figure 3-2 shows the model area for the MIKE SHE SR-Site model and the model area in the preceding MIKE SHE SDM-Site model.

The reason for extending the model area in the MIKE SHE SR-Site model is the future cases to be simulated in the present project. In the sea, the model area was extended to reach the shoreline at 10,000 AD, see Figure 3-3. The SR-Site model area for MIKE SHE covers an area of c. 80 km^2.

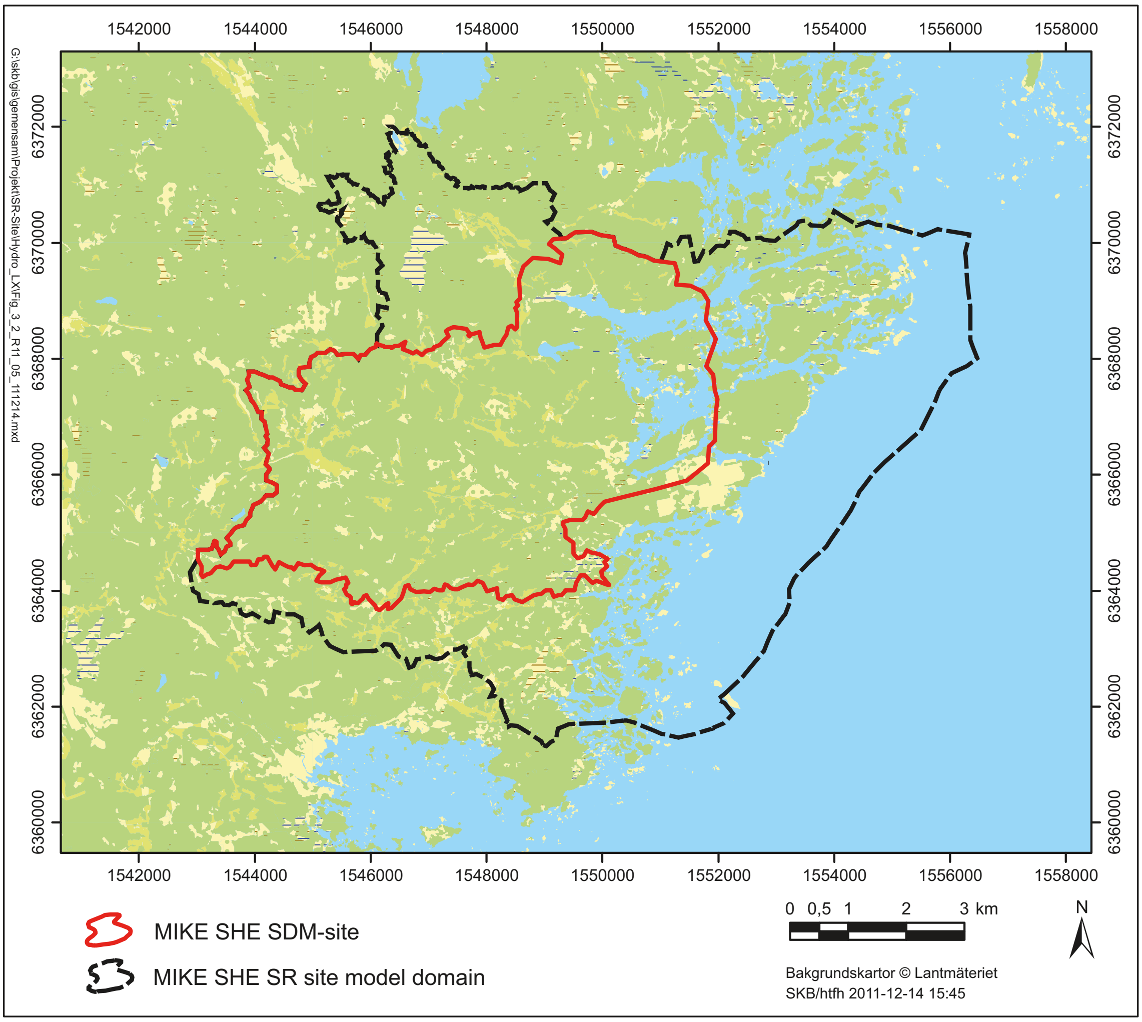

Figure 3-2. Model area for the MIKE SHE SDM-Site model (red line) and model area for the MIKE SHE SR-Site model (black line).

The horizontal resolution of the computational grid is 80 m by 80 m, which is applied to all of the flow components in MIKE SHE, i.e. the overland flow, the unsaturated zone (including evapotranspiration), and the saturated zone. The hydrogeological input data for the bedrock and the Quaternary deposits (QD) and geometrical data for the bedrock and QD layers are also given on an 80 m by 80 m grid.

3.3 Shoreline displacement and surface stream network

The shoreline displacement as described in Brydsten (2009) has been applied to the hydrological models. Three different shorelines have been studied, i.e. the modelled locations for 2000 AD, 5000 AD and 10,000 AD. The corresponding shoreline elevations are placed at –0.04 m.a.s.l. –3.61 m.a.s.l. and –9.09 m.a.s.l. (Figure 3-3). The present sea level variation measured at the site is applied to all different models, which means that the variation in sea level during the year is assumed to be the same in all simulations whereas the mean level in each case describing the future is given by the shoreline elevation at that time.

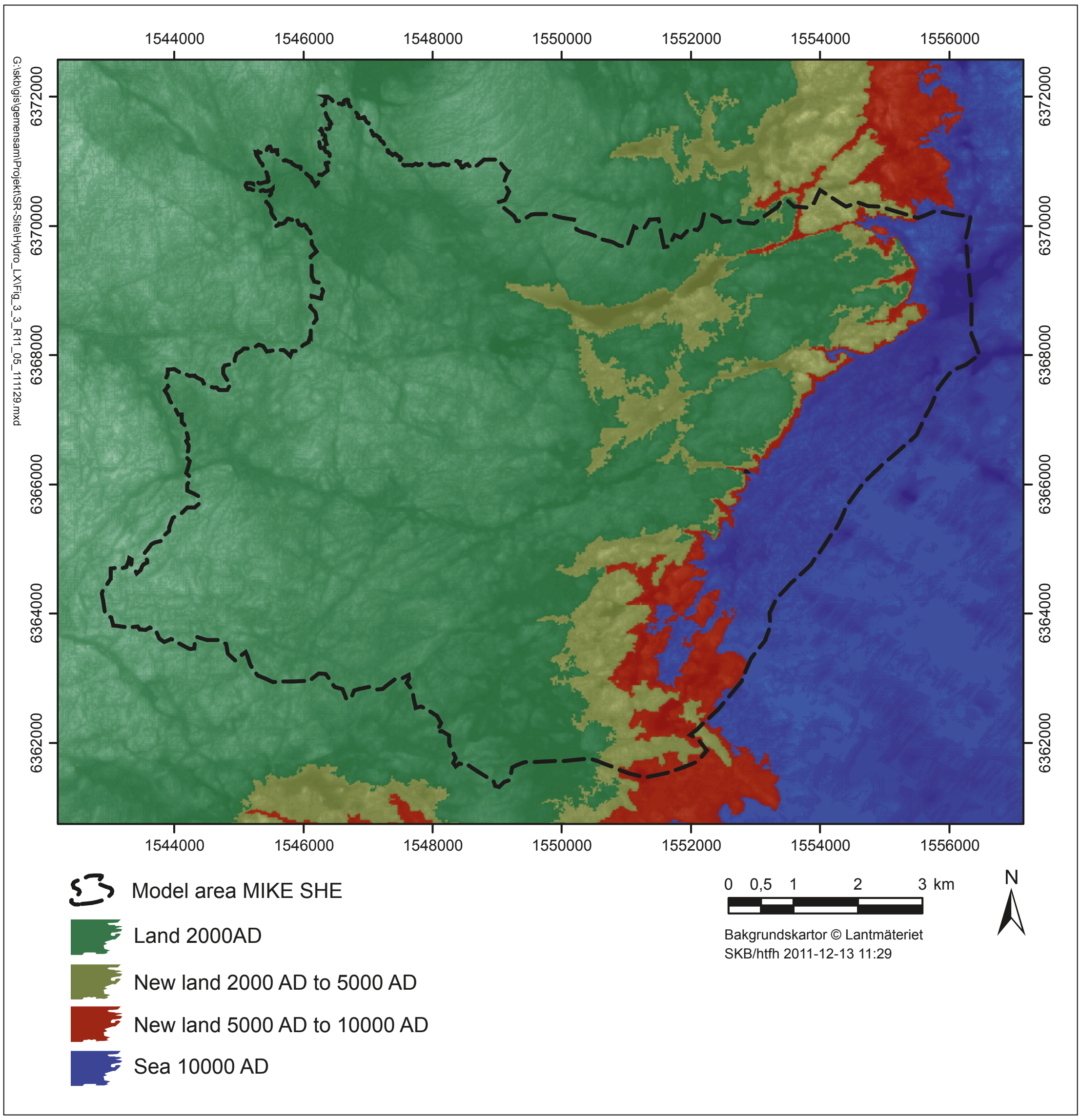

Figure 3-3. The shoreline locations at 2000 AD, 5000 AD and 10,000 AD in the Laxemar area.

The surface water system implemented in the MIKE SHE SDM-Site model (Bosson et al. 2009) was further extended to include the surface water streams in the areas within the extended model domain, i.e. new streams were added mainly in the northwest part and in the south-eastern part. Figure 3-4 shows the surface stream network used in the MIKE SHE SDM-Site model and the complementary streams included in the MIKE SHE SR-Site model.

As explained above, the model was created for three different times, corresponding to 2000 AD, 5000 AD and 10,000 AD. Since the shoreline is displaced with time and new land areas form, the surface stream networks have to be extended for each time. Figure 3-5 shows the surface stream networks for the three models. At 2000 AD the stream network follows the red lines in Figure 3-5. In the year 5000 AD the network is extended with the blue lines, and at 10,000 AD the network is further extended by the orange lines.

The total length of the surface stream network in the 2000 AD model is approximately 91.4 km; in 5000 AD model the total length is c. 121.9 km, and the 10,000 AD network has a total length of 128.5 km. The numbers of stream cross sections describing the geometry of the streams in the 2000 AD model is 292, whereas the 5000 AD model has 367 cross sections and the 10,000 AD model 382 cross sections.

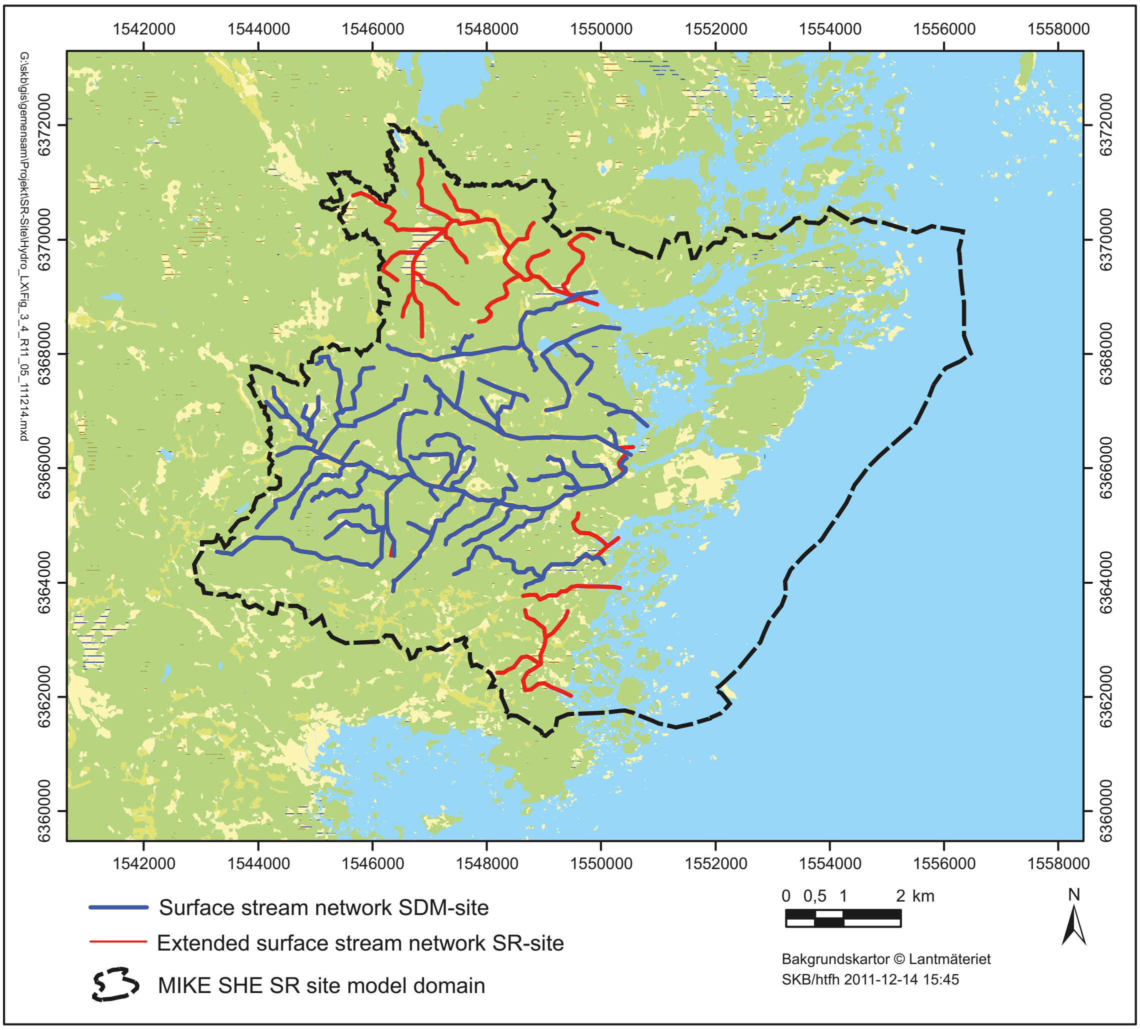

***Figure 3-4.** The surface stream network in the MIKE SHE SDM-Site model (blue lines) and the extensions made in the MIKE SHE SR-Site 2000 AD model (red lines).*

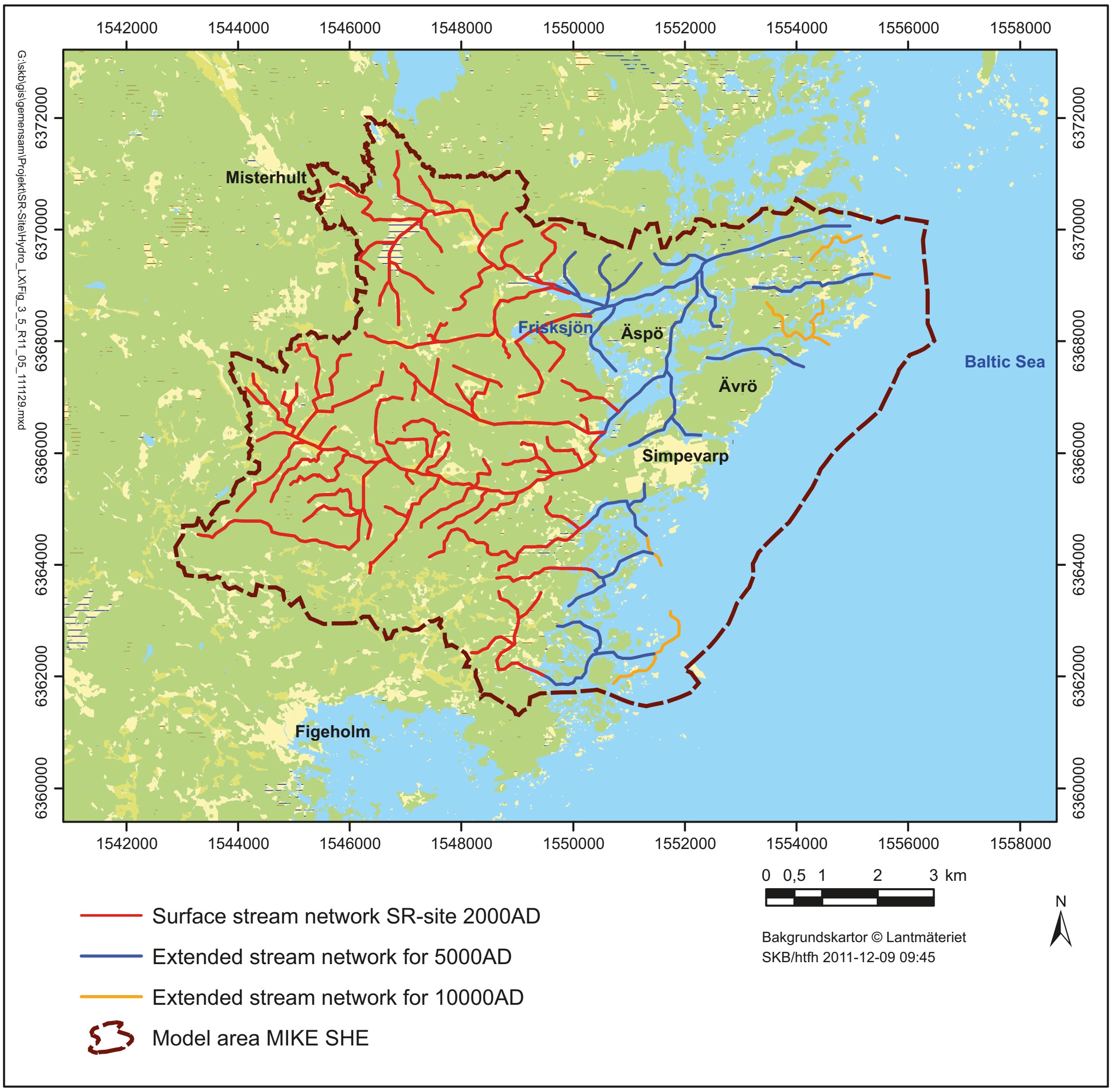

Figure 3-5. Surface stream networks in the MIKE 11 modules of the MIKE SHE SR-Site model for 2000 AD (red lines), and the extensions for 5000 AD (blue lines) and 10,000 AD (orange lines).

3.4 Unsaturated and saturated zone descriptions

In order to speed up the simulations, only a limited number of grid cells are simulated in the unsaturated zone. The selection is done through a special classification system where those unsaturated zone columns that have the same conditions (i.e. the same soil profile, land use, meteorology and approximate groundwater depth) are grouped together. From each group only one column, randomly selected, is simulated.

In the Laxemar model, an exception from this is made in areas with ponding water on the surface, i.e. lakes and wetland areas (excluding the sea). In these areas, the unsaturated zone simulation is executed in all grid cells. This has been found important in order to ensure a proper simulation of the evapotranspiration, since the handling of the evapotranspiration calculations in MIKE SHE is connected to the unsaturated zone. If the lakes are a part of the randomly selected unsaturated zone cells, the evaporation from the surface water of the lakes might be underestimated.

The unsaturated zone description in the Laxemar SR-Site model follows the same principles as the Laxemar SDM-Site model (Bosson et al. 2009). The input data for the Quaternary deposits are described in Section 2.2.4. The vertical discretisation of the unsaturated zone is presented in Table 3-1.

Table 3-1. Vertical discretisation of the unsaturated zone.

Depth interval	Cell height (m)	Number of cells
0–1 m	0.1	10
1–5 m	0.5	8
5–10 m	1	5
10–20 m	2	5

The ground surface, as given by the topographic model, the DEM, is the upper model boundary. The bottom boundary of the model is at 600 m.b.s.l. The MIKE SHE model distinguishes between geological layers and calculation layers. The geological layers are the basis for the model parameterisation, which means that the hydrogeological parameters are assigned to the different geological layers. The calculation layers are the units considered in the numerical flow model. In cases where several geological layers are included in one calculation layer, the properties of the latter are obtained by averaging of the properties of the former. A description of how the averaging of the saturated zone properties is made in the model is given in Bosson et al. (2010). For the present model, the model setup consists of 20 calculation layers.

In general, the calculation layers follow the geological layers. However, one exception is the calculation layers in the Quaternary deposits. The lake sediments and other Quaternary deposits are included in the two uppermost calculation layers. In the initial model setup, the uppermost calculation layer has a minimum thickness of 0.5 m and the other calculation layers have a minimum thickness of 1 m. The sediments under Lake Frisksjön are included in the uppermost calculation layer. If the depth of the lake sediments is larger than 0.5 m, the lower level of calculation layer 1 follows the lower level of the lake sediments. More details about the model layers are found in Bosson et al. (2009).

The layer thickness of the uppermost geological layer has been extrapolated from the model boundary of the MIKE SHE SDM-Site model to the boundary of the model area in the MIKE SHE SR-Site model. All bedrock layers in the geological-hydrogeological model have a thickness of 40 m, except near the surface where the layer thickness varies with the thickness of the Quaternary deposits. The model also includes thinner surface and near-surface bedrock layers, which represent the more fractured and hydraulically conductive upper bedrock, present just below the Quaternary deposits and in bedrock outcrops (Bosson et al. 2009).

