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Summary

The Forsmark area consists of a number of natural wetlands. As a part of the evaluation of wetlands in the safety assessment for the area, possible future wetlands are being studied with respect to hydrology and transport mechanisms. A sensitivity analyses is performed to point out the governing parameters for the wetland hydraulics. The analysis of future wetlands is carried out using the hydrological model system MIKE SHE. MIKE SHE has been used to describe the near-surface hydrology for a regional model area in Forsmark.

Three types of areas have been chosen. Today’s lake Bolundfjärden is because of its shallow depth likely to develop into a mire in the future. As it is situated in the downstream part of the regional model area, the runoff to the lake from upstream surface water system is significant. Lake Eckarfjärden is situated in the upstream part of the catchment at a higher altitude and with a smaller inflow. Lake Puttan is situated above a planned layout of the repository and has a potential to receive discharges from a repository. It also lies in the downstream part of a large discharge area. The topography of the future mires is assumed to be flat, up to today’s mean water level in each lake. To transport the surface runoff through the wetland, streams or water courses are assumed to form within the peat.

The analyses of future wetlands in the Forsmark area show that the hydraulic conditions that exists today will somewhat alter as the peat is formed. For Bolundsfjärden, where there during present conditions are weak discharge areas, a recharge area has formed during the summer. This can be explained by the amount of surface water that forms on the surface which increases the head elevation in the upper soil layers. The same holds for Eckarfjärden, while Puttan after the peat has developed still is a discharge area due to its naturally strong discharge position close to the sea.

Different vegetation and development stages for the peat have been analyzed.

Results from the transport modelling show that a solute in the bedrock is transported quickly towards the peat surface in discharge areas for Bolundsfjärden. After around 10 years, a stationary condition is reached. For the recharge area that develops in large parts of the mire, the solute is transported through horizontal dispersion, which results in much lower concentrations. The solute concentration is at the lowest where the overland water pressure is at the highest close to the south western inlet. Puttan has a vertical flow pattern that differs from Bolundsfjärden. The pressure from water on the peat surface is considerably lower and for a major part of the year Puttan is a discharge area with an upwards flow direction. The spatial distribution of solutes is more even over the surface than for Bolundsfjärden, but higher concentrations are found around today’s shoreline.

A solute reaching the wetland through surface runoff is transported relatively slow through the mire at Bolundsfjärden. Due to the recharge conditions, the solute is spread to the underlying soil layers. The vertical solute transport follows the discharge and recharge areas, where high concentrations, up to the source strength, are reached in major parts of the formation, while lower concentrations are reached in the discharge areas and underneath clay sediment.

Sammanfattning

Området kring Forsmark består idag av ett antal naturliga våtmarker och myrar. Som en del i säkerhetsanalysen av området har funktionen hos eventuella framtida myrar utvärderats med avseende på hydrologi, vattenbalans och transportmekanismer. En känslighetsanalys har genomförts för att peka på de styrande parametrarna för hydrauliken i myrarna.

Analyserna har genomförts med det hydrologiska modellsystemet MIKE SHE. MIKE SHE har använts för att beskriva den ytnära hydrologin för ett regionalt modellområde i Forsmark.

Tre typer av områden har valts ut i studien. Dagens Bolundsfjärden är grund och kan därmed utvecklas till en torvformation i framtiden. Bolundsfjärden ligger i nedströmsdelen av det regionala modellområdet och får en betydande avrinning från uppströms liggande sjöar och grundvatten. Eckarfjärden ligger långt uppströms i avrinningsområdet och har en mindre belastning från grund- och ytvattenavrinning. Puttan ligger i nedströmsdelen av avrinningsområdet, i ett generellt starkt utströmningsområde ovan ett planerat djupförvar.

Topografin för de framtida myrarna har antagits vara platt, upp till en nivå motsvarande dagens medelvattenyta i respektive område. För att transportera ytvattenavrinningen som belastar dagens sjöar har det antagits att mindre vattendrag eller bäckar skapas i torven.

Analyserna av de framtida myrarna visar att de hydrauliska förhållanden som råder idag kommer att förändras i samband med att torven utvecklas. För Bolundsfjärden, som idag består av ett svagt utströmningsområde, skapas ett inströmningsområde under sommaren. Detta kan förklaras genom mängden vatten som samlas på torvens yta och som höjer trycknivån i de övre jordlagren. Motsvarande sker för torven i Eckarfjärden, däremot är Puttan även efter torvens utveckling ett utströmningsområde på grund av dess läge i ett starkt utströmningsområde nära havet.

Olika typer av vegetation och olika utvecklingsstadier hos torvformationerna har analyserats.