Subsurface drainage is implemented to the model in the same way as in the MIKE SHE SDM-Site model (Bosson et al. 2009). In short, the subsurface drainage level is set to 1.0 m below ground in areas with arable land, while in areas with bedrock outcrops the drainage level is 0.35 m below ground. The reason for implementing the subsurface drainage is to be able to describe the surface dynamics better. Without the drainage function, the model response is too slow, which leads to too small peaks and too large base flows. More details on the implementation of the subsurface drainage are found in Bosson et al. (2009).

3.5 Boundary conditions and numerical calculation parameters

The groundwater divides are assumed to coincide with the surface water divides; the latter are reported in Brunberg et al. (2004). Thus, a no-flow boundary condition is used for the on-shore part of the model boundary. The sea forms the uppermost calculation layer in the off-shore parts of the model. The sea is represented by a geological layer consisting of highly permeable material. The hydraulic conductivity of this material is set to 0.001 m/s. The sea part of the uppermost calculation layer has a time-varying boundary condition. The measured time-varying sea level is used as input data.

Only small parts of the model area are exposed towards the sea; therefore, a no-flow boundary is specified also for the off-shore parts of the model. In the QD-layers the boundary towards the sea is the time-varying boundary condition describing the sea-level in the area, whereas in the bedrock layers there is a no-flow boundary condition.

The top boundary condition is expressed in terms of the precipitation and potential evapotranspiration (PET). The precipitation and PET are assumed to be distributed over the model area based the three different zones described in Section 2.2.1 (Figure 2-4), and are given as time series for the selected one-year period (Section 2.2.1). The actual evapotranspiration is calculated during the simulation. A no-flow bottom boundary condition is applied in the model. Below 650 m.b.s.l. the hydraulic conductivities in the bedrock hydrogeology model are very low, which means that a no-flow boundary condition is considered a good approximation at 600 m.b.s.l.

Transient simulations are performed by cycling the time series input for the selected year until stable results are obtained. Initial conditions are calculated in an iterative procedure, where in the first step the initial conditions are based on results from previous Laxemar modelling. A three-year cycle is simulated, followed by an update of the initial conditions, and then a new cycle is simulated; this procedure is repeated until results have stabilised. In MIKE SHE a maximum time step is defined for each compartment of the model. During the simulation the time step may be reduced. The maximum time steps for all compartments are listed in Table 3-2.

Table 3.2. Maximum time steps for the different compartments of the MIKE SHE-MIKE 11 model.

Compartment	Maximum time step
Overland water	1 h
Unsaturated zone	1 h
Saturated zone	12 h
MIKE 11 (water streams)	5 s

3.6 Summary of model updates

Table 3-3 gives a summary of the input data changes in the MIKE SHE SR-Site model compared to the MIKE SHE SDM-Site model. The main changes are the enlargement of the model area and the grid size, and the new model variants describing future shoreline locations.

Table 3-3. Summary of model updates from the MIKE SHE SDM-Site model to the regional MIKE SHE SR-Site model.

	SDM-Site	SR-Site
Model area	34 km^2	80 km^2
Horizontal resolution	40 m × 40 m	80 m × 80 m
Shoreline locations	2000 AD	2000 AD, 5000 AD, 10,000 AD
QD-map for the unsaturated zone	Same as saturated zone	As SDM-Site, extrapolated to new model boundary
Bedrock model	SDM-Site bedrock hydrogeology	As SDM-Site, extrapolated to new model boundary

4 Results

In this chapter, the results from the flow and transport modelling using the Laxemar MIKE SHE SR-Site model are presented. Section 4.1 describes a comparison between results from the MIKE SHE SDM-Site model and the present MIKE SHE SR-Site model; this comparison is based on site data for the period 2004–2007. In Section 4.2, results from the three different times 2000 AD, 5000 AD and 10,000 AD, describing the hydrology at the Laxemar site today and in the future, are presented. Finally, Section 4.3 describes the delivery of data from the MIKE SHE modelling to the radionuclide transport and dose modelling.

4.1 Comparison with the MIKE SHE SDM-Site model

To evaluate the effects of the model updates described in Chapter 3, especially the increase in the horizontal grid size from 40 m to 80 m, a comparison between results from the MIKE SHE SDM-Site model (Bosson et al. 2009) and those from the MIKE SHE SR-Site model for 2000 AD was made. For the purpose of the comparison, the updated MIKE SHE SR-Site model for 2000 AD was run with the same input time series as the MIKE SHE SDM-Site model. The results were compared to measured surface water and groundwater levels and surface water discharges.

Figure 4-1 shows the locations of the monitoring points used for the calibration of the MIKE SHE SDM-Site model. The aim with running the SR-Site model with the same meteorological input data as in the SDM-Site model was to test the model performance. In particular, it needed to be shown that the differences between measured and calculated water levels and discharges were not significantly larger in the updated model, as an effect of (primarily) the coarser spatial discretisation.

4.1.1 Surface water

In the SDM-Site MIKE SHE model, four surface water discharge stations and one surface water level station were included. The SR-Site model for Laxemar included one additional surface discharge station, PSM000368 (Figure 4-1). Figures 4-2 to 4-12 show the resulting surface water levels and discharges from both the SDM-Site model and the SR-Site model; the model results are also compared to measurements. The figures show that the differences between the two MIKE SHE models are relatively small. Both models capture the main events with high discharges and also the long periods with low discharges.

Figure 4-2 shows the measured and calculated water levels at the outlet of Lake Frisksjön. The discharge through the outlet of Lake Frisksjön is restrained by a large boulder, and the model cross section geometry was in the SDM-Site MIKE SHE model modified to account for the boulder, see Bosson et al. (2009) and Werner (2009) for more details on the lake outlet. However, as shown in Figure 4-2 the differences in results between the SDM-Site and SR-Site models are small, although somewhat higher levels are seen in the results from the SR-Site model; the mean difference is 1.6 cm.

In Figures 4-3 and 4-4 the results from the surface discharge station PSM000347, situated upstream of Lake Frisksjön, are presented. Figure 4-3 shows the surface water discharge time series and Figure 4-4 shows the accumulated discharge. The figures show that the accumulated water volume for station PSM000347 is somewhat higher for the SR-Site MIKE SHE model than for the SDM-Site model; the difference is approximately 11% for the entire simulation period of approximately three years.

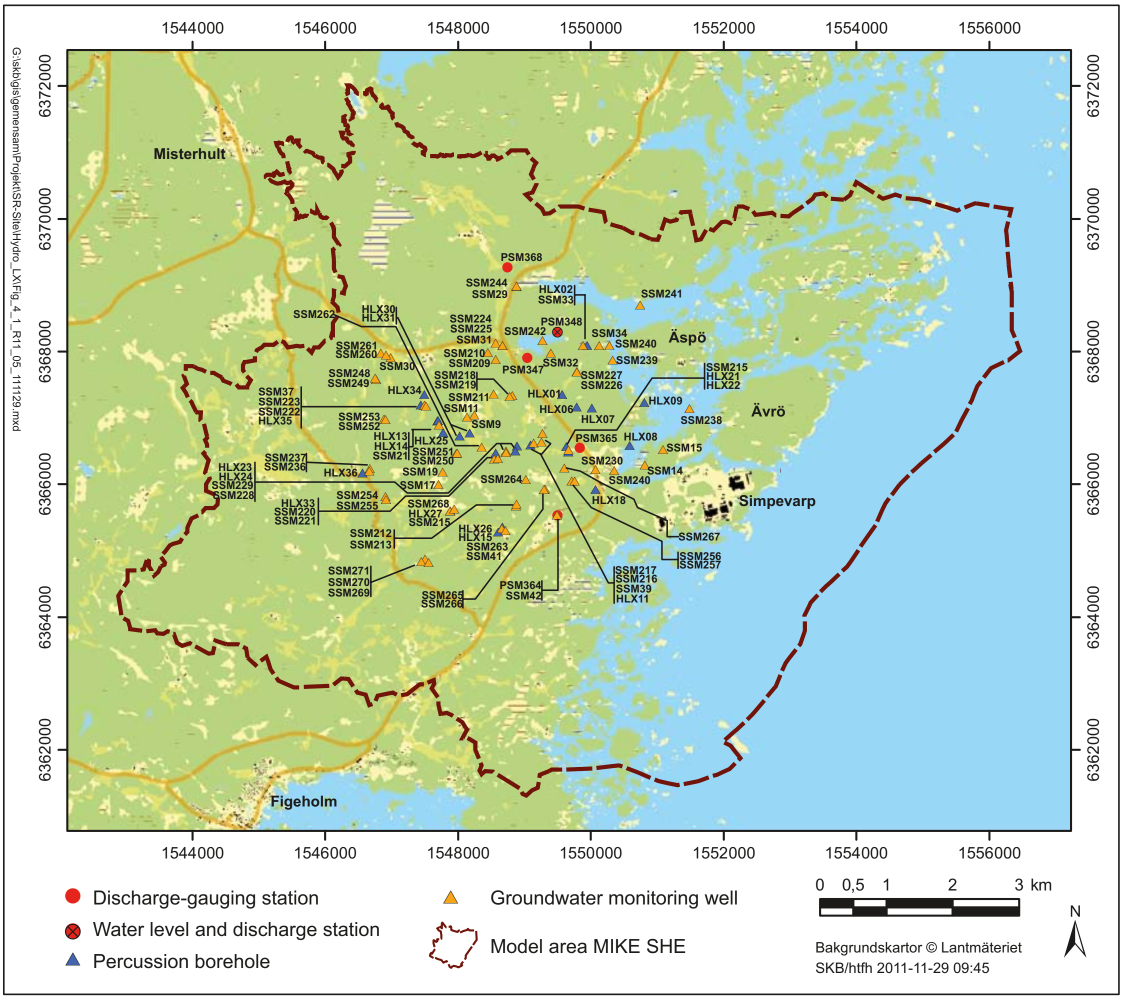

Figure 4-1. *Location of monitoring points used for calibration of the SDM-Site MIKE SHE model in Bosson et al. (2009) and for the comparison between models and between models and measurements in the present report.*

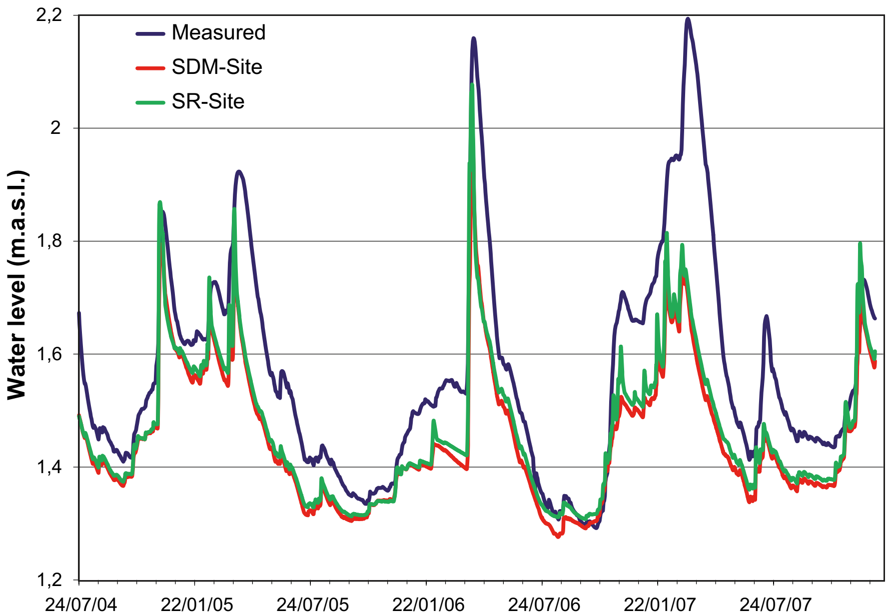

Figure 4-2. *Comparison of measured (blue line) and modelled water levels at station PSM000348; the red line is water level modelled with the SDM-Site MIKE SHE model and the green line is water level modelled with the SR-Site MIKE SHE model.*

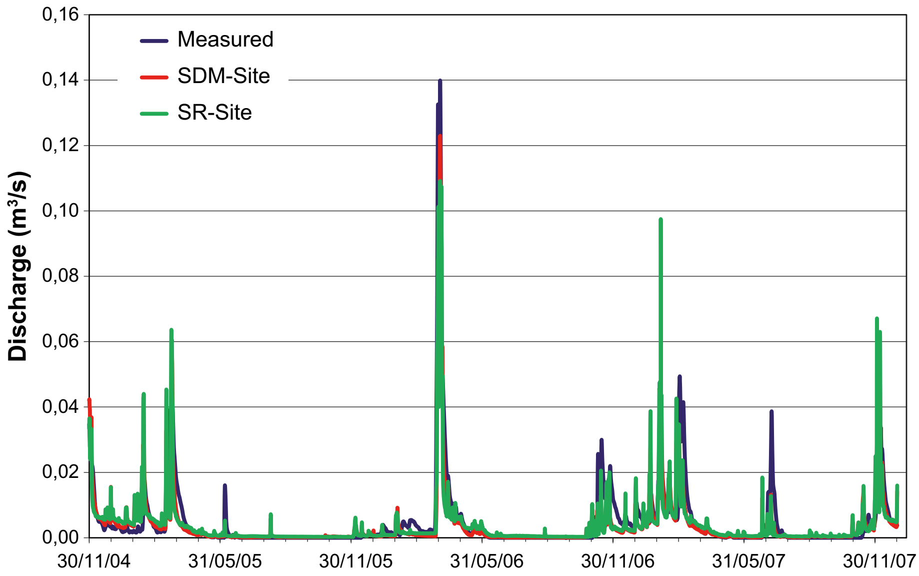

Figure 4-3. *Comparison of measured (blue line) and modelled surface water discharges at station PSM000347; the red line is surface water discharge modelled with the SDM-Site MIKE SHE model and the green line is discharge modelled with the SR-Site MIKE SHE model.*

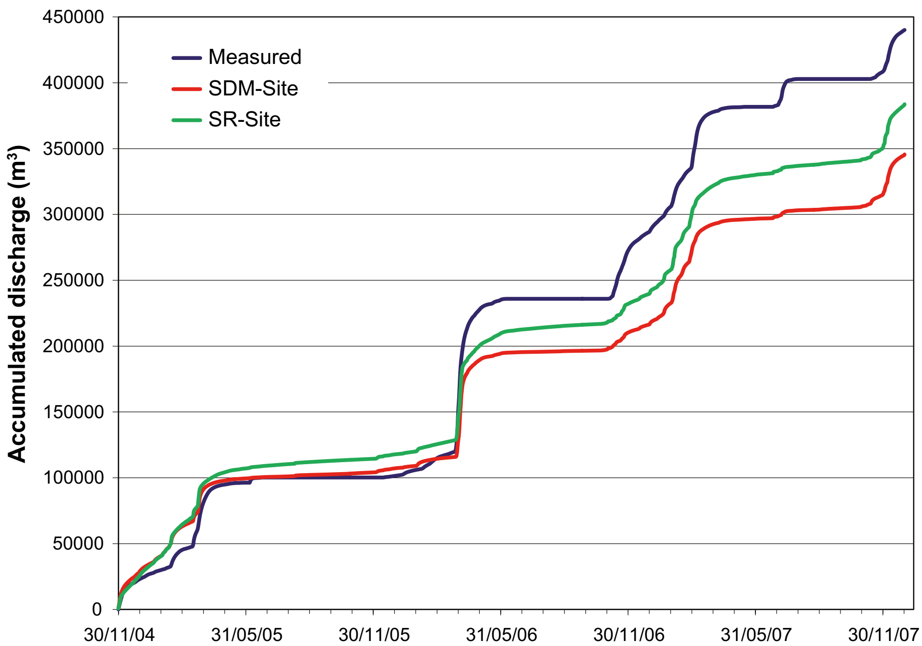

Figure 4-4. *Comparison of measured (blue line) and modelled accumulated surface water discharges at station PSM000347; the red line is accumulated discharge modelled with the SDM-Site MIKE SHE model and the green line is the accumulated discharge modelled with the SR-Site MIKE SHE model.*

For station PSM000348, see Figures 4-5 and 4-6, the discharge results differ more between the SDM-Site and SR-Site calculations. However, since the discharge measurements in PSM000348 suffer from several problems, see Werner et al. (2008) and Bosson et al. (2009), the results from this station are uncertain and difficult to evaluate. The results in terms of the total accumulated discharges for the SDM-Site and the SR-Site models differ by c. 16% after the simulated period of almost 3.5 years.

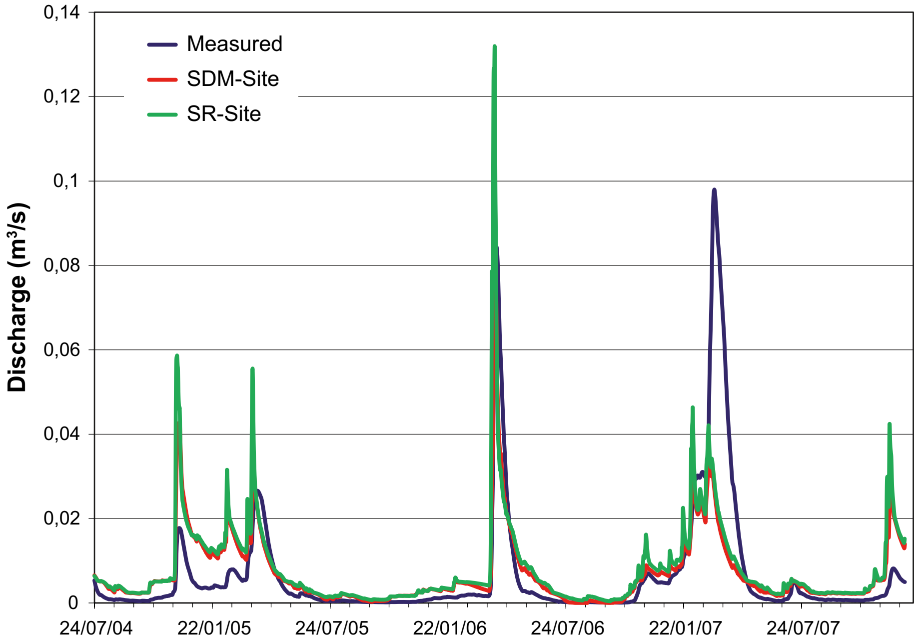

Figure 4-5. *Comparison of measured (blue line) and modelled surface water discharges at station PSM000348; the red line is surface water discharge modelled with the SDM-Site MIKE SHE model and the green line is discharge modelled with the SR-Site MIKE SHE model.*

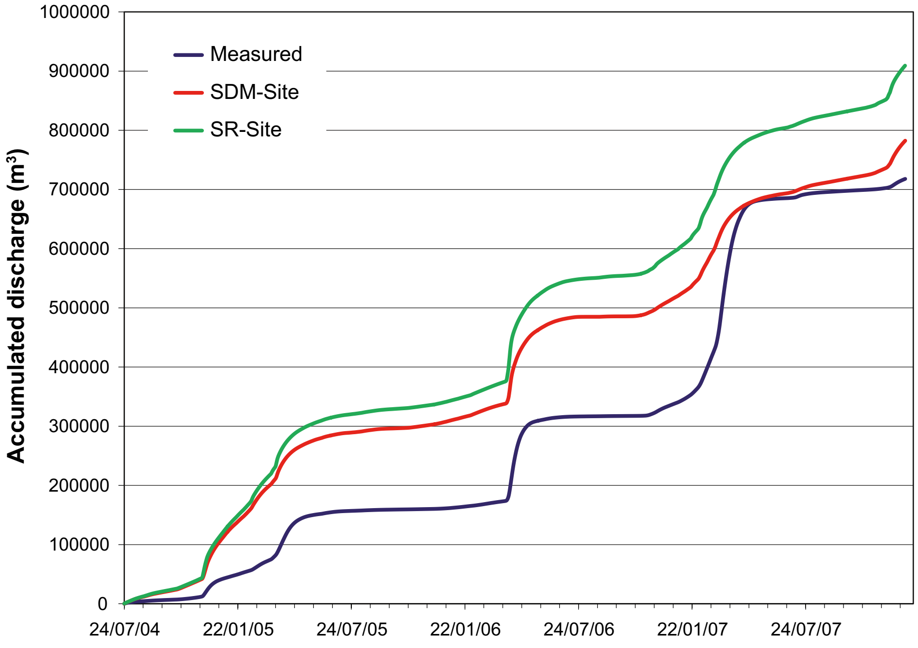

Figure 4-6. *Comparison of measured (blue line) and modelled accumulated surface water discharges at station PSM000348; the red line is accumulated discharge modelled with the SDM-Site MIKE SHE model and the green line is the accumulated discharge modelled with the SR-Site MIKE SHE model. Due to the poor quality of the measured data for this station, it was not used for calibration.*

Station PSM000364 is located in the Laxemarån stream. The results for PSM000364 are illustrated in Figures 4-7 and 4-8. The difference between the calculated accumulated discharges for the SDM-Site and SR-Site models is very small for PSM000364, only about 2% for the simulation period of three years. However, more than 50% of the total runoff at the PSM000364 station is introduced to the model at the boundary and calculated based on a NAM model (see Bosson et al. 2009), which probably is one reason for the small differences between measurements and results obtained from the MIKE SHE SDM-Site and SR-Site models for this station.