Resultat från transportberäkningarna visar att en förorening introducerad i berget transporteras snabbt mot ytan i utströmningsområden för torven i Bolundsfjärden. Efter ungefär 10 år har ett stationärt förhållande nåtts. För inströmningsområdet som skapas i stora delar av torven transporteras föroreningen främst via dispersion, vilket ger betydligt lägre koncentrationer.

Den framtida torven i Puttan har ett vertikalt strömningsmönster som skiljer sig från Bolundsfjärden. Trycket från vatten på torvytan är betydligt lägre och under en stor del av året är Puttan ett utströmningsområde med en uppåtgående tryckgradient. Den areella fördelningen av föroreningar är betydligt jämnare än för Bolundsfjärden. Högre koncentrationer återfinns kring dagens strandkanter.

En förorening som når torven via ytavrinning transporteras relativt långsamt genom Bolundsfjärden. Som en följd av det inströmningsområde som bildas i samband med torvens utbredning sprids föroreningen från ytan till underliggande jordlager. Den vertikala föroreningstransporten följer in- och utströmningsområdena med höga koncentrationer, nära källkoncentrationen, i stora delar av torven i anslutning till inströmningsområdet. Lägre koncentrationer erhålls i utströmningsområdena och under lersediment.

Contents

1 Introduction

SKB performs site investigations and risk analyses for localisation of a deep repository for high level radioactive waste. The site investigations are performed at two sites: Forsmark in Östhammar Kommun and Simpevarp in Oskarshamn Kommun.

At both the Simpevarp site the Forsmark site, numerical modelling is being performed both for the bedrock as well as for the near-surface groundwater aquifer above the bedrock surface. The near-surface hydrology has been modelled using the hydrological model system MIKE SHE /Bosson 2005/. The Forsmark area has been chosen in this study to illustrate the significance of future wetlands in the area. Modelling performed in this study is based on results from the regional groundwater model as the boundary conditions at smaller local models are drawn from the regional model.

The Forsmark area consists of a number of natural wetlands or mires. Due to land-rise and natural aging of the landscape, the process of new mires forming is ongoing in the area /Brunberg and Blomqvist 2000/.

Mires have been found to be formations with a potential of high doses of pollutants from a deep repository /SKB 1999/. As a part of the evaluation of wetlands in the risk analyses for the area, possible future wetlands are being studied with respect to hydrology, water balance and transport mechanisms. A sensitivity analyses is performed to point out the governing parameters for the wetland hydraulics. The result of this study is presented in the following report.

2 Modelling tool

2.1 Overview of the modelling tool

The modelling tool used in the analyses is MIKE SHE, developed by DHI (Danish Hydraulic Institute).

MIKE SHE is a dynamic, physically based, modelling tool that describes the main processes in the land phase of the hydrological cycle.

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. 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.