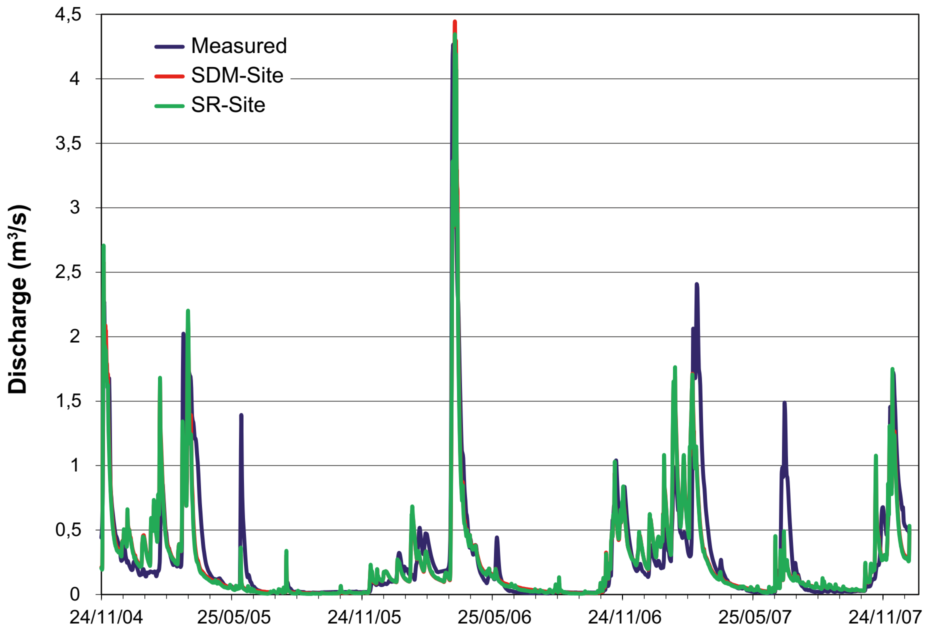

Figure 4-7. *Comparison of measured (blue line) and modelled surface water discharges at station PSM000364; the red line is surface water discharge modelled with the SDM-Site MIKE SHE model and the green line is discharge modelled with the SR-Site MIKE SHE model.*

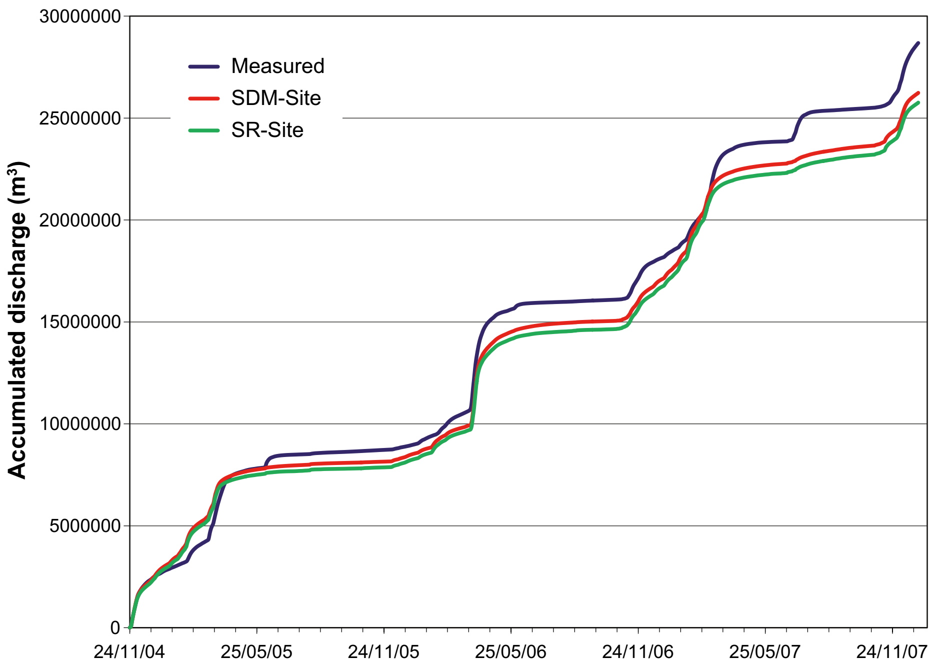

Figure 4-8. *Comparison of measured (blue line) and modelled accumulated surface water discharges at station PSM000364; the red line is accumulated discharge modelled with the SDM-Site MIKE SHE model and the green line is the accumulated discharge modelled with the SR-Site MIKE SHE model.*

In Figures 4-9 and 4-10 the results for station PSM000365, located in the stream Ekerumsån, are shown. The accumulated discharge volumes differ only by c. 3% between the SDM-Site MIKE SHE model and the SR-Site model at the end of the considered simulation period.

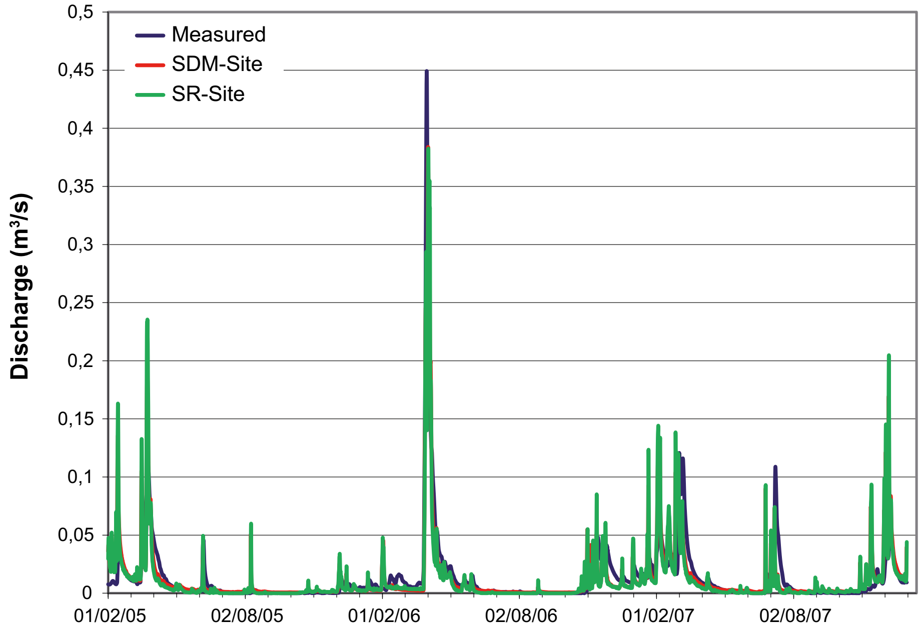

Figure 4-9. *Comparison of measured (blue line) and modelled surface water discharges at station PSM000365; the red line is surface water discharge modelled with the SDM-Site MIKE SHE model and the green line is discharge modelled with the SR-Site MIKE SHE model.*

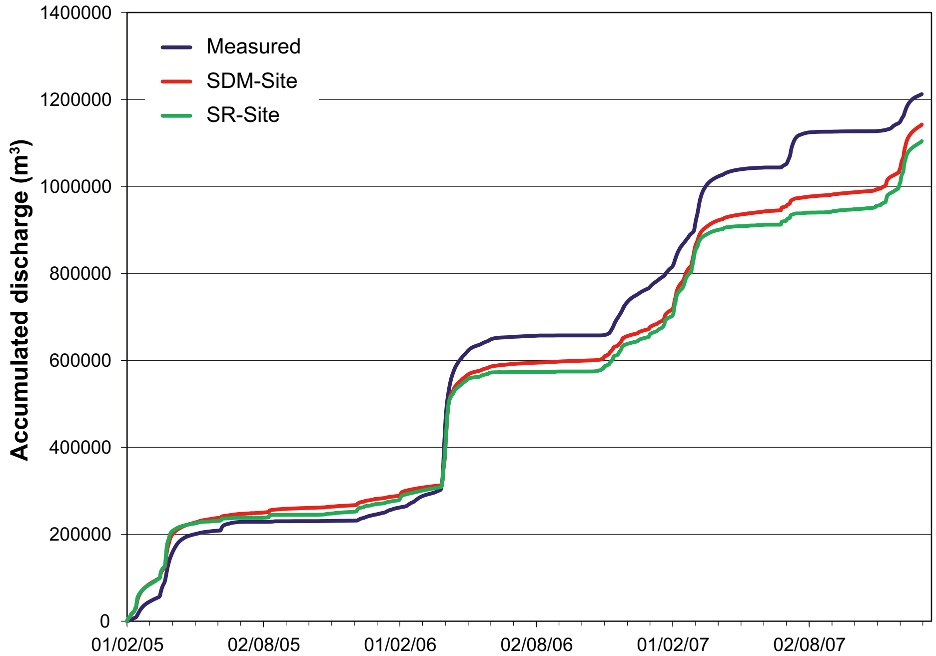

Figure 4-10. *Comparison of measured (blue line) and modelled accumulated surface water discharges at station PSM000365; the red line is accumulated discharge modelled with the SDM-Site MIKE SHE model and the green line is the accumulated discharge modelled with the SR-Site MIKE SHE model.*

Figures 4-11 and 4-12 show the simulated discharges and accumulated discharge volumes for station PSM000368 (Kärrviksån). The station is located in the northern part of the present MIKE SHE model area, and was not part of the SDM-Site model area. Therefore, simulation results are only available for the SR-Site MIKE SHE simulation for PSM000368. A comparison between measured and calculated values shows that the difference in accumulated surface discharge is only c. 5%, which is considered to be satisfactory.

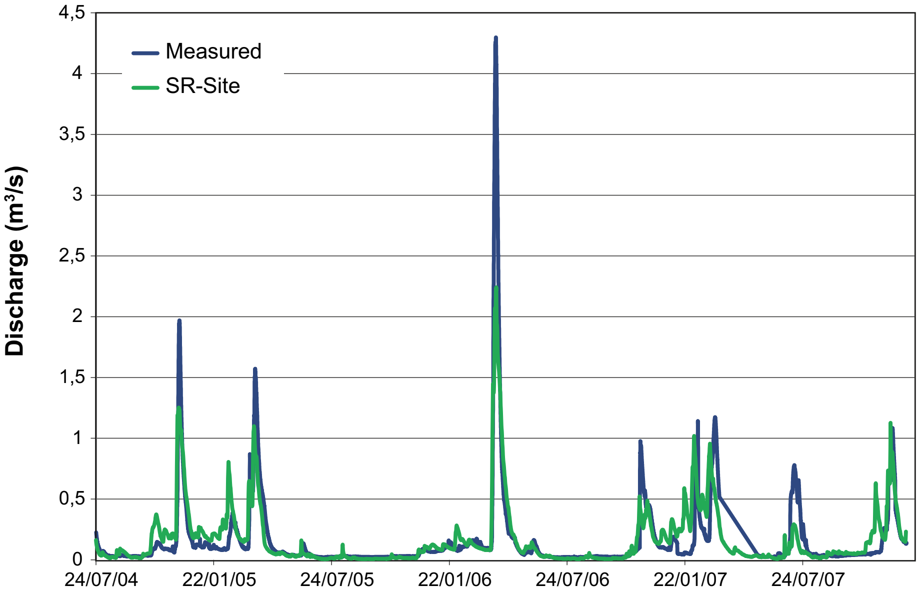

Figure 4-11. *Comparison of measured (blue line) and modelled (green line) surface water discharges at station PSM000368. Since station PSM000368 was not included in the SDM-Site MIKE SHE modelling, model results are available from the SR-Site MIKE SHE model only.*

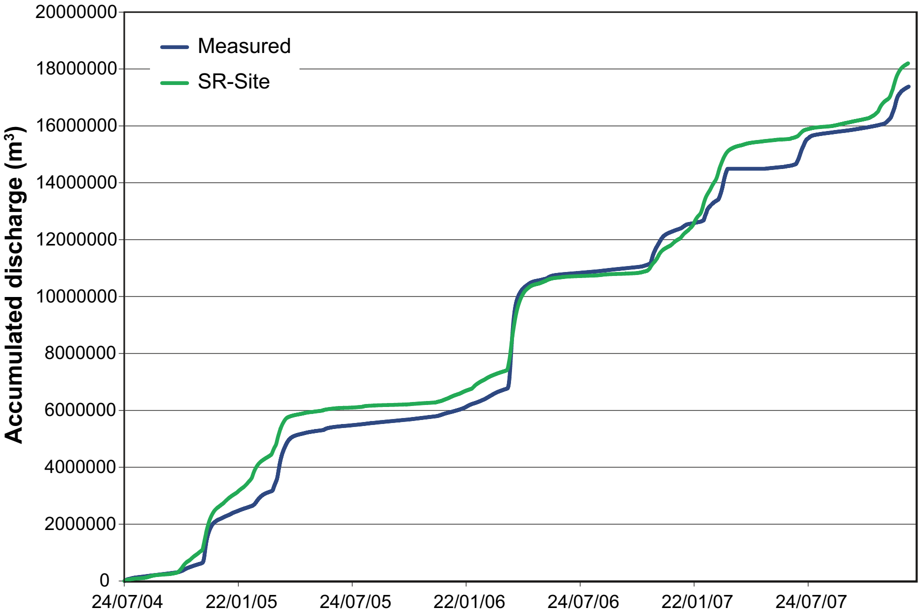

Figure 4-12. *Comparison of measured (blue line) and modelled (green line) accumulated surface water discharges at station PSM000368. Since station PSM000368 was not included in the SDM-Site MIKE SHE modelling, model results are available from the SR-Site MIKE SHE model only.*

4.1.2 Water balance

A water balance for the entire simulation period of three years for the land area at 2000 AD was extracted from the SR-Site MIKE SHE model results. The resulting mean precipitation was 605 mm/year, the total runoff 175 mm/year, and the total evapotranspiration was 419 mm/year. Based on the three years of simulation, there was a mean storage in the unsaturated zone of 6 mm/year, and in the overland model compartment another 6 mm/year. If looking at when the storage occurred, it is seen that it was during the last few months of the simulation; the reason for this is that the last months of the simulation were very rainy. A comparison with the water balance for the same period in the SDM-Site MIKE SHE modelling shows that the differences are very small.

In the SDM-Site MIKE SHE model, the annual mean precipitation was 608 mm. The difference in climate input can be explained by the different model domains; the mean precipitation for the whole model area differs because different parts of the domain are based on precipitation values from different stations, see Figure 2-4. The annual mean of the total evapotranspiration in the MIKE SHE SDM-Site model was 432 mm, which is somewhat higher than that in the MIKE SHE SR-Site model; however; the difference is only 3%. The annual mean total runoff was 170 mm in the SDM-Site MIKE SHE model, which is 5 mm less than in the SR-Site MIKE SHE model; this also corresponds to a difference of 3%.

4.1.3 Groundwater

The calculated groundwater head elevations in the Quaternary deposits in the calibrated SDM-Site MIKE SHE model showed good agreement with measurements, see Bosson et al. (2009). The differences between measured and calculated heads were expressed in terms of mean absolute errors (MAE) and mean errors (ME), see Bosson et al. (2009) for details. The mean MAE for the monitoring wells in the Quaternary deposits was 0.55 m and the mean ME was 0.17 m. Monitoring wells located in slopes generally showed poorer agreement with measurements than wells located in flat areas. The reason is that since the MIKE SHE model is based on a discretisised grid net, the elevation in a grid cell is the mean elevation within that grid cell. The monitoring well may be located at a different level than the mean and sometimes close to the boundary of the cell.

When changing the horizontal grid cell size from 40 m to 80 m, the difference in level between two adjacent cells becomes larger in slope areas. For some of the wells located close to a cell boundary, the adjacent grid cell yields a better agreement in the groundwater head elevation when compared to measurements. In these cases, the neighbouring cell was selected for evaluation instead. Table 4-1 shows a comparison between the MAE and ME values for all monitoring wells located in the QD layers that were evaluated in the MIKE SHE SDM-Site modelling.

The mean ME- and MAE-results for SR-Site are very close to the mean results from the MIKE SHE SDM-Site modelling, with slightly smaller errors for the SR-Site MIKE SHE model. However, when looking at individual wells, several differences between the SDM-Site and SR-Site models are noted. For some wells, for example SSM000033 and SSM000220, the MAE is significantly lower in the SDM-Site model, while for others, for example SSM000213 and SSM000219, the MAE is significantly higher in the SDM-Site MIKE SHE model. The local differences are most likely due to the changed grid cell size, since this causes local changes in the modelled topography.

Figure 4-13 shows a correlation plot with the mean simulated head elevation for each monitoring well in the QD compared to the mean measured head elevation. In the figure, results are plotted for both the SDM-Site model and the SR-Site model. A 1:1 line, which corresponds to a perfect fit, is also indicated. The figure illustrates that the results from the SR-Site MIKE SHE model give a fit that is as good as the results from the SDM-Site model. Since the purpose of the SR-Site MIKE SHE modelling is not to redo the model calibration, but only to check that the model gives results that are in agreement with those from the SDM-Site model (and site data), the results shown in Table 4-1 and Figure 4-13 are considered satisfactory.

For the monitoring wells measuring heads in the bedrock, Table 4-2 shows a comparison between the MAE and ME values from the SDM-Site and SR-Site MIKE SHE models. The table shows that the mean MAE is slightly lower for the SDM-Site model, 0.78 m, compared to 0.89 m for the SR-Site model. The largest error is found in well HLX28. This was the case also in the SDM-Site model, although the error is even larger for this monitoring well in the SR-Site model. So far, no explanation of the large discrepancy for HLX28 has been found. If HLX28 is excluded, the mean MAE value for the bedrock part of the SDM-Site MIKE SHE model is 0.70 m and for the SR-Site model 0.78 m, showing that the difference between the mean values decreases when HLX28 is excluded.

Table 4-1. Comparison between results for monitoring wells located in the QD for the SDM-Site and SR-Site models, in terms of mean absolute errors (MAE) and mean errors (ME); MAE and ME are expressed in meters.

ID SSM-well	SDM-Site		SR-Site	
	MAE	**ME**	**MAE**	**ME**
SSM00011	0.66	–0.58	0.43	0.29
SSM00017	0.70	0.66	0.82	0.82
SSM00019	0.34	0.09	0.46	0.32
SSM00021	0.22	–0.18	0.45	–0.44
SSM00030	0.10	0.00	0.19	0.19
SSM00031	0.27	0.27	0.25	–0.25
SSM00032	0.33	–0.33	0.40	–0.40
SSM00033	0.65	0.37	1.79	–1.79
SSM00034	0.47	–0.45	0.36	–0.06
SSM00037	0.72	–0.72	0.22	–0.21
SSM00039	0.37	–0.19	0.29	–0.03
SSM00041	0.37	–0.37	0.39	–0.39
SSM00042	0.29	0.28	0.13	0.09
SSM000210	0.49	–0.18	0.84	0.83
SSM000213	1.16	1.16	0.34	0.06
SSM000219	1.36	1.36	0.59	0.15
SSM000220	0.85	0.77	1.14	1.14
SSM000221	0.88	0.81	0.92	0.90
SSM000222	0.14	–0.03	0.13	0.05
SSM000223	0.14	–0.04	0.21	–0.18
SSM000224	0.21	0.19	0.12	–0.04
SSM000225	0.22	0.20	0.13	–0.03
SSM000226	0.83	0.74	0.79	0.79
SSM000227	0.53	0.44	0.76	0.76
SSM000228	0.22	0.18	0.36	–0.26
SSM000229	0.84	0.79	0.39	0.04
SSM000230	1.08	–1.08	0.61	0.61
SSM000237	0.98	0.98	0.65	0.46
SSM000239	0.14	–0.14	0.03	–0.03
SSM000240	0.04	0.02	0.05	–0.04
SSM000242	0.43	–0.43	0.58	–0.58
SSM000249	0.73	–0.64	0.75	0.66
SSM000250	1.50	1.50	1.01	1.01
MEAN SSM	**0.55**	**0.17**	**0.50**	**0.13**

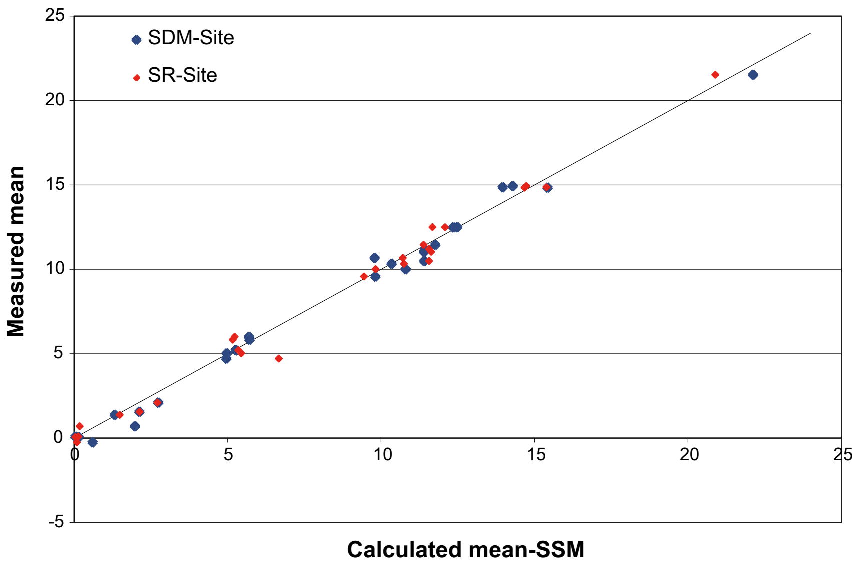

***Figure 4-13.** Correlation between measured and calculated mean head elevations for wells located in Quaternary deposits for the SDM-Site (blue) and SR-Site (red) MIKE SHE models, based on data for the entire simulation period from 2003 to 2007.*

The mean ME value for the SDM-Site MIKE SHE model is 0.19 m if HLX28 is excluded and the corresponding value for the SR-Site model is 0.10 m. The difference between the two models is not very large, and the results are judged satisfactory for the SR-Site model. Figure 4-14 shows a correlation plot with the mean simulated head elevation for each monitoring well in the bedrock compared to the mean measured head elevation. In the figure, results are plotted for both the SDM-Site and the SR-Site model, and also in this case a 1:1 line is provided that indicates a perfect fit. The figure illustrates that the results from the SR-Site model gives a fit that is almost as good as the results from the SDM-Site MIKE SHE model.