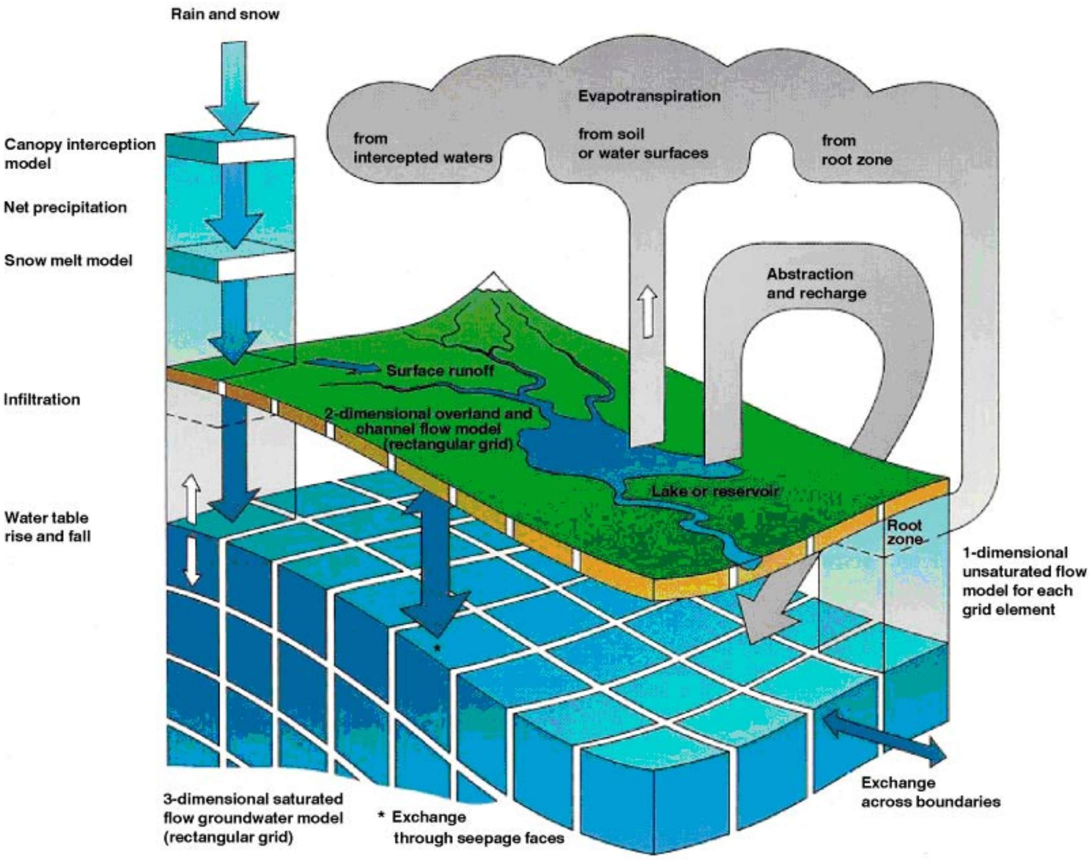


Figure 2-1. *Overview of the model structure and the included processes in MIKE SHE /DHI 2003a/.*

MIKE SHE is developed primarily for modelling of groundwater flow in porous media. However, in the present modelling the bedrock is also included. The bedrock is parameterised by use of data from the Forsmark 1.2 groundwater flow model developed using the Darcy Tools code /SKB 2004/. In Darcy Tools, a discrete fracture network (DFN) is used as a basis for generating hydrogeological properties for a continuum model /Svensson et al. 2004/. Thus, hydrogeological parameters can be imported directly to the corresponding elements in the MIKE SHE model.

MIKE SHE consists of the following model components:

- Precipitation (rain or snow).
- Evapotranspiration, including canopy interception, which is calculated according to the principles of /Kristensen and Jensen 1975/.
- Overland flow, which is calculated with a 2D finite difference diffusive wave approximation of the Saint Venant equations using the same 2D mesh as the groundwater component. Overland flow interacts with the river, the unsaturated zone, and saturated groundwater zone.
- Channel flow, which is described through MIKE SHE's river modeling component; the MIKE 11 modeling system for river hydraulics. MIKE 11 is a dynamic, 1D modeling tool for the design, management and operation of river and channel systems. MIKE 11 supports any level of complexity and offers simulation engines that cover the entire range from simple Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations.
- Unsaturated sub-surface, which in MIKE SHE is described as a vertical soil profile model that interacts with both the overland flow (through ponding) and the groundwater model (the groundwater table is the lower boundary condition for the unsaturated zone). MIKE SHE offers three different approaches including a simple 2-layer root-zone mass balance approach, a gravity flow model and a full Richards's equation model.
- Saturated groundwater flow, which allows for a fully 3D flow in a heterogeneous aquifer with shifting conditions between unconfined and confined conditions. The spatial and temporal variations of the dependent variable (the hydraulic head) is described mathematically by the 3D Darcy equation and solved numerically by an iterative implicit finite difference technique.

For a detailed description of the processes included in MIKE SHE, see /Werner et al. 2005/ and /DHI 2003a/.

2.1.1 Description and development of the evapotranspiration component in MIKE SHE

The calculation of evapotranspiration uses meteorological and vegetative data to predict the total evapotranspiration and net rainfall due to

- Interception of rainfall by the canopy.
- Drainage from the canopy to the soil surface.
- Evaporation from the canopy surface.
- Evaporation from ponded water and/or the soil surface.
- Uptake of water by plant roots and its transpiration, based on soil moisture in the unsaturated root zone.

In MIKE SHE, the evapotranspiration processes are split up and modeled in the following order:

1. A proportion of the rainfall is intercepted by the vegetation canopy, from which part of the water evaporates.
2. The remaining water reaches the soil surface, producing either surface water runoff or infiltrating to the unsaturated zone.
3. Part of the infiltrating water is evaporated from the upper part of the root zone or transpired by the plant roots.
4. The remainder of the infiltrating water recharges the groundwater in the saturated zone.

The primary evapotranspiration model is based on empirically derived equations that follow the work of /Kristensen and Jensen 1975/, which was carried out at the Royal Veterinary and Agricultural University (KVL) in Denmark. In this model, the actual evapotranspiration and the actual soil moisture status in the root zone is calculated from the potential evaporation rate, along with maximum root depth and leaf area index for the plants. The empirical equations in the model are based on actual measurements.

The parameters used in the evapotranspiration calculations can be divided into three groups, which regulate interception, soil evaporation and plant transpiration, respectively.

Calculation procedure for different components

Specific for the code being used in this project is that when there is ponded water on the surface, the transpiration is being reduced with a factor according to the anaerobic tolerance of the plant, which defines the plants capability to survive and transpire under saturated conditions. In case of no ponding, the factor is equal to one.