Table 4-2. Comparison between results for monitoring wells located in the bedrock for the SDM-Site and SR-Site models, in terms of mean absolute errors (MAE) and mean errors (ME); MAE and ME are expressed in meters.

ID HLX-well	SDM-Site		SR-Site	
	MAE	ME	MAE	ME
HLX01_1B	0.44	–0.23	0.75	–0.59
HLX02_1	2.66	2.66	1.78	1.78
HLX06_1	1.07	0.83	1.57	0.01
HLX07_1	0.56	–0.05	0.89	0.74
HLX08_1	0.63	–0.63	0.42	–0.42
HLX09_1B	1.03	–1.03	1.06	–1.06
HLX09_2B	0.33	0.02	0.33	–0.05
HLX11_1	0.38	–0.06	0.36	–0.09
HLX11_2	0.39	–0.13	0.35	–0.11
HLX13_1	1.17	1.17	0.82	0.82
HLX14_1	0.79	0.79	0.60	0.58
HLX15_1	0.65	0.65	2.39	2.39
HLX18_1	0.67	–0.67	0.41	–0.40
HLX18_2	0.41	–0.41	0.50	–0.50
HLX21_1C	0.38	0.26	0.62	–0.60
HLX21_2B	0.35	0.26	0.40	0.21
HLX22_1B	0.69	0.65	0.47	0.30
HLX22_2	1.10	–1.09	1.38	–1.36
HLX23_1	0.83	0.81	0.38	–0.23
HLX23_2	0.45	0.25	0.32	–0.03
HLX24_1C	0.72	0.66	0.38	0.18
HLX24_2B	0.74	0.74	0.35	0.31
HLX25_1B	0.52	0.08	0.46	–0.31
HLX25_2B	0.49	–0.11	1.23	–1.21
HLX26_1	1.08	–1.08	0.84	0.84
HLX27_1B	0.46	–0.43	1.62	1.62
HLX27_2	0.52	–0.51	1.01	–0.99
HLX28_1	3.45	3.45	5.27	5.27
HLX30_1B	0.42	–0.18	0.42	–0.21
HLX30_2B	0.38	–0.16	0.36	0.04
HLX31_1A	0.40	–0.18	0.42	0.22
HLX31_1B	0.47	0.23	0.49	0.37
HLX31_2	0.37	0.36	0.72	0.72
HLX33_1	0.62	0.58	0.27	–0.21
HLX33_2	0.43	0.39	0.19	0.08
HLX34_1	1.80	1.80	1.57	1.57
HLX35_1	1.43	1.21	1.46	1.31
HLX35_2	0.56	–0.44	1.04	–1.04
HLX36_1A	0.38	0.20	0.90	–0.89
MEAN HLX	**0.78**	**0.27**	**0.89**	**0.23**

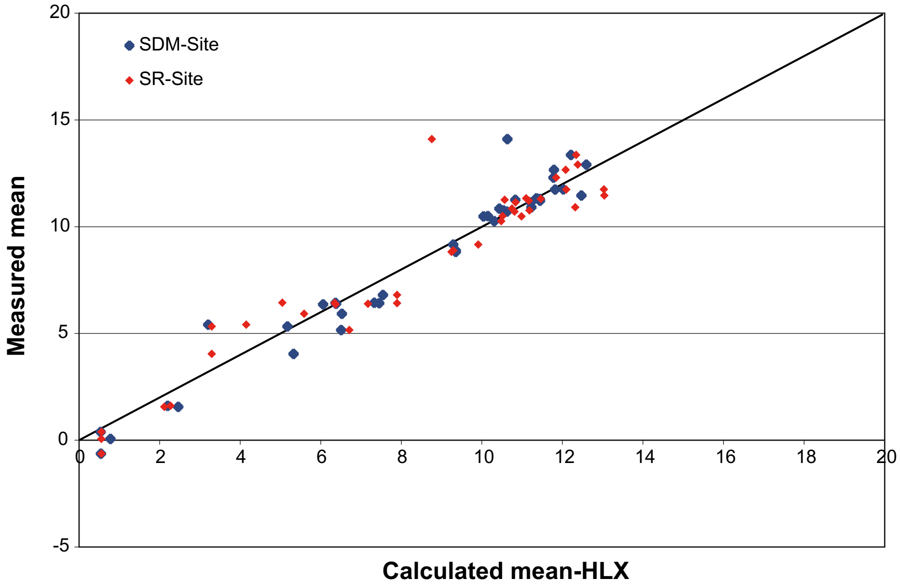

Figure 4-14. *Correlation between measured and calculated mean head elevations for wells located in the bedrock for the SDM-Site (blue) and SR-Site (red) MIKE SHE models, based on data for the entire simulation period from 2003 to 2007.*

4.2 Results from models describing present and future condtions

In the same way as for the Forsmark SR-Site calculations presented in Bosson et al. (2010), models were created for the three different times, 2000 AD, 5000 AD and 10,000 AD, representing present and future conditions at the site in terms of the different shoreline locations calculated for each year. All three models were run with meteorological data based on a selected year with a temperate climate, see Section 2.2.1. However, a difference compared to the corresponding modelling of the Forsmark site (Bosson et al. 2010) was that only one QD model, i.e. the model representing present conditions, was implemented in the SR-Site MIKE SHE model for Laxemar.

This means that the changes in the QD over time were not considered in the present study. In reality, the QD are affected by erosion and sedimentation processes as the land is rising, which leads to a redistribution of the QD in the area that could change their stratigraphy and thickness. In Bosson et al. (2010) it was concluded that changing the QD model from that describing present conditions to models representing future QD conditions did not have a strong influence on the pattern of the recharge and discharge areas at Forsmark, although the magnitudes of hydraulic gradients could differ between the different models.

Besides the water movement simulations, particle tracking simulations were made for each of the three selected times. In the following sections, the water balances, the depths of overland water, the depths to the groundwater table, the recharge and discharge areas, and the results from the particle tracking simulations are discussed.

4.2.1 Water balance

Water balances for the three different times, 2000 AD, 5000 AD and 10,000 AD, were extracted and are shown in Figures 4-15 to 4-19. For all three simulations, water balances were extracted for the area constituting land at 2000 AD in order to see how the land area of today is affected by the shoreline displacement. For the model for 5000 AD an additional water balance was extracted for the area constituting land at 5000 AD, and for the model for 10,000 AD a water balance for the land constituting land at 10,000 AD was extracted as well. Table 4-3 shows the yearly mean values of the precipitation, evapotranspiration and total runoff for all cases.

Table 4-3. Yearly mean values of precipitation (P), total evapotranspiration (E), total runoff (R) and total storage change (S) in all water balances extracted from the SR-Site MIKE SHE results; all results are in mm/year.

Model year (shoreline)	Water balance extracted for	P	E	R	S
2000 AD	Land at 2000 AD	569	425	142	–2
5000 AD	Land at 2000 AD	569	436	135	–2
5000 AD	Land at 5000 AD	569	439	130	–2
10,000 AD	Land at 2000 AD	567	431	141	–3
10,000 AD	Land at 10,000 AD	566	435	134	–3

In the Forsmark SR-Site study, see Bosson et al. (2010), it was concluded that the variations in the overall water balance were small, although it was possible to see some patterns in the variations related to the distance to the shoreline. For the Laxemar SR-Site model, a comparison of the water balance results for the three models for the area constituting land at 2000 AD shows that the variations are similar to those found in Forsmark. For example, the drain outflow decreases from 91 mm at 2000 AD to 20 mm at 10,000 AD. In the same way, the saturated zone outflow increases from an 11 mm inflow at 2000 AD to approximately 20 mm outflow in the later models. This is because the sea area has moved from the present shoreline out to the shorelines of 5000 AD or 10,000 AD.

The reason for the decreased drain outflow is also the shoreline displacement. The drainage function implemented in the model is only active when the groundwater table rises above the drainage level, which is 1.0 m below ground for arable land and 0.35 m below ground for bedrock outcrops in the present model. The sea in the 2000 AD model causes relatively large areas along the coastline with groundwater levels close to or above ground, and consequently larger amounts of water handled via the drainage system. In the 5000 AD and 10,000 AD models the shoreline is far away from the area for which the water balance is evaluated, and therefore the amount of water leaving the model area via the drainage system decreases.

The detailed water balance results also show that the main changes occur when going from 2000 AD to 5000 AD, while the changes are small when going from 5000 AD to 10,000 AD. The main reason for this is probably that the main shoreline displacement takes place between 2000 AD and 5000 AD (see Figure 3-3), which, for example, causes changes in the depth to the groundwater table. The new land

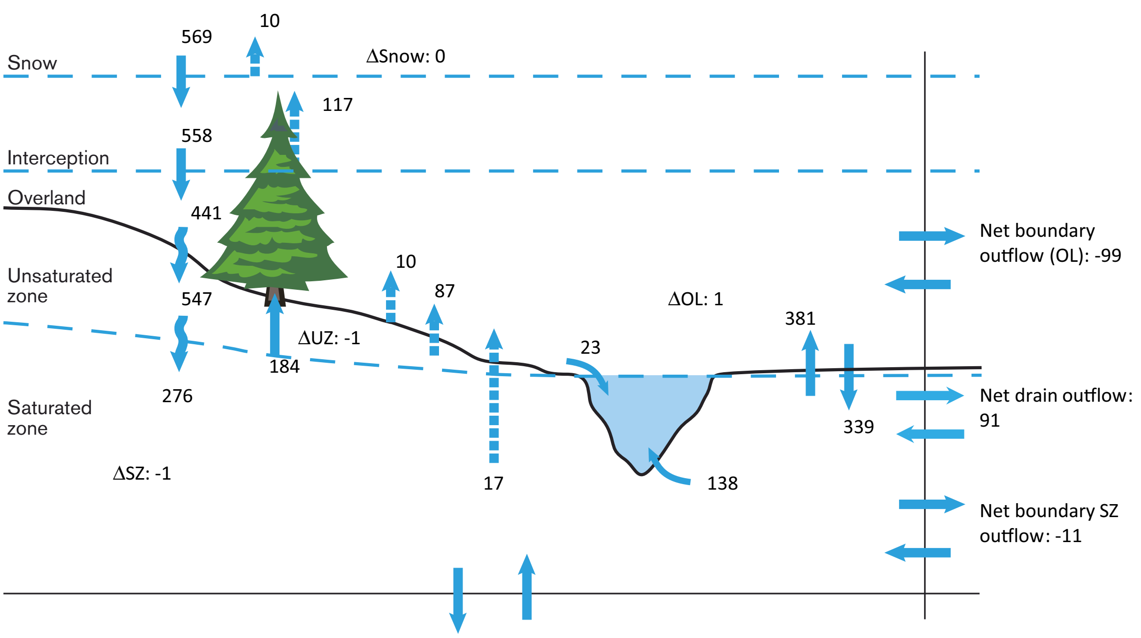

Figure 4-15. Water balance from the 2000 AD model extracted for the area constituting land at 2000 AD.

areas created by the shoreline displacement between 5000 AD and 10,000 AD are comparatively small. However, the changes in the overall water balance parameters are generally small, even when going from 2000 AD to 5000 AD; the total evapotranspiration increases by approximately 3% from present to future conditions, and the total runoff decreases by about 6%.

Furthermore, when comparing the water balances for the different land areas in the models for 5000 AD and 10,000 AD, it is seen that even though individual parameters increase or decrease slightly, the total runoff and evapotranspiration remain almost the same. For both 5000 AD and 10,000 AD, the total evapotranspiration is somewhat increased when looking at the entire land area instead of the 2000 AD land area, while the runoff is slightly decreased. However, the changes are very small, less than 5%.

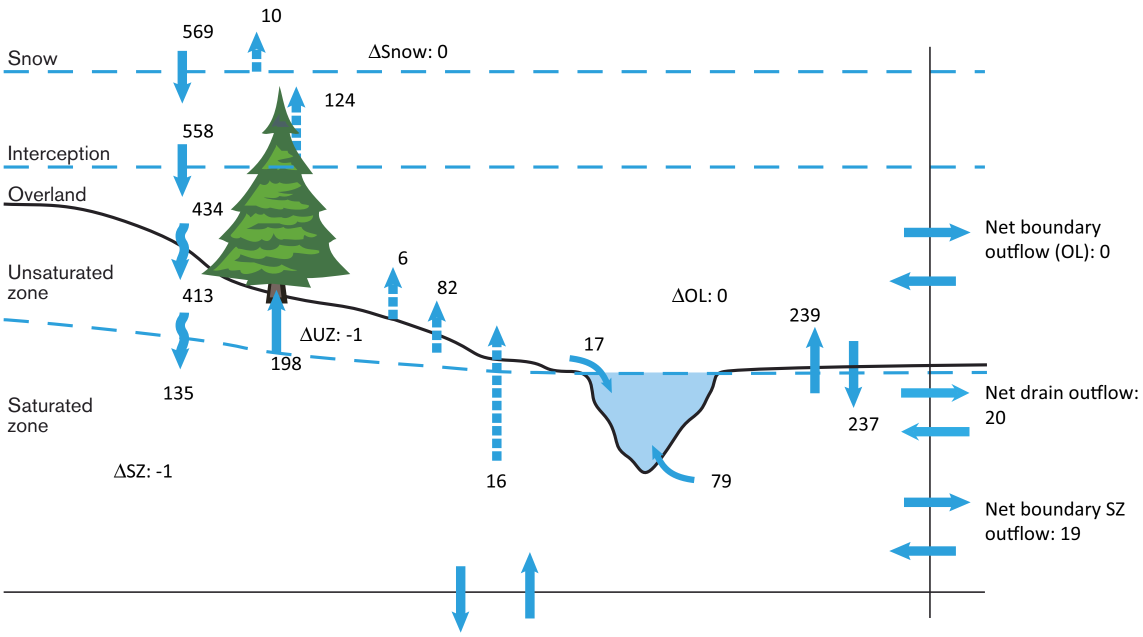

***Figure 4-16.** Water balance from the 5000 AD model extracted for the area constituting land at 2000 AD.*

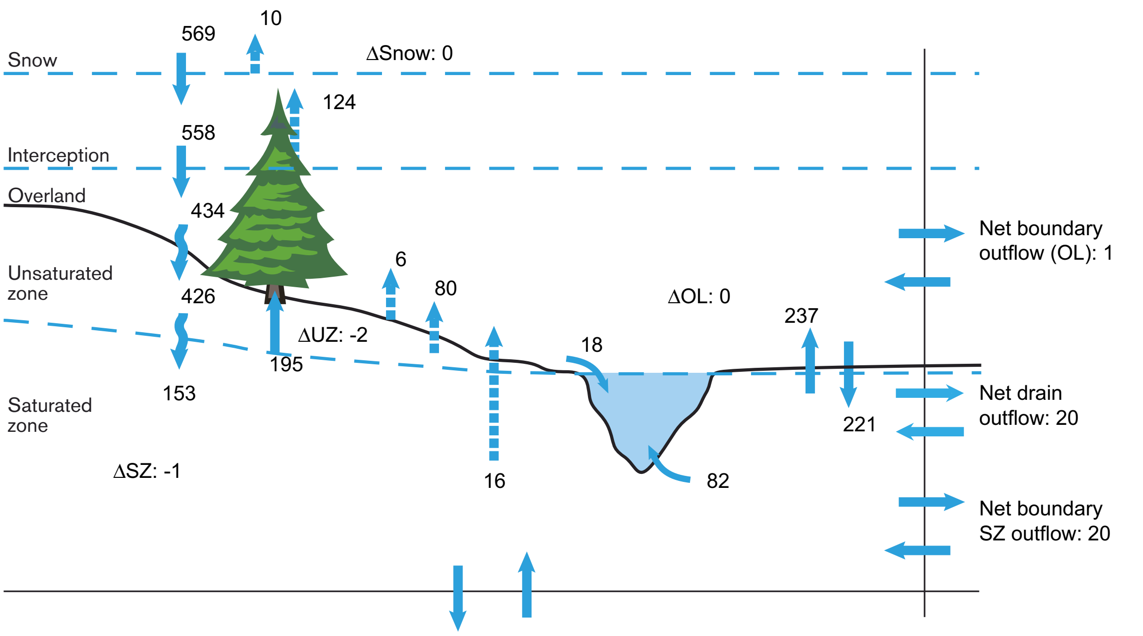

***Figure 4-17.** Water balance from the 10,000 AD model extracted for the area constituting land at 2000 AD.*

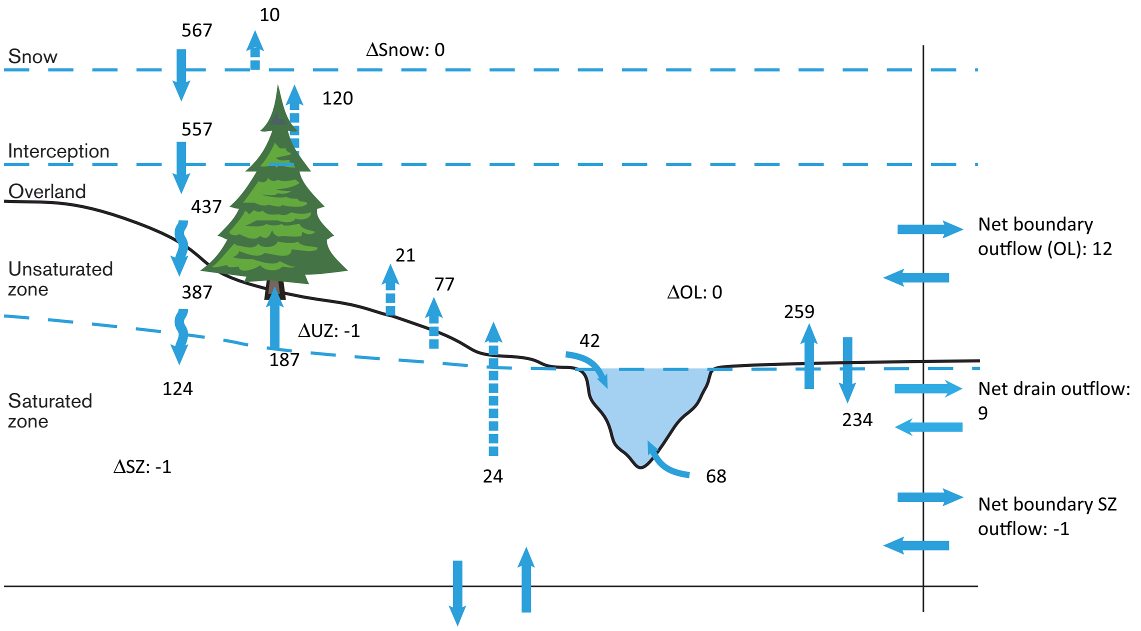

__Figure 4-18.__ Water balance from the 5000 AD model extracted for the area constituting land at 5000 AD.

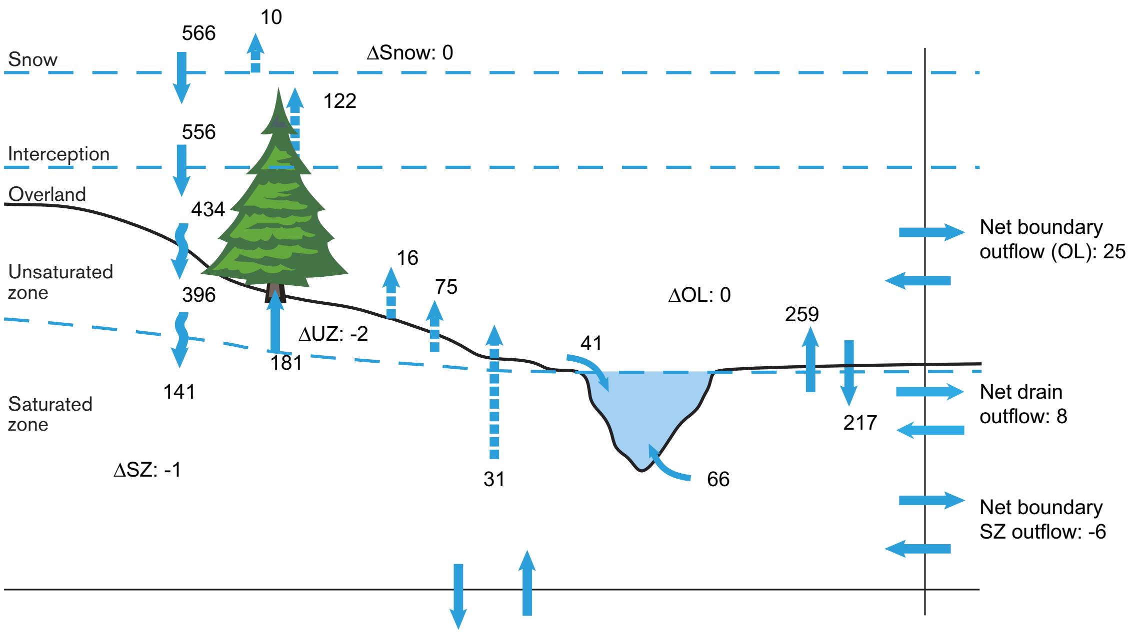

__Figure 4-19.__ Water balance from the 10,000 AD model extracted for the area constituting land at 10,000 AD.

4.2.2 Depth of overland water

The calculated depth of overland water is an indication of where future lakes and wetlands will build up. It is also a way to check that the model for present conditions is working as it should, i.e. that lakes and wetlands are formed and act as expected during periods of wet and dry weather conditions. Figures 4-20 to 4-23 show the depths of overland water under wet or dry conditions.

Figure 4-20 shows the depth of overland water in the 2000 AD model under wet conditions at the end of March. The area defined as sea in the model is white in the figure. In Figure 4-20, Lake

Frisksjön is clearly identified as an area with a water depth of more than two metres. Besides Lake Frisksjön, there are several small areas, represented by only a few grid cells, with water depths larger than one metre. The topography in the Laxemar area consists of both large and small valleys. In the model, the small valleys will occupy only a few cells; this gives the pattern seen in the figure.

Since the averaging of the topography is made for cells with a size of 80 m by 80 m, the differences in topography between adjacent cells may be rather large. In some cases, this may lead to cells having overland water in the model, while in reality the water is transported away naturally. During periods of dry weather conditions, see Figure 4-21, many of the small, wet areas disappear as they dry out.

Since the shoreline at 10,000 AD is situated close the shoreline at 5000 AD, the difference between the results for 10,000 AD and 5000 AD is very small. Therefore, only figures based on the results for the 10,000 AD model are presented here. Figure 4-22 shows the depth of overland water for the 10,000 AD model under wet conditions. A comparison with corresponding results for the 2000 AD model shows that the former two large sea armlets have been transformed into new lake areas.

Also along the former coastline in the southern part of the model domain some smaller lakes have developed. In the area constituting land at 2000 AD the differences between the models are small. Figure 4-23 also shows the depth of overland water at 10,000 AD, but during a period of dry conditions. The overall pattern is the same as for wet conditions, although some areas have dried out.

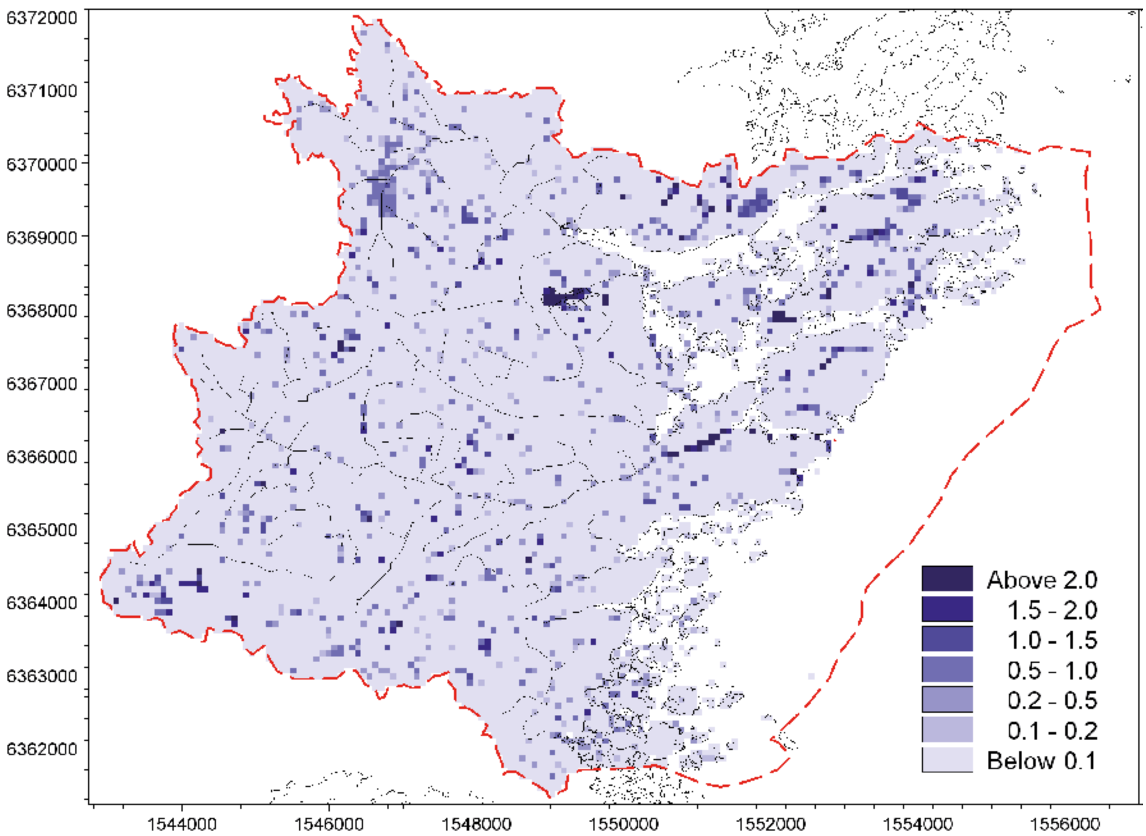

Figure 4-20. *Depth of overland water (metres) in the model representing 2000 AD during a period of wet conditions in March.*

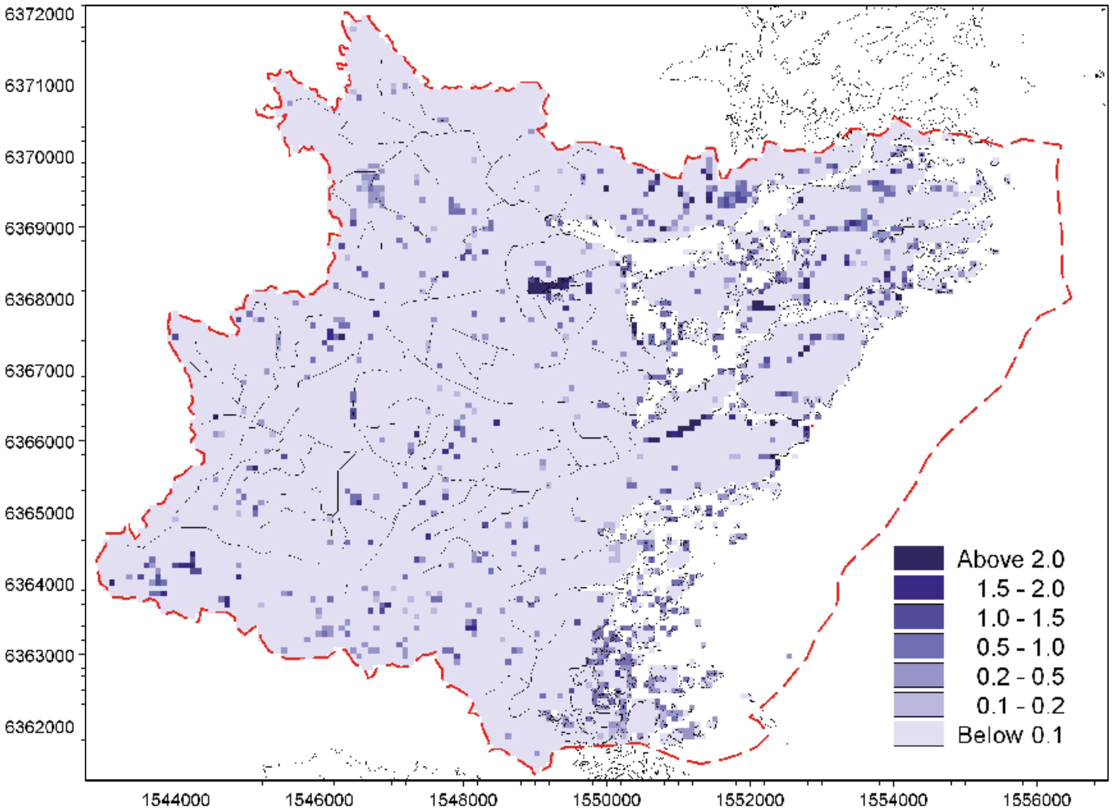

Figure 4-21. *Depth of overland water (metres) in the model representing 2000 AD during a period of dry conditions in September.*

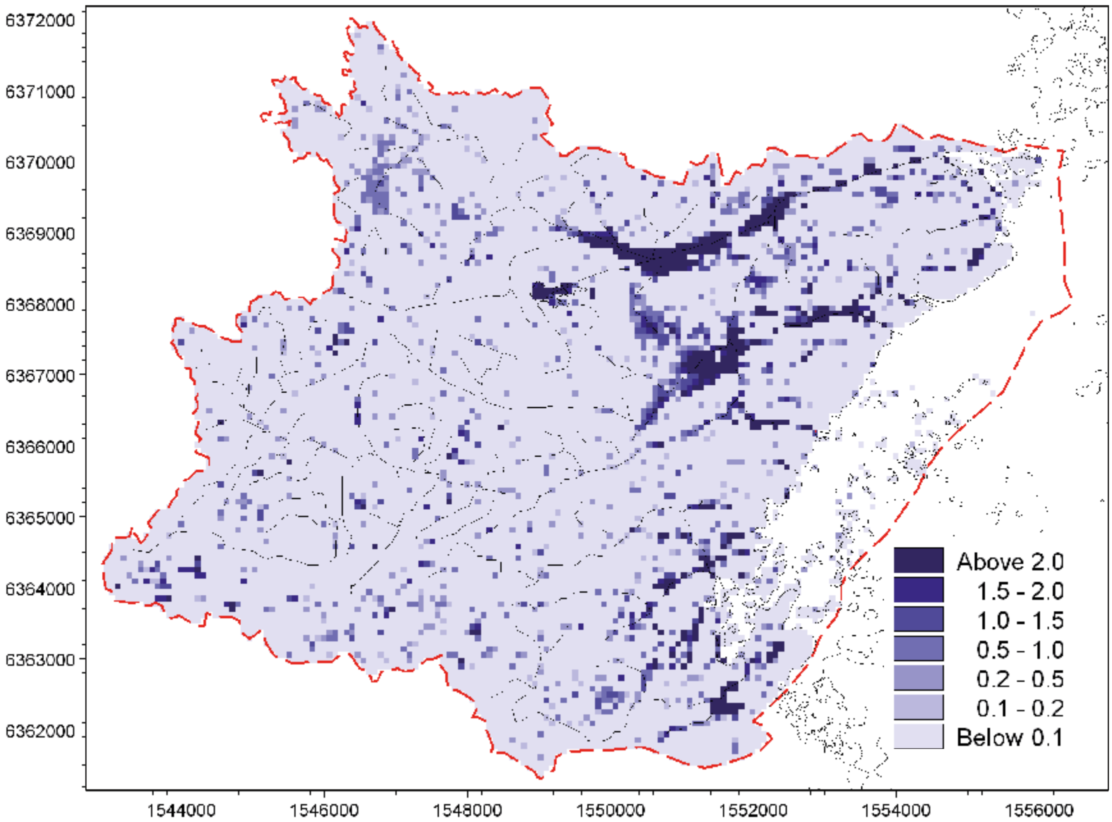

Figure 4-22. *Depth of overland water (metres) in the model representing 10,000 AD during a period of wet conditions in March.*

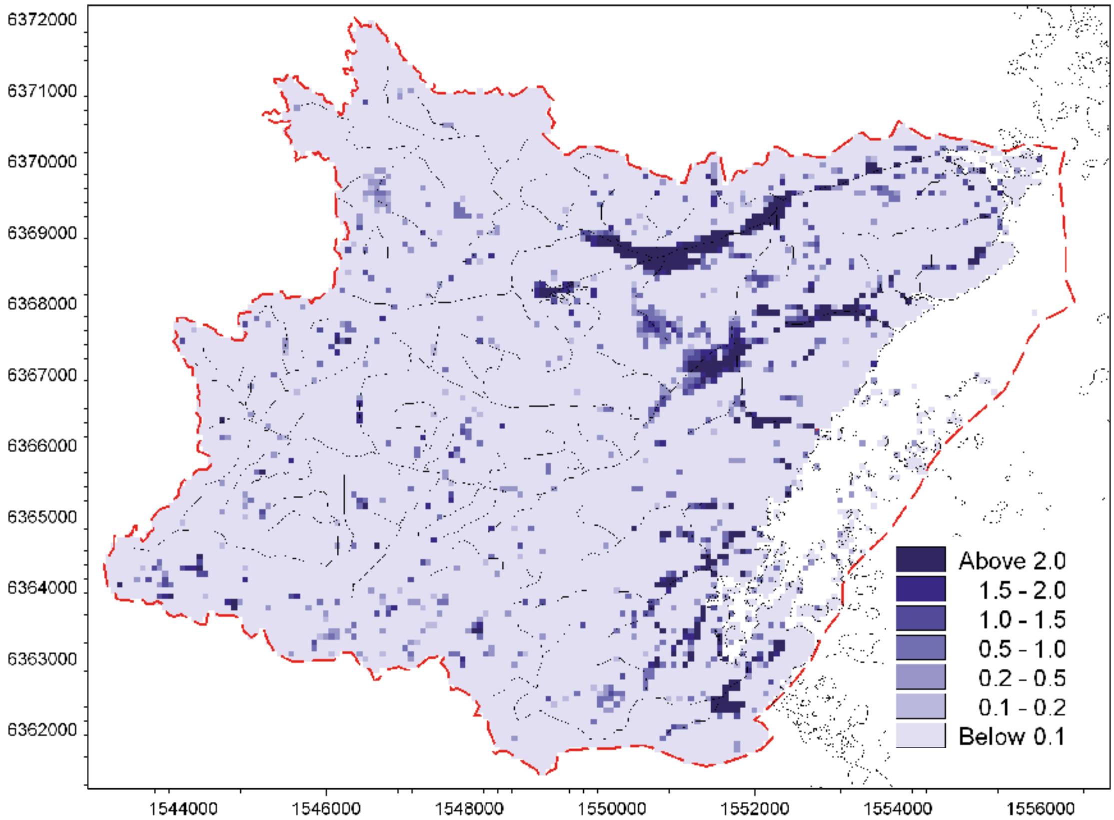

Figure 4-23. *Depth of overland water (metres) in the model representing 10,000 AD during a period of dry conditions in September.*

4.2.3 Groundwater table

In the SDM-Site MIKE SHE modelling (Bosson et al. 2009), it was concluded that the groundwater level in the stream valleys was close to the ground surface, whereas it was at considerably larger depths in the more elevated areas. In Figures 4-24 to 4-27, the results for the MIKE SHE SR-Site model are presented in term of the depth to the phreatic surface. For the 2000 AD simulation, Figure 4-24 shows the result for a wet period, and Figure 4-25 the result for a dry period. The figures show that there is a big difference in the depth to the phreatic surface between the wet and the dry periods. During a wet period the phreatic surface is shallow in most areas, whereas during the dry period the phreatic surface is very deep in some areas.

A comparison between the results in terms of depth to the phreatic surface for 5000 AD and 10,000 AD shows that the difference is very small, both for wet and dry conditions. As a consequence, only results from the 10,000 AD simulation are presented and shown in Figures 4-26 and 4-27. These figures show that the two former sea armlets in the 2000 AD model are cut off from the sea and instead become lakes in the 5000 AD and 10,000 AD models. Furthermore, the figures show that the area close to the sea shoreline is being flooded during the wet period.

Since all SR-Site MIKE SHE simulations for the Laxemar site are made with a QD model based on the conditions in 2000 AD, the differences between the 2000 AD and 10,000 AD models are very small in present land areas, see for example Figure 4-24 compared to Figure 4-26. In reality, the landscape will be affected by sedimentation and/or erosion processes, leading to changes in the surface topography and QD stratigraphy. This will lead to changes also in the depth to the phreatic surface. This is further discussed for Forsmark in Bosson et al. (2010).

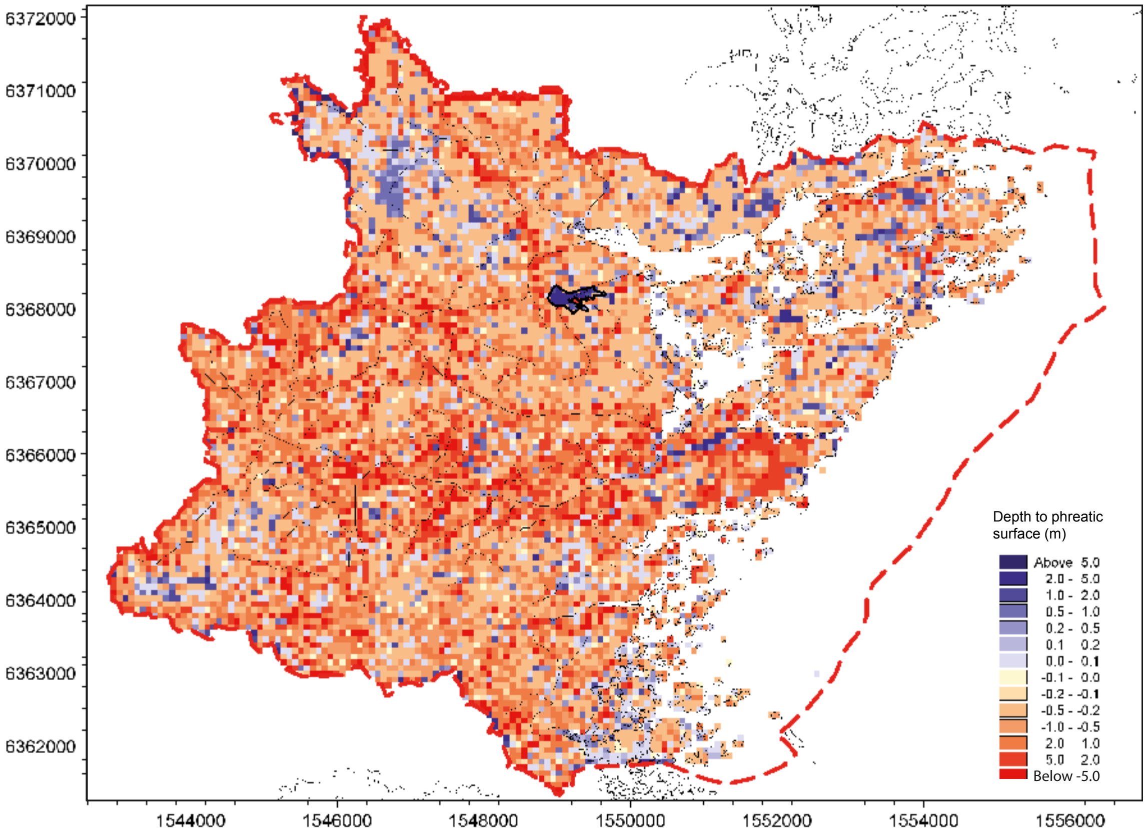

Figure 4-24. *Calculated depth to the phreatic surface under wet conditions in the 2000 AD model.*