In the standard code, when there is ponded water on the surface, all of the evaporative demand is taken from canopy and ponded water, i.e. no transpiration. This was not satisfactory in this project, when evapotranspiration from mires were to be simulated.

The code being used in this project uses the following order in the calculation procedure:

1. Evaporation from canopy storage.
2. Transpiration.
3. Evaporation from ponded water on the surface.
4. Soil Evaporation.

The maximum value is however always less or equal to the given potential evaporation. When, or if, the calculated sum reaches the value of the potential evaporation, no further evaporation is calculated in that time step.

3 Principles for modelling

The Forsmark area was chosen for the study as the larger parts of the regional model area was already described in a MIKE SHE model /Bosson 2005/. Results from this modelling are used as boundary conditions for the hypothetical detailed local models.

To define cases for a sensitivity analyses for future wetlands, three types of areas have been chosen.

Today’s lake Bolundfjärden is because of its shallow depth likely to develop into a mire in the future. As it is situated in the downstream part of the regional model area, the runoff to the lake from upstream surface water system as well as from groundwater is significant.

Lake Eckarfjärden is situated in the upstream part of the catchment at a higher altitude and with a smaller inflow from surrounding ground- and surface water.

Lake Puttan is situated above a planned layout of the repository and has a potential to receive discharges from a repository. It also lies in the downstream part of a large discharge area.

The sub-catchments and lakes within the Forsmark model area are shown in Figure 3-1. Eckarfjärden is situated in sub-catchment 2:10, Bolundsfjärden in sub-catchment 2:3 and Puttan in sub-catchment 2:11. All catchment areas in the Forsmark area are described in /Johansson et al. 2005/. The local models are shown in Figure 3-2. Details of input data to the local models are shown in chapter 4.

Four different properties are altered for the sensitivity analyses:

- Boundary conditions, e.g. where the wetland is being formed in the landscape.
- Topography, e.g. the type of mire.
- Vegetation, e.g. type of plants and vegetation properties.
- Stage of development, e.g. type of peat throughout a profile.

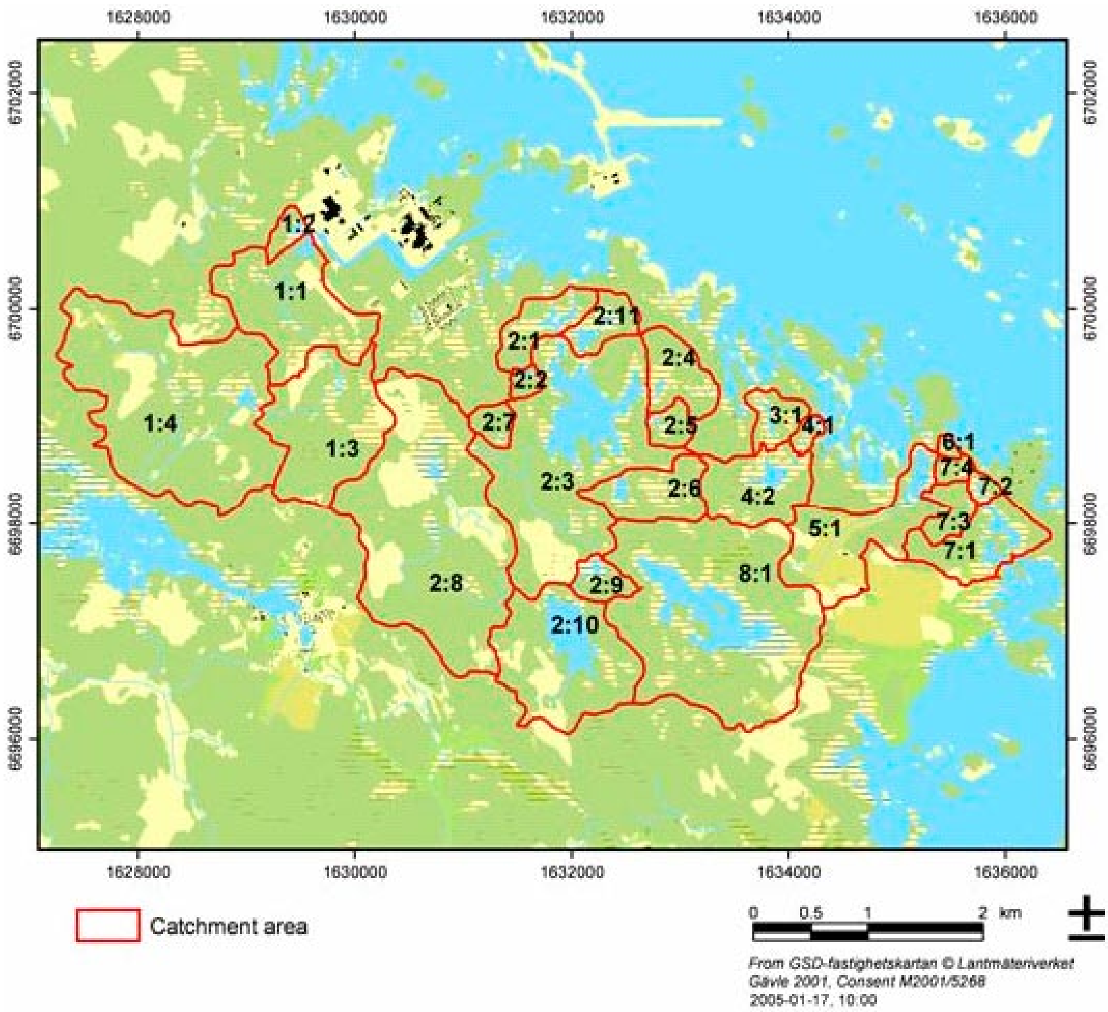


Figure 3-1. *Sub-catchments in the regional groundwater model with lakes within the model area. Eckarfjärden is situated in sub-catchment 2:10, Bolundsfjärden in sub-catchment 2:3 and Puttan in sub-catchment 2:11.*

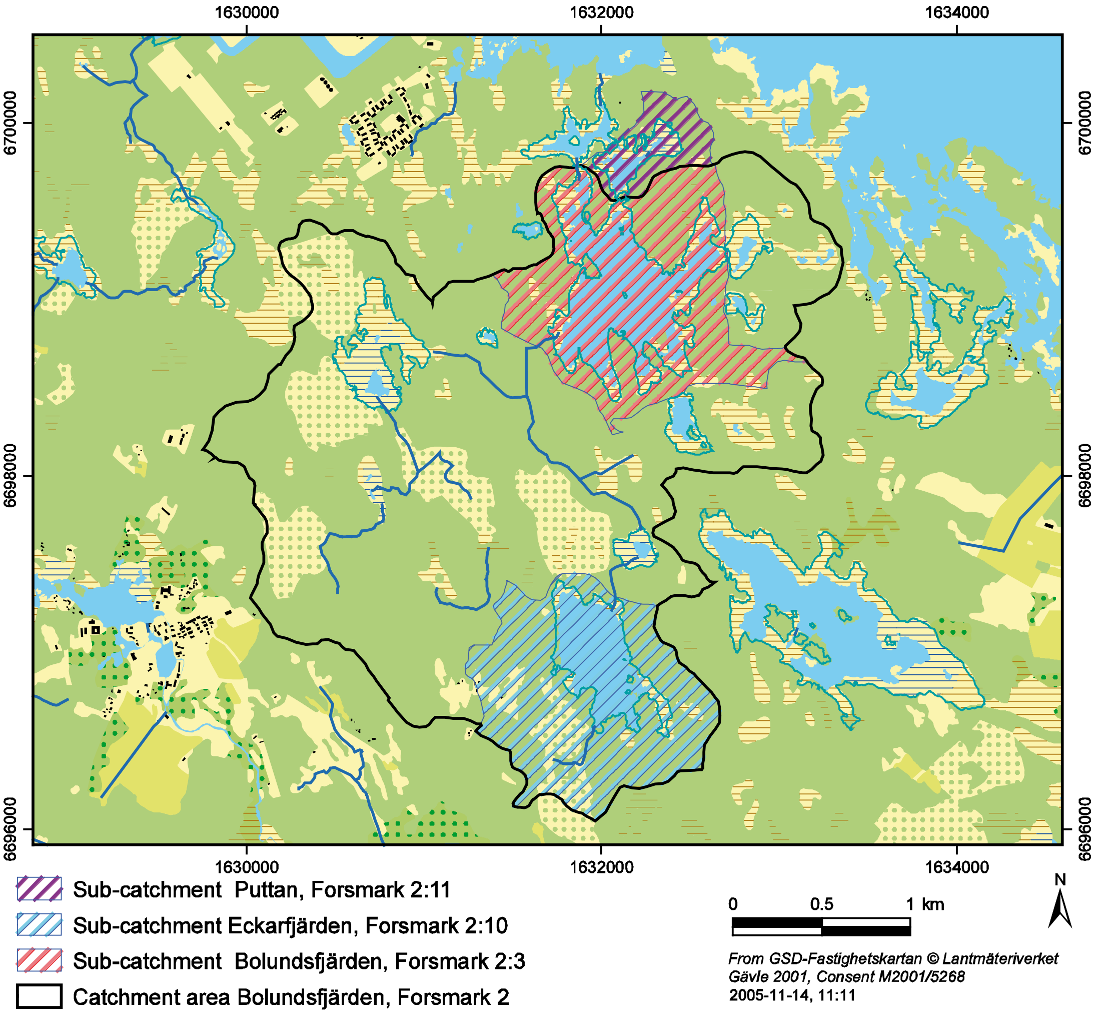


Figure 3-2. *Sub-catchments used for wetland modelling.*

4 Input data

The input data to the MIKE SHE model include data on topography, land use, geology, hydrogeology and meteorology. Input data used for modelling in this project is mainly based on input data described in /Bosson 2005/, such as topography and lake bathymetries, geological layers and lenses, hydraulic properties for the geological units and calculation layers. Some of the input data listed below have been modified for the model simulations of the wetland catchments.