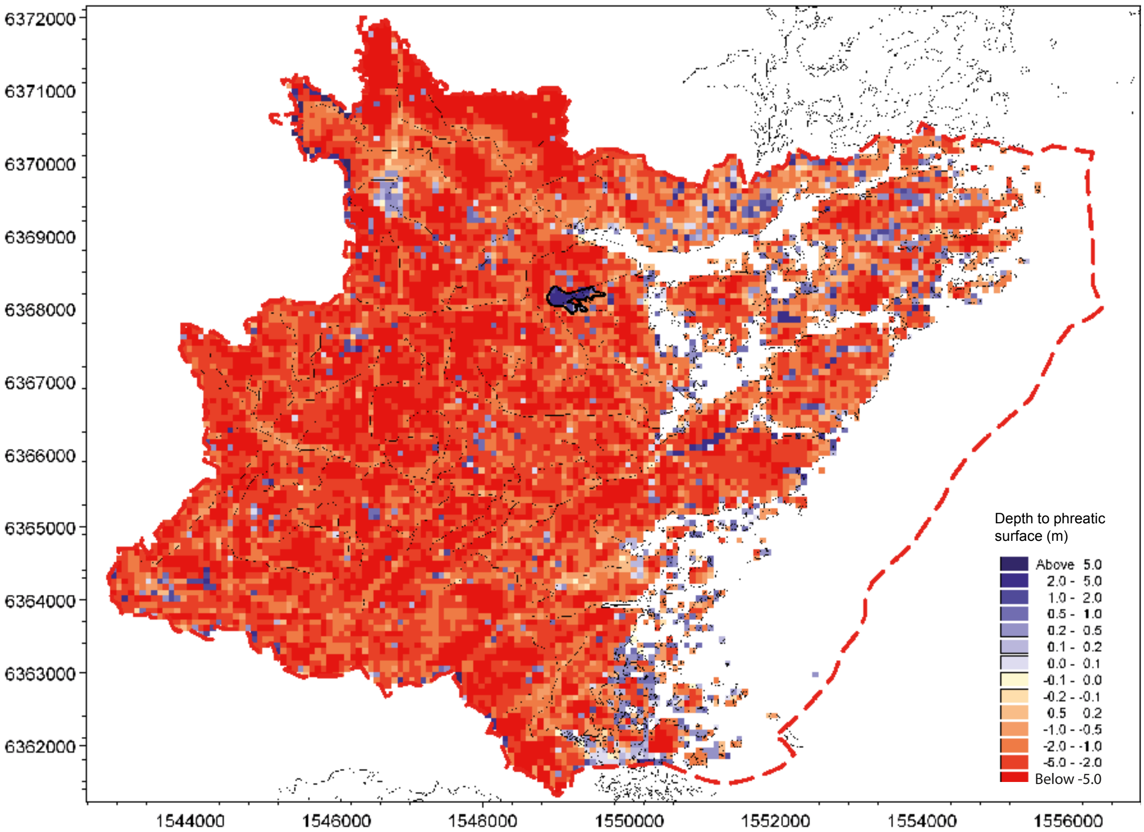

Figure 4-25. *Calculated depth to the phreatic surface under dry conditions in the 2000 AD model.*

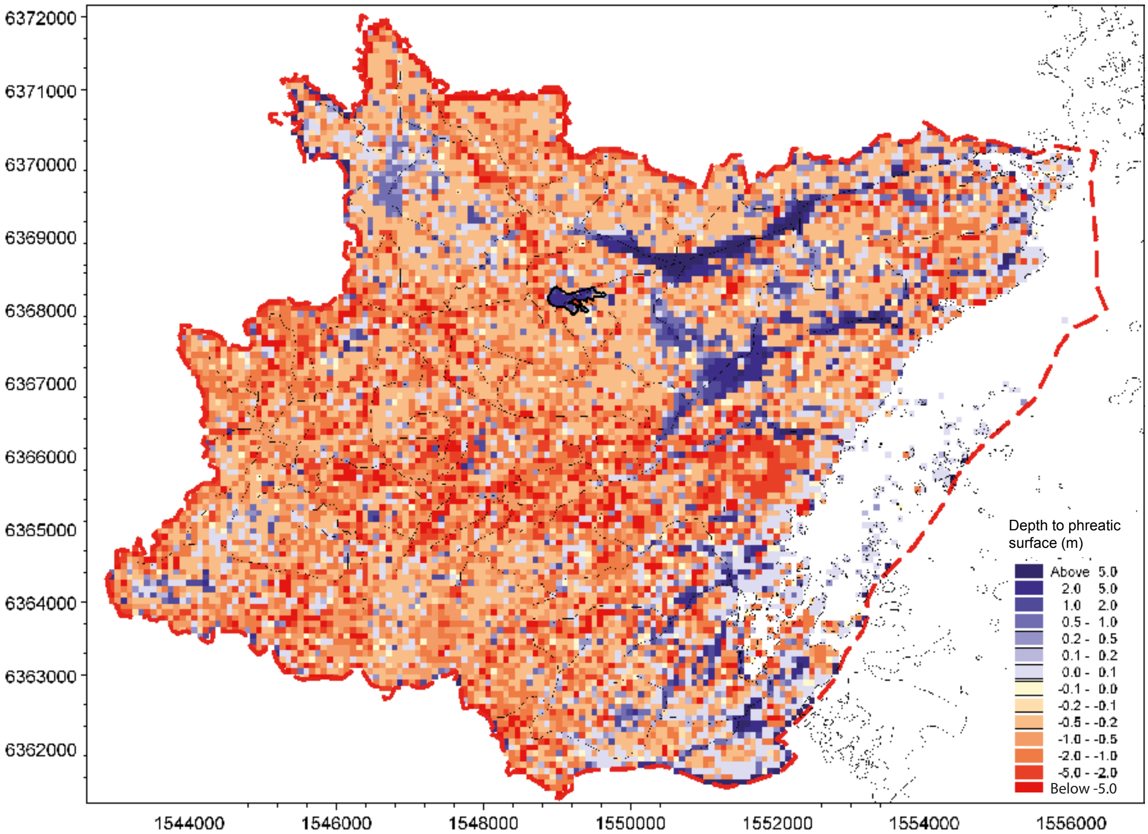

Figure 4-26. *Calculated depth to the phreatic surface under wet conditions in the 10,000 AD model.*

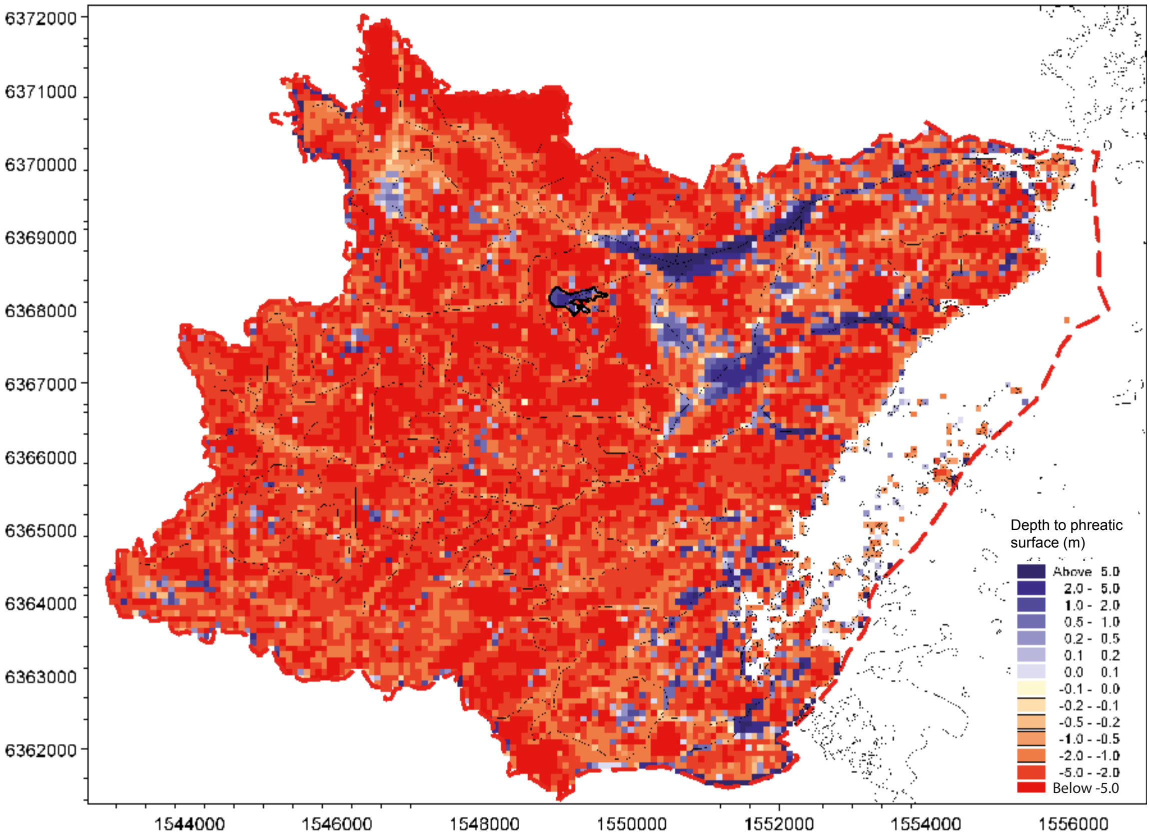

Figure 4-27. *Calculated depth to the phreatic surface under dry conditions in the 10,000 AD model.*

Figure 4-28 illustrates the cumulative frequency of the depth to the phreatic surface for the three models describing the conditions at 2000 AD, 5000 AD and 10,000 AD. All three curves are based on the same area, which is the area constituting land at 2000 AD. Furthermore, the curves are all based on the yearly mean depth to the phreatic surface during the last year of the simulation.

The figure shows that the difference between the three models is small. The largest difference is found when going from 2000 AD to 5000 AD. The reason is that the largest displacement of the shoreline takes place between 2000 AD and 5000 AD. The displacement between 5000 AD and 10,000 AD is very small, see Figure 3-3. For the 2000 AD model, the 50th percentile represents a depth of approximately 2.5 metres below ground, while for the 5000 AD and 10,000 AD models the 50th percentile corresponds to a depth to the groundwater table of c. 2.7 metres.

Figure 4-29 shows the cumulative frequency distributions of the depths to the groundwater table during wet and the dry periods in 2000 AD model. The blue line illustrates the frequency distribution under wet conditions and the red line under dry conditions. The effect of the subsurface drainage is seen clearly in the curve for wet conditions. In areas with bedrock outcrops, where the top soil layer is modelled as very thin but highly conductive, see Tables 2-4 and 2-5 in Bosson et al. (2009), the drainage depth is located at 0.35 meters below the ground surface.

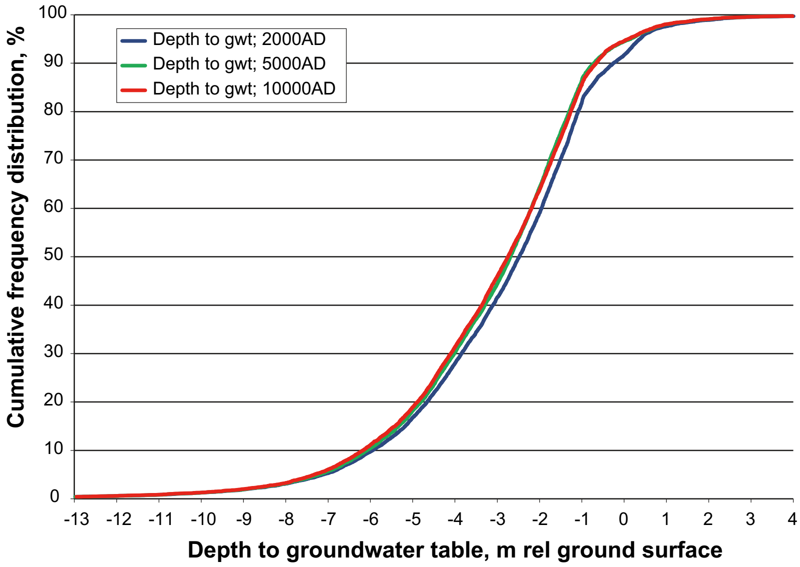

Figure 4-28. *Cumulative frequency of the depth to the phreatic surface for the models at 2000 AD, 5000 AD, and 10,000 AD. The curves are based on the annual mean values for the area constituting land at 2000 AD.*

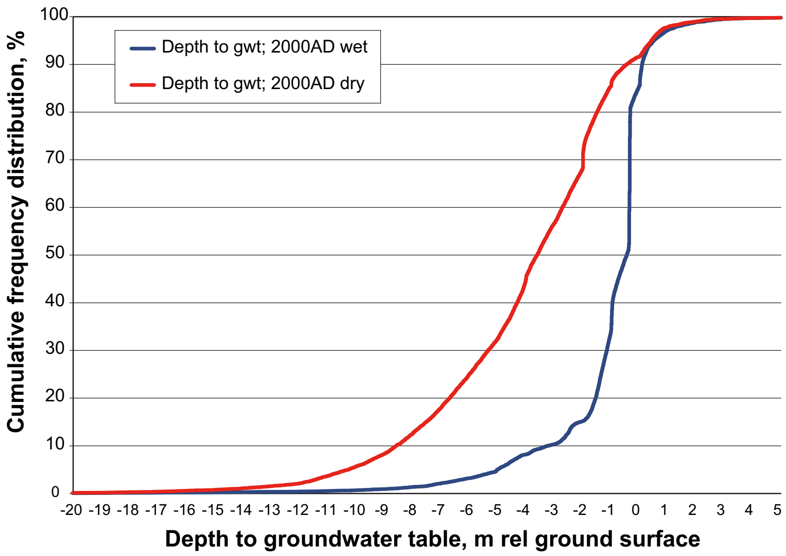

Figure 4-29. *Cumulative frequency for depth to phreatic surface under wet (blue line) and dry (red line) conditions in the 2000 AD model. The curves are based on the area constituting land at 2000 AD.*

In Figure 4-29, the gradient for the relative frequency is practically vertical at a depth of 0.35 meters below ground, implying that a lot of cells have a groundwater depth of 0.35 metres where the water then is transported away by drains. Furthermore, at the depth of one metre below the ground surface the drainage for the arable land is active, which is seen in the figure by another practically vertical gradient at that depth. Figure 4-29 also shows that there is a large difference in the depth to the groundwater level represented by the 50th percentile. For the wet case the 50th percentile is at a depth of approximately 0.5 metres, while for the dry case it is at 3.6 metres below ground. This means that the mean depth to the groundwater table is lowered more than 3 metres during a dry period.

4.2.4 Recharge and discharge areas

Recharge and discharge areas, i.e. areas of downward and upward groundwater flow, respectively, were estimated using the mean head difference between model layers 1 and 2 in the Quaternary deposits and between layers 5 and 6 in the bedrock; layers 5 and 6 correspond to an approximate depth of 50 meters below ground. Figures 4-30 to 4-33 show the results for the 2000 AD model and the 10,000 AD model. Since the results for the 5000 AD model are almost the same as those for the 10,000 AD model, results are not shown for the 5000 AD model. All figures are based on annual mean values of the head elevation.

Figure 4-30 shows the recharge and discharge areas in the Quaternary deposits in the 2000 AD model. The results are very similar to what was seen in the SDM-Site MIKE SHE model (Bosson et al. 2009). The discharge areas are located along the valleys where the surface streams are situated, while the recharge areas are located at the heights between the valleys. A comparison between the results for 2000 AD (Figures 4-30 and 4-31) and 10,000 AD (Figures 4-32 and 4-33) shows that no major differences occur in the present land areas. For the new land areas forming between 2000 AD and 10,000 AD the overall pattern is the same as for the present land areas.

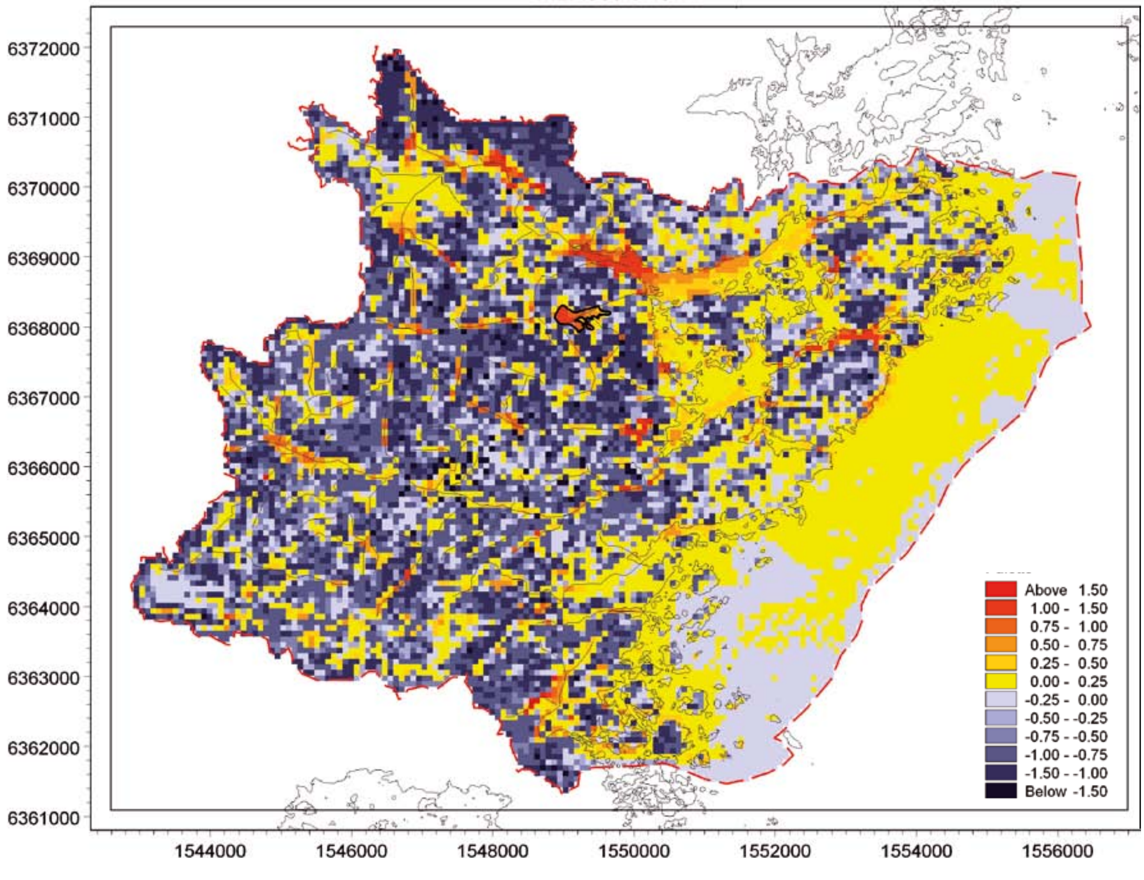

Figure 4-30. Mean head differences between calculation layers 1 and 2, i.e. recharge and discharge areas in the Quaternary deposits, in the SR-Site 2000 AD MIKE SHE model. Positive values indicate discharge conditions (upward flow).

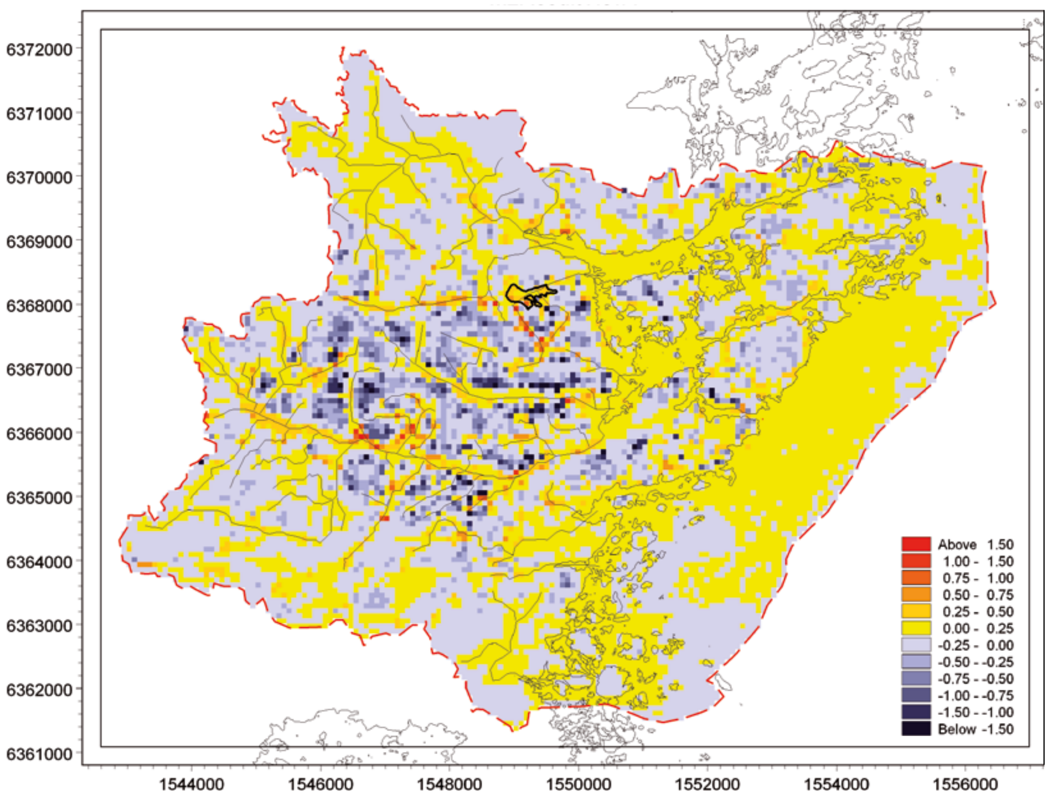

Figure 4-31. *Mean head differences between calculation layers 5 and 6, i.e. recharge and discharge areas in the upper bedrock, in the SR-Site 2000 AD MIKE SHE model. Positive values indicate discharge conditions (upward flow).*