4.1 Meteorology

Data on temperature, precipitation and potential evapotranspiration are used in the MIKE SHE modelling. The meteorological input data is taken from two local meteorological stations /Bosson 2005/. The potential evapotranspiration is calculated with the Penman-Monteith Equation with data from the local station in Forsmark.

The annual precipitation for the simulation period, May 2003–May 2004, is 597 mm, and the potential evaporation 534 mm.

4.2 Boundaries

For two of the local wetland catchments, Eckarfjärden and Puttan, there is no additional inflow by streams through the local sub-catchment; all surface runoff to the present lakes is produced within the area. Bolundsfjärden's sub-catchment, however, receives inflow from several other sub-catchments. The sub-catchments to each local model area are shown in Figure 3-2.

4.2.1 Surface flow

Surface inflow to the local model catchment for Bolundsfjärden is based on results from the regional groundwater model /Bosson 2005/.

Surface inflow from Eckarfjärden, Stocksjön and Gällsboträsket, referred to as inflow SW, is significantly larger than inflow from Vambörsfjärden and Graven, referred to as inflow SE respectively inflow N. Figure 4-1 shows the calculated inflow to Bolundsfjärden over one year of simulation, from the regional model. Position of each inflow is shown in Figure 4-2.

The runoff areas are 5.65 km^2 from inflow SW, 0.48 km^2 from inflow SE and 0.53 km^2 from inflow N. This can be compared with the sub-catchment area for Bolundsfjärden on 1.49 km^2. The sub-catchment areas for Eckarfjärden and Puttan are 1.34 km^2 and 0.26 km^2 respectively.

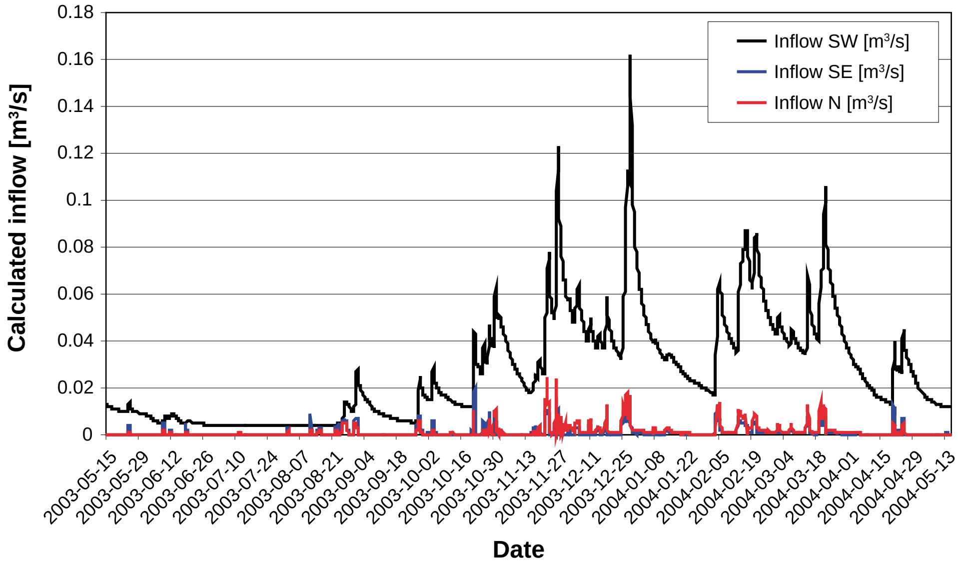


***Figure 4-1.** Calculated inflow to Bolundsfjärden (from regional groundwater model). The position of each inflow is shown in Figure 4-2.*