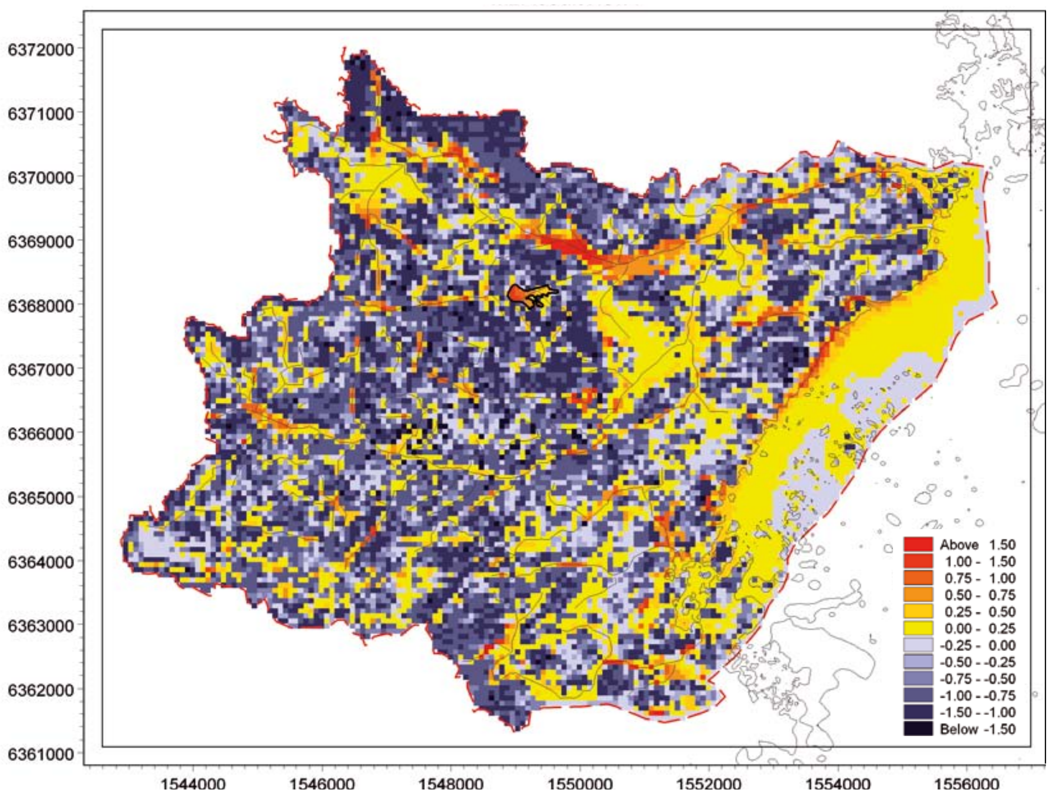

Figure 4-32. *Mean head differences between calculation layers 1 and 2, i.e. recharge and discharge areas in the Quaternary deposits, in the SR-Site 10,000 AD MIKE SHE model. Positive values indicate discharge conditions (upward flow).*

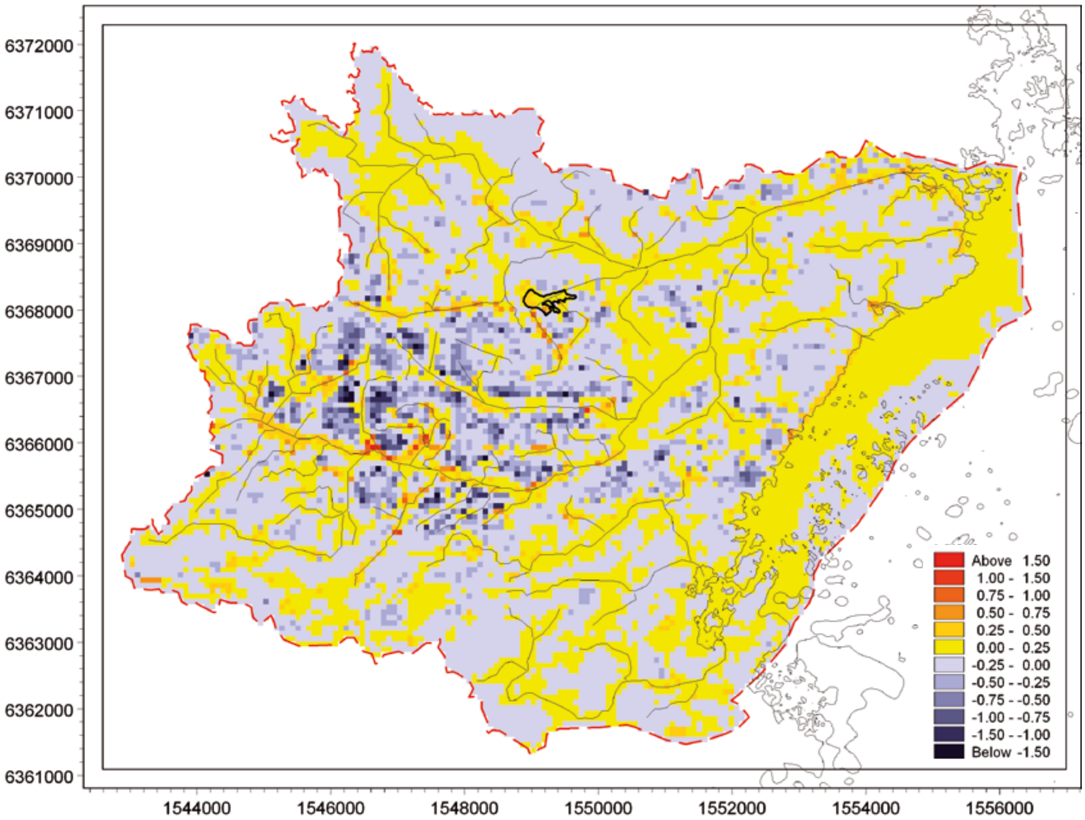

Figure 4-33. *Mean head differences between calculation layers 5 and 6, i.e. recharge and discharge areas in the upper bedrock, in the SR-Site 10,000 AD MIKE SHE model. Positive values indicate discharge conditions (upward flow).*

Table 4-4 shows the fractions of the MIKE SHE model area with upward and downward gradients during dry and wet weather conditions for the three different models representing the years 2000 AD, 5000 AD and 10,000 AD. The calculation of recharge and discharge fractions is made for the land part of the model area only, i.e. the sea area is excluded.

The table shows that the fractions do not change significantly over time. In the QD layers, there is an upward gradient during the dry period in approximately 25–30% of the model area, and consequently a downward gradient in 70–75% of the area. The upward gradient fraction decreases somewhat from 2000 AD to later times, but only with a few percent. During the wet period, there is an upward gradient in the QD layers in 1/3 of the land area and consequently a downward gradient in 2/3 of the land area. These proportions are more or less the same for all the models.

Table 4-4. Fractions (%) of the land parts of the MIKE SHE model areas with upward or downward gradients under wet and dry weather conditions.

	Dry period		Wet period	
	Upward gradient (%)	Downward gradient (%)	Upward gradient (%)	Downward gradient (%)
QD				
2000 AD	28	72	33	67
5000 AD	25	75	34	66
10,000 AD	25	75	34	66
Bedrock				
2000 AD	42	58	41	59
5000 AD	42	58	42	58
10,000 AD	41	59	42	58

In the bedrock, the area with an upward gradient is just above 40% of the total land area, under both wet and dry conditions. This fraction is relatively constant over time. Thus, the fraction of areas with downward gradients is just below 60% at all times and for both wet and dry weather conditions.

4.2.5 Particle tracking

For each of the three different models, i.e. for the 2000 AD, 5000 AD and 10,000 AD shoreline locations, a simulation with the MIKE SHE particle tracking (PT) module was made. In all simulations the source was introduced at c. 150 m.b.s.l. and with one particle in each grid cell. Table 4-5 shows a summary of the sinks for the introduced particles for each of the three simulations. The results in the table are all given in percent of the total number of introduced particles. All PT simulations were run for 5,000 years.

Table 4-5. Summary of different sinks for particles in the three PT simulations.

	2000 AD	5000 AD	10,000 AD
Particles left in the model, %	24	18	14
Particles gone to streams, %	29	29	29
Particles gone to boundary, %	3	2	2
Particles gone to overland water or the unsaturated zone, %	28	38	42
Particles gone to the sea, %	16	14	13

In the same way as was seen in the Forsmark SR-Site study (Bosson et al. 2010), the amount of particles that are left in the model domain after the simulation period decreases for the models representing 5000 AD and 10,000 AD. The reason is that the part of the model domain that consists of sea decreases with time. At 2000 AD approximately 25% of the model domain is covered by sea, at 5000 AD c. 16% and at 10,000 AD c. 11% is sea. The low gradients below the sea cause very low flow velocities and as a consequence many of the particles released below the sea remain in the model at the end of the simulation.

Figure 4-34 shows how the number of particles in the model decreased with time for the three model simulations. The figure shows that the decrease is more rapid for the 10,000 AD simulation, which is due to that the sea part of the domain is smaller at that time. Figure 4-34 also shows that about 2/3 of the introduced particles leave the model domain within the first 200 years. After 500 years more than 80% of the introduced particles in the 10,000 AD simulation have left the model. The corresponding number for the 5000 AD simulation is more than 75%, and for the 2000 AD simulation more than 70%. After 500 years of simulation, the decrease in number of particles remaining in the model domain is small.

Figures 4-35 to 4-40 show the exit points and end locations of the introduced particles in the simulations with the 2000 AD, 5000 AD and 10,000 AD models. Exit points are the positions where the particles left the model domain, while end locations are the positions at the end of the simulation of the particles still left in the model volume. Figure 4-35 shows the exit points of the particles introduced in the 2000 AD model. In the figure, it is seen that the exit points are located along the surface streams, in the lake areas and along the coastline.

Figure 4-36 shows the end locations of the particles still within the model domain for the 2000 AD model after 5,000 years of simulation. The particles were introduced at a depth of c. 150 m. Red and yellow dots show particles that have been transported downwards and are at locations below the level where they started at the end of the simulation. The end locations that are below the level of introduction are mainly located under the sea, but also in some of the recharge areas on land. Blue dots are particles that have been transported upwards, but have not yet reached the surface.

Figure 4-37 shows the exit points for particles released in the 5000 AD model. The pattern of the exit points is very similar to what was seen for the 2000 AD model (Figure 4-35). The main difference is in connection to the shoreline, which in the 5000 AD model is located further to the east than in the 2000 AD model. As a consequence of shoreline displacement, the 5000 AD model has surface streams located in areas covered by the sea in the 2000 AD model, and the particles are concentrated to these surface streams.

Figure 4-38 shows the end locations after 5,000 years of simulation for particles released in the 5000 AD model. Also for the end locations, the pattern is very similar to the results from the 2000 AD model (see Figure 4-36). In the land part of the model area, there are only a few small differences between the results. Since the area covered by the sea is smaller in the 5000 AD model than in that for 2000 AD, there are fewer particles remaining under the sea area at the end of the simulation.

Figure 4-39 shows the exit points in the 10,000 AD model. The results are very similar to those of the 5000 AD model, see Figure 4-37. Only in connection to the sea a few differences can be noted. Figure 4-40 shows the end locations after 5,000 years of simulation with the 10,000 AD model. The results are very similar to the results for both the 2000 AD and 5000 AD models, although there are a few differences along the shoreline. Since the sea area is smaller in the 10,000 AD model, there are even fewer particles remaining under the sea at the end of the simulation.

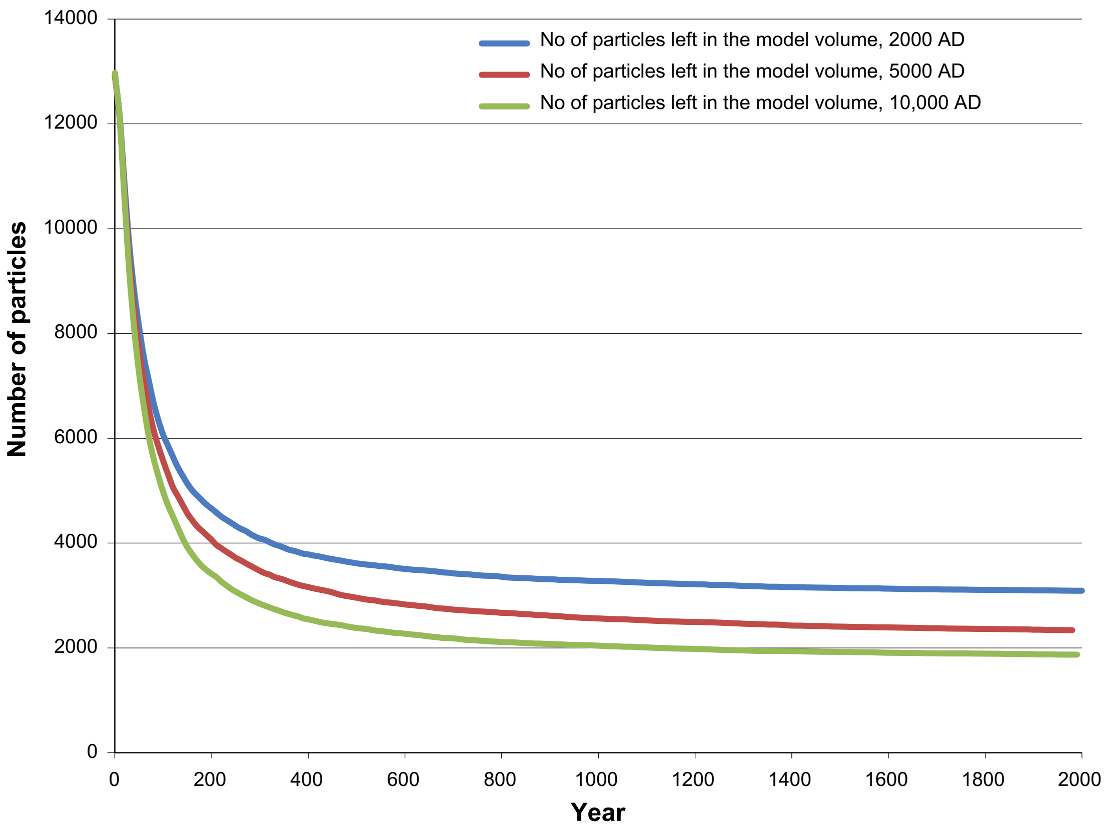

Figure 4-34. *Number of particles left in the model as a function of time for all three models (2000 AD, 5000 AD and 10,000 AD). In total, approximately 13,000 particles were introduced in each model.*

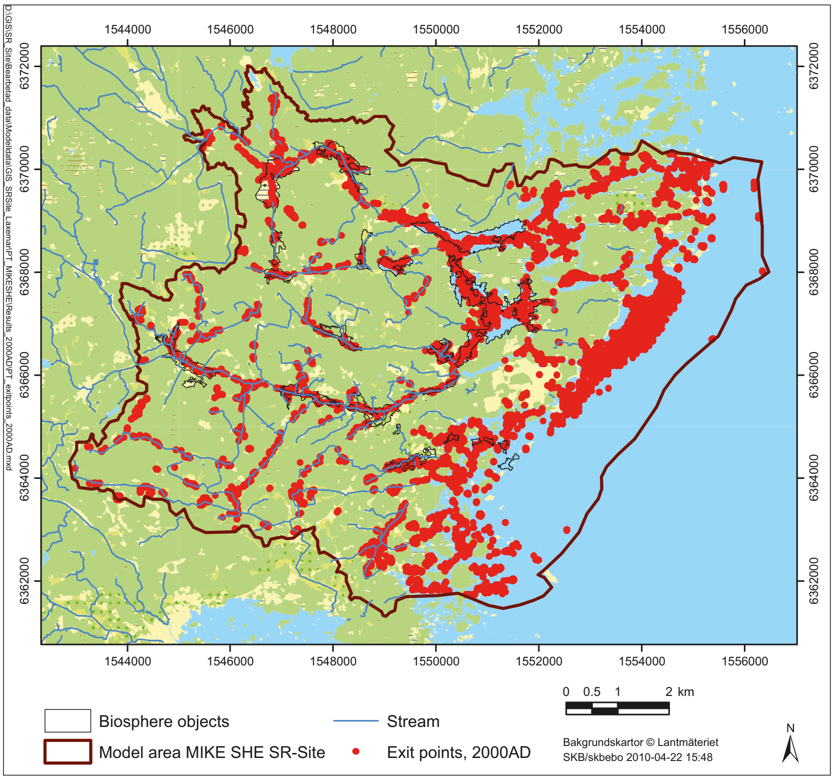

***Figure 4-35.** Exit points of particles recorded in a 5,000-year particle tracking simulation with the 2000 AD model.*

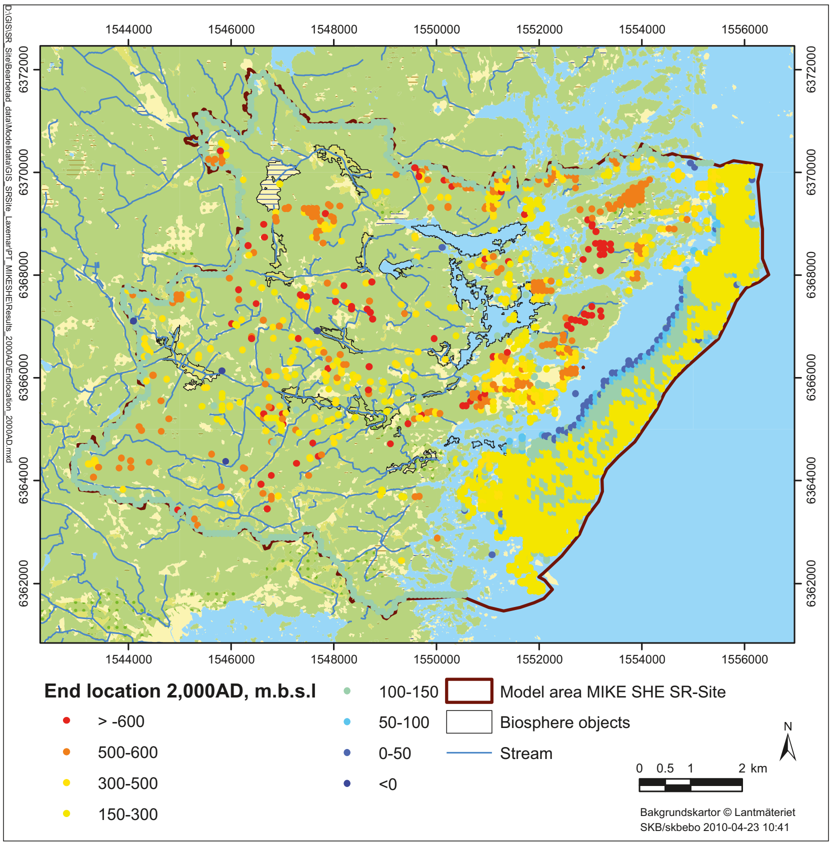

***Figure 4-36.** End locations of particles left in the model after 5,000 years of simulation with the 2000 AD model.*

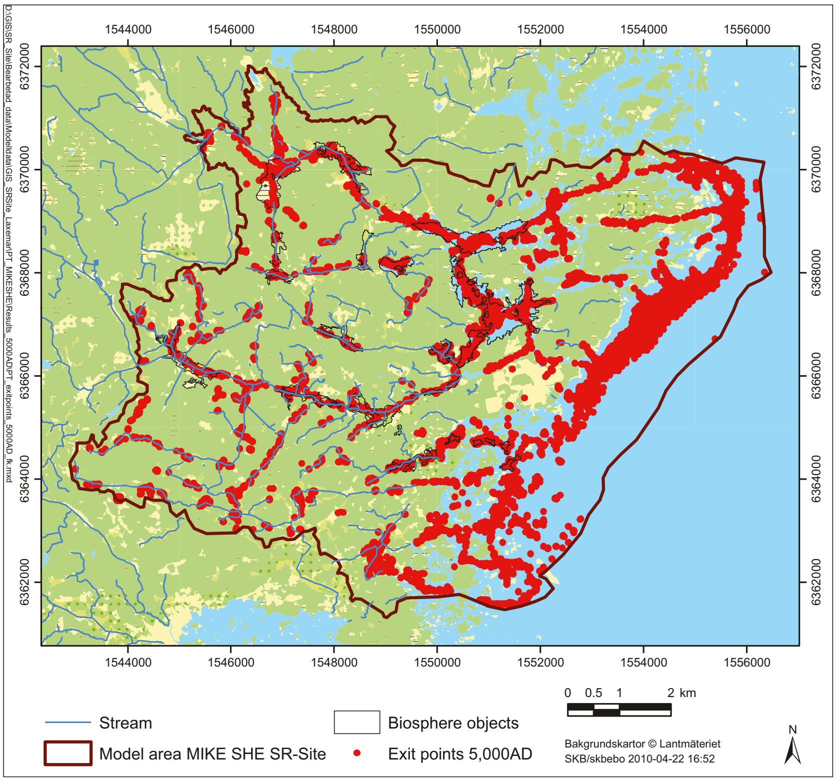

Figure 4-37. Exit points of particles recorded in a 5,000-year particle tracking simulation with the 5000 AD model.