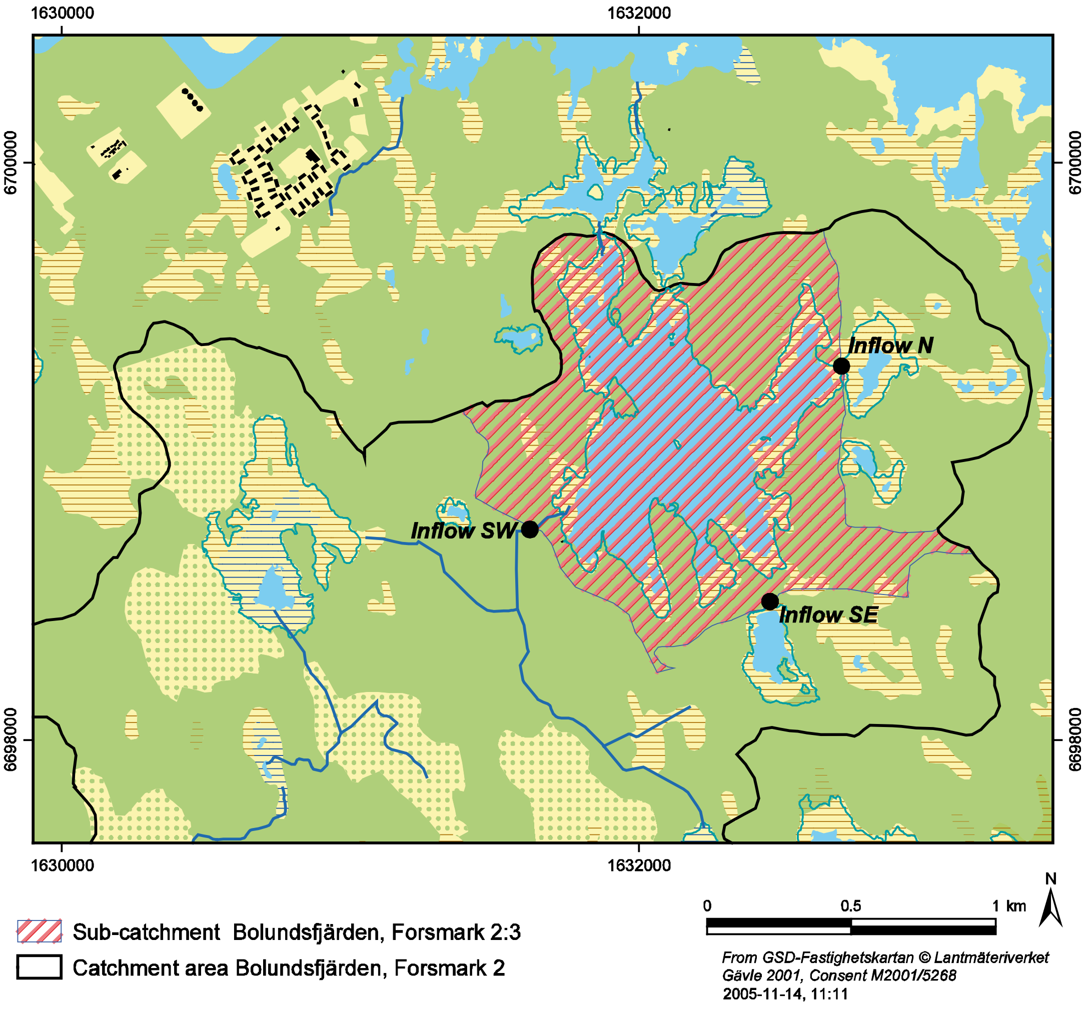


***Figure 4-2.** Position of the inflows to the local model of Bolundsfjärden.*

4.2.2 Saturated zone

The regional groundwater model which has been used as input data and boundary conditions for the detailed local models is described in /Bosson 2005/. The regional model provides time-varying boundary conditions for the outer boundary at each calculation layer, as well as for the whole bottom layer of the local models. Further comments are given in chapter 5.3.

4.3 Present geology

The geological model in the regional model consists of 11 layers, three in the Quaternary deposit and eight layers in the bedrock /Bosson 2005/.

The uppermost Quaternary deposit, named Z1, is characterized by the impact from surface processes, roots and biological activity. The bottom layer of Quaternary deposits, Z3, is characterized by contact with the bedrock. The middle layer, Z2, is assumed to have different hydraulic qualities than Z1 and Z3. The lake sediments have been modelled according to six classes of typical deposits /Vikström 2005/. The six types of lake sediments shown in the profiles have been simplified to three classes in the hydrological models. The uppermost layer consists of gyttja, which is underlain by sand. The deepest layer consists of clay. The lake sediments are described as geological lenses that complement the geological layers. Each geological layer and each geological lens have separate hydraulic properties.

Figure 4-3 show the position of profiles that illustrate the modelled thickness of the Quaternary deposits and lake sediments in Figure 4-4 to 4-6 /Vikström 2005/. The profiles are drawn through the lakes and future wetlands of each local model.

In Eckarfjärden, a bottom layer of glacial clay with an extension corresponding to the area of the lake is found. The clay layer has a maximum measured layer thickness of about 2 m. Postglacial clay is found in parts of the area. The clay layers are covered by postglacial sand and gravel throughout the lake. The sand is covered by nested layers of clayey gyttja, gyttja and calcareous gyttja. Figure 4-4 shows a profile through Lake Eckarfjärden.