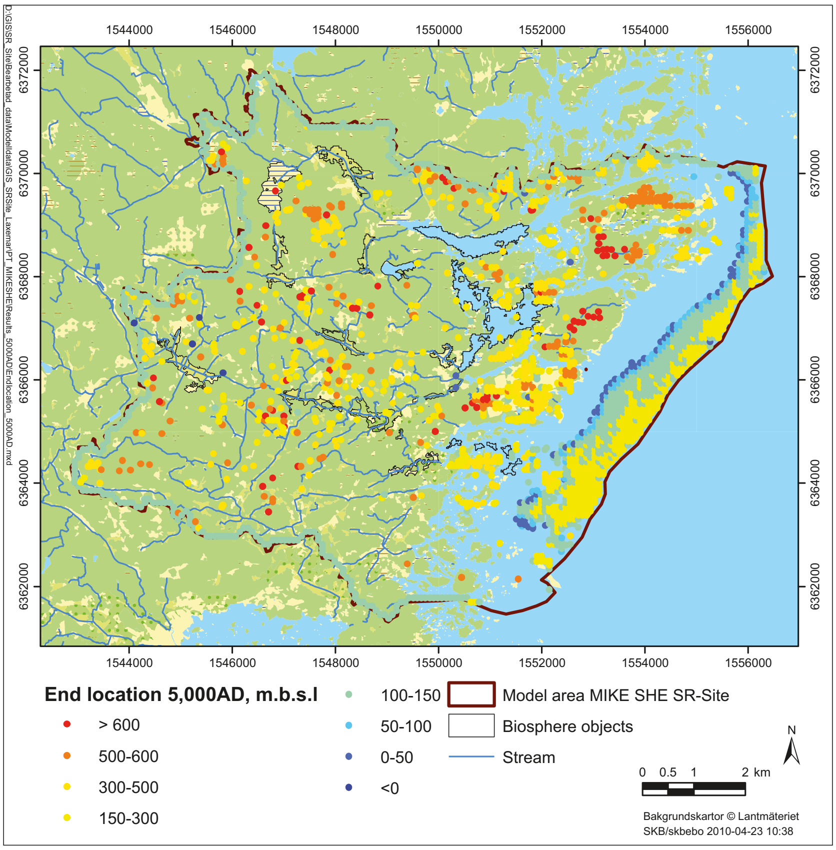

Figure 4-38. End location of particles left in the model after 5,000 years of simulation with the 5000 AD model.

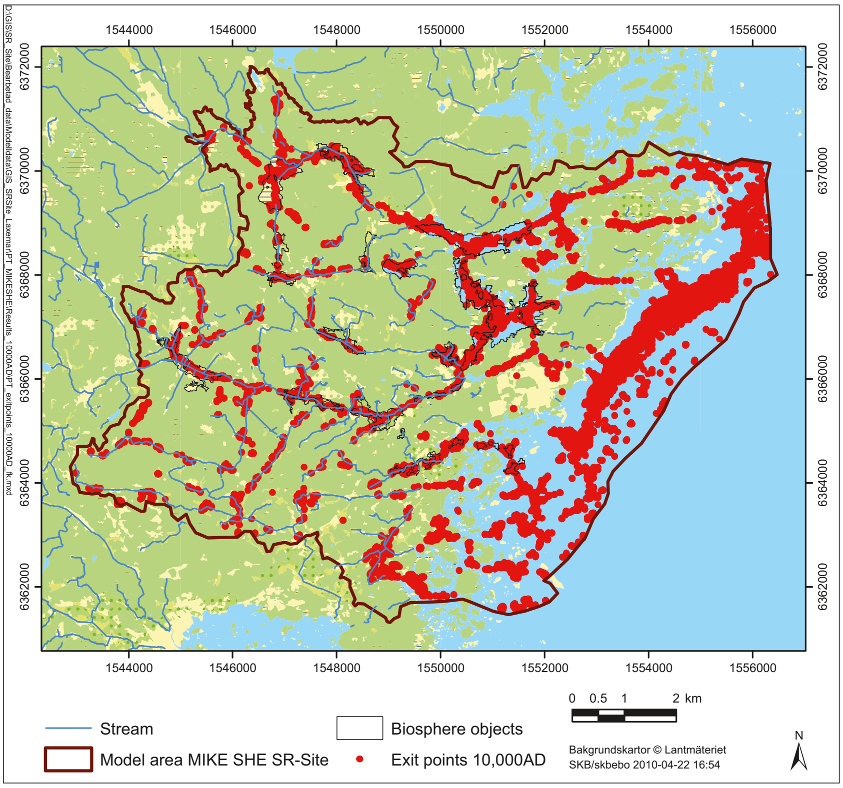

Figure 4-39. *Exit points of particles recorded in a 5,000-year particle tracking simulation with the 10,000 AD model.*

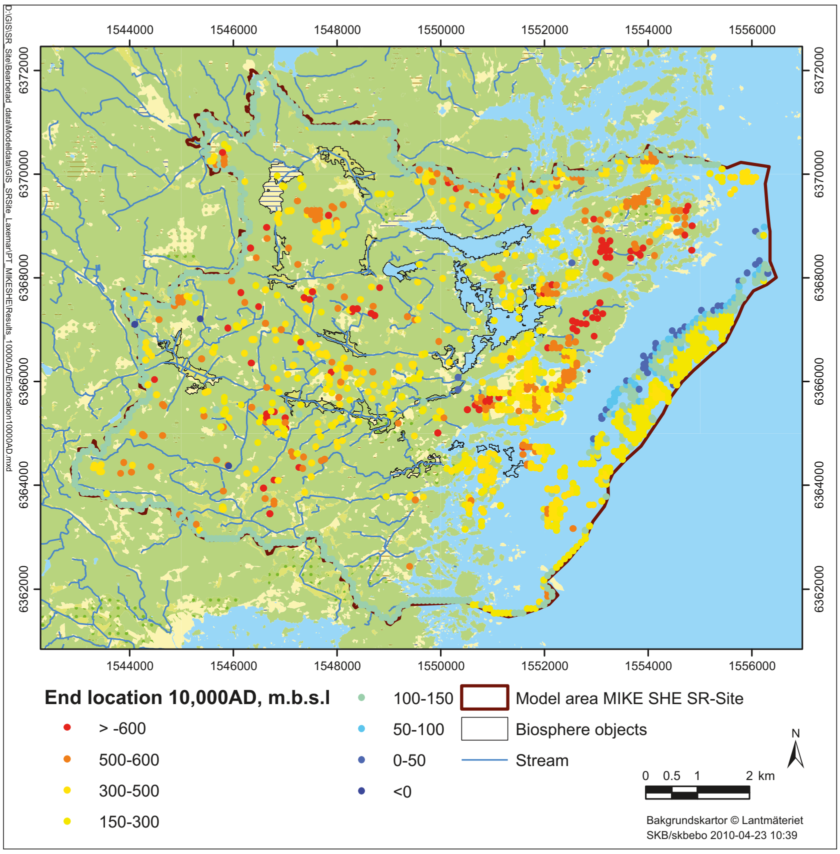

Figure 4-40. *End locations of particles left in the model after 5,000 years of simulation with the 10,000 AD model.*

4.3 Delivery of MIKE SHE results to dose calculations

In the same way as for SR-Site Forsmark, see Bosson et al. (2010), results were extracted from the MIKE SHE model for Laxemar and delivered to be used for radionuclide transport and dose calculations performed with the Pandora model. The radionuclide calculations for Laxemar are summarised in SKB (2010a) and a more detailed description of the method for extracting MIKE SHE model results is given in Bosson et al. (2010, Chapter 8). In this section, a short description of the results extracted for Laxemar is presented.

For Laxemar, results were extracted from the 10,000 AD model. In total, 17 landscape objects were identified and described in the Laxemar landscape model, and 10 of those were used when calculating the Laxemar landscape dose conversion factors (LDFs); for more details on the LDF calculations, see SKB (2010a). Of the 10 objects, 3 are lake objects and water balance data were extracted from the SR-Site MIKE SHE model for parameterisation of these objects, see Figure 4-41. The three objects are referred to as object 201 (Inre Granholmsfjärden), object 207 (Frisksjön) and object 208 (Borholmsfjärden) in the landscape model.

Lake areas were defined as areas with a yearly mean depth of overland water larger than or equal to 0.5 meters. The lake areas are completely surrounded by mires. For all three lake objects, extractions of layer thicknesses, porosities, hydraulic conductivities and sizes of the areas were made, and the resulting data were delivered to the radionuclide modelling.

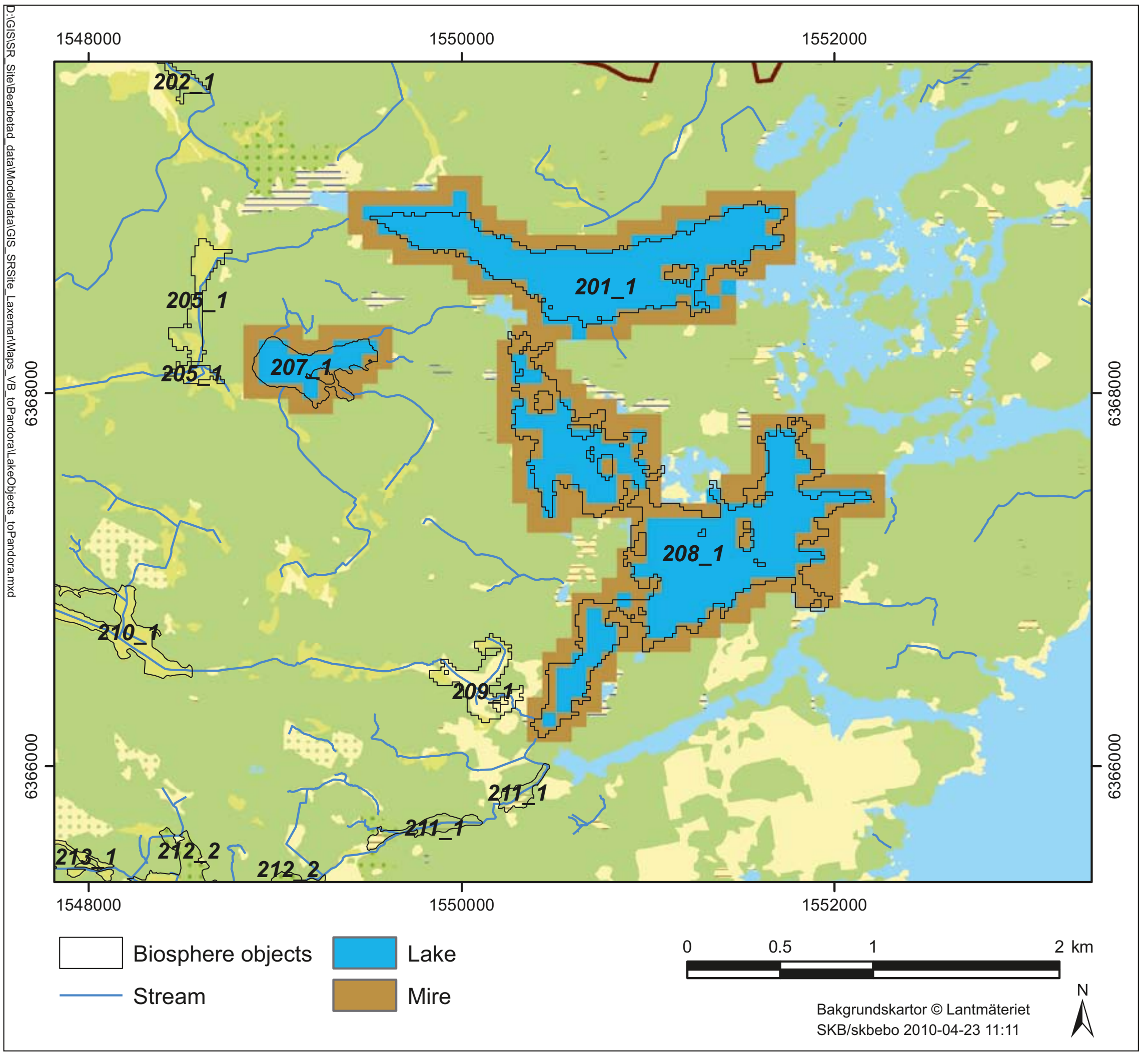

Figure 4-41. *Locations and extents of the three biosphere objects for which MIKE SHE results were extracted and delivered to the radionuclide transport and dose calculations.*

Based on the modelling results for the three lake objects, mean values of flow components were calculated. Figure 4-42 shows the mean values obtained from the water balances. In the figure, all parameter names starting with "Aqu_" refer to the lake area in the MIKE SHE model. All names starting with "Ter_" refer to the MIKE SHE mire areas. The name "_regoLow" corresponds to calculation layer L2 in MIKE SHE, and the name "_regoMid" to the MIKE SHE calculation layer L1. The "_Water" name corresponds to the MIKE SHE overland water compartment. The terminology is the same as in the SR-Site modelling of Forsmark, and a more detailed description of the parameters illustrated in the figure is given in Bosson et al. (2010, Chapter 8).

A comparison between the results for the Forsmark site (Bosson et al. 2010, Figure 8-5) and the Laxemar results (Figure 4-42) shows several differences. However, although the magnitudes of the various flow components show some differences, almost all net fluxes have the same directions in Laxemar as was seen in Forsmark. The only net flux that differs from Forsmark is the horizontal exchange between the Ter_regoLow and the Aqu_regoLow, where in Laxemar the net flux is towards the lake area while in Forsmark it has the opposite direction. However, the net flux for this exchange is small in both cases.

The upward flux from the bedrock towards the lake areas is much larger for the three objects studied in the analysis of the Laxemar area than for the objects considered in the Forsmark area. In Forsmark, the main flux was released to the mire area, while in Laxemar the main flux is directed towards the lake part of the biosphere object. The biosphere objects included in the Laxemar study are much stronger discharge areas than the objects in Forsmark, see Figures 4-32 and 4-33, which is consistent with the more pronounced topographic variations in Laxemar. Figure 4-33 shows that all the objects have upward flow in the bedrock. Figure 4-32 shows that both object 201 and object 207 are strong discharge areas in the QD layers, not only close to the lake shorelines but across the whole lake areas. Also object 208 has discharge conditions (upward flow) in the QD layers, although with stronger discharge areas along the lake shoreline.

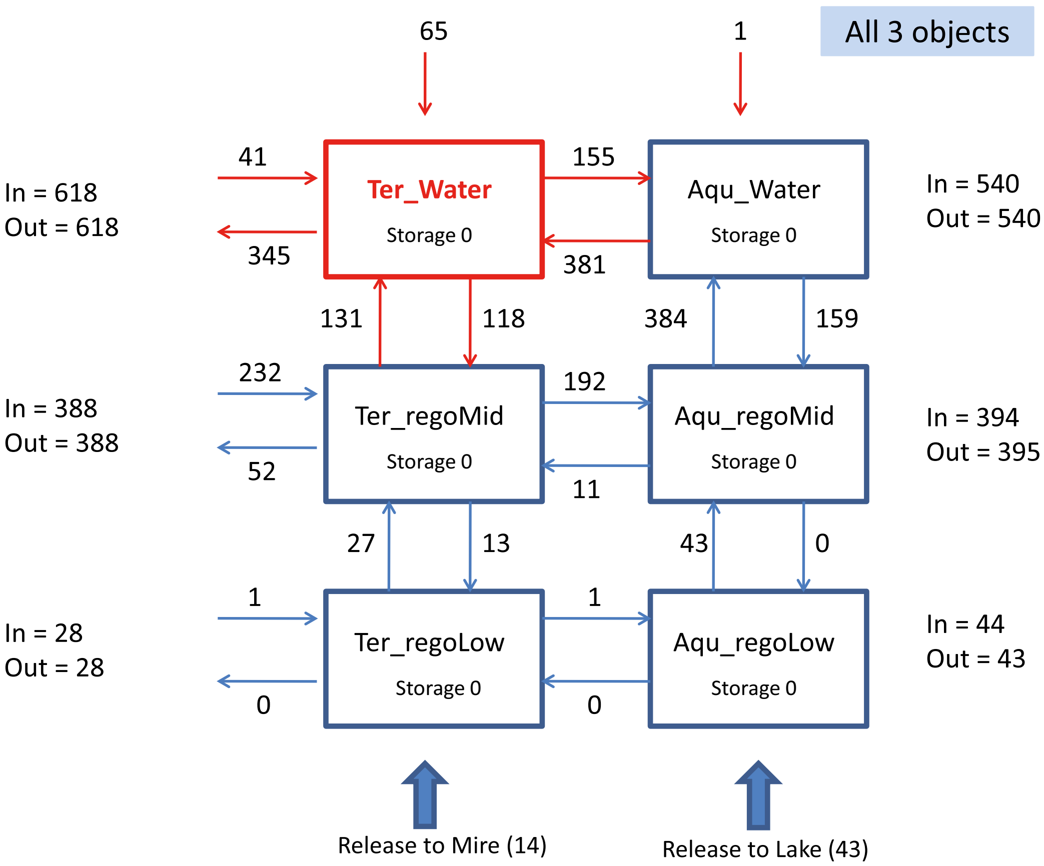

Figure 4-42. *Mean values of flow components in lake-mire biosphere objects in the Laxemar landscape model delivered to the radionuclide transport and dose calculations. Detailed information about the parameter names is found in Bosson et al. (2010).*

5 Discussion and conclusions

The numerical MIKE SHE model used in the Laxemar SDM-Site study, see Bosson et al. (2009), was used as the basis for the model development describing present and future conditions in the present Laxemar SR-Site study. The main changes compared to the SDM-Site MIKE SHE model were the extended model area and the reduced spatial resolution (i.e. increased cell size in the numerical model grid). The general objective of the SR-Site MIKE SHE modelling of Laxemar was to study the surface hydrology and near-surface hydrogeology for present and future conditions. Models were created for describing the hydrological conditions at 2000 AD, 5000 AD and 10,000 AD. The main difference between the models was the different locations of the coastline, which are due to the on-going shoreline displacement at the site, and the associated differences in the proportions of land and sea within the model area.

When comparing the results from the SDM-Site and SR-Site MIKE SHE models, it was found that the change in horizontal grid cell size from 40 m to 80 m did not result in large changes in mean groundwater levels, surface water levels or surface water discharges. Although some of monitoring points showed MAE values (quantifying the deviations from measured values) that differed significantly between the SDM-Site and SR-Site MIKE SHE models, the mean values for all points were quite similar. The mean MAE for monitoring points in the QD layers was 0.55 m for the SDM-Site model and 0.50 m for the SR-Site model. For the monitoring points in the bedrock, the mean MAE increased slightly, from 0.78 m for the SDM-Site model to 0.89 m for the SR-Site model. Furthermore, a comparison between surface water discharges in the SDM-Site and SR-Site MIKE SHE models showed very small differences.

A comparison between the water balances extracted from the three different SR-Site models, i.e. the 2000 AD, 5000 AD and 10,000 AD models, shows that the variation in the overall water balance is small, although individual parameters change. The total runoff and the total evapotranspiration remain almost the same; the changes are within 10% regardless of the time or the land area studied. In general, the main changes occur when going from 2000 AD to 5000 AD, because during this time the shoreline is displaced more than when going from 5000 AD to 10,000 AD. The shoreline displacement is the main cause of changes in the water balance.

For the Laxemar area, the depth to the groundwater table is highly dependent on the meteorological situation. During periods of wet weather conditions, the mean groundwater table is located at a depth of approximately 1 m below ground, while under dry weather conditions the mean depth is at c. 3.5 m below ground. The effect of the shoreline displacement is small with regard to the depth to the annual mean groundwater level in the area. The largest difference is found when going from 2000 AD to 5000 AD; the mean annual groundwater depth for the land area at 2000 AD increases from 2.4 m to 3.1 m below ground during that period.

Particle tracking simulations were made for all three models, i.e. for the 2000 AD, 5000 AD and 10,000 AD shorelines. In all cases, one particle was released in each grid cell at an elevation of approximately 150 m.b.s.l. The exit locations of particles reaching the ground surface within the 5,000-year simulation period are concentrated along the surface streams, in the lake areas and along the coastline. The results from all three models are very similar. Differences are noted in connection to the sea only, which is due to the shoreline displacement and the associated creation of new land areas.

The amount of particles left in the model volume decreases from the 2000 AD model to the 5000 AD and 10,000 AD models. This was noted also in the Forsmark SR-Site study (Bosson et al. 2010), and the reason is that the part of the model domain covered by sea decreases with time. The low gradients below the sea cause very low flow velocities, and as a consequence many particles that are released below the sea remain in the model at the end of the simulation.

The particle tracking simulations were run for 5,000 years, but already after 200 years about 2/3 of the introduced particles had left the model domain. After 500 years of simulation, between 70% and 80% of the introduced particles had left the model domain, and further decreases in the number of particles remaining in the model domain were small.

As in the Forsmark SR-Site modelling, see Bosson et al. (2010), results were extracted from the MIKE SHE model of Laxemar and delivered to be used in the radionuclide transport and dose calculations made with the Pandora model (SKB 2010a). For Laxemar, water balances were extracted for three lake objects from the 10,000 AD model. A comparison between the results for the Forsmark and Laxemar sites shows that even though all net fluxes except one have the same directions in Laxemar as was seen in the Forsmark results, the magnitudes of the various flow components differ significantly in some cases.

The upward groundwater fluxes from the bedrock towards the lake areas are much larger for the three objects used in the analysis of the Laxemar area than for the objects used in the Forsmark area. In Forsmark, the main flux was released to the mire area, while in Laxemar the main flux is directed towards the lake part of the lake-mire biosphere object. The objects studied in the Laxemar study are also found to be much stronger discharge areas than the objects in Forsmark.

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