The layer structure in Lake Bolundsfjärden differs from Lake Eckarfjärden There is only one layer consisting of algae-gyttja covering the major parts of the lake. The layer of gyttja covers lower layers of clayey gyttja and postglacial sand and gravel. The lowest layer of glacial clay is not present in the major part of Bolundsfjärden, see Figure 4-5.

The layer structure in Puttan consists of gyttja and postglacial sand and gravel. The lowest layer of glacial clay is not present; see Figure 4-6.

The sediment layers underneath the lake or peat bottom form a barrier for vertical groundwater flow to and from the mire. Figure 4-7 show the horizontal extent and layer thickness of the glacial clay sediment layer for the Bolundsfjärden and Eckarfjärden. Puttan has no glacial clay sediment underlying the lake bottom. All three locations have sediments of gyttja and postglacial sand and gravel underlying lake.

The maximum thickness of the clay sediments is around 0.6 m for Bolundsfjärden and 6 m for Eckarfjärden.

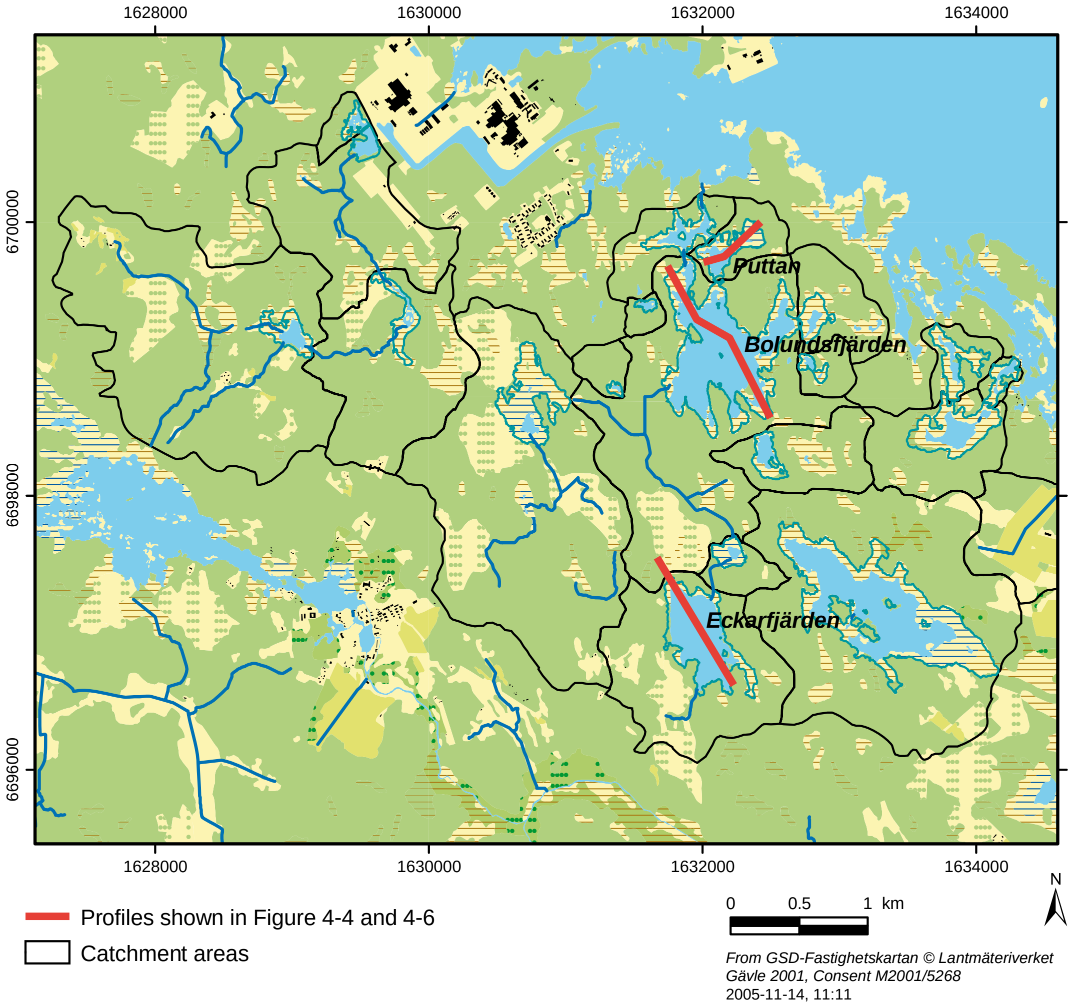


***Figure 4-3.** Position of profiles shown in Figure 4-4 to 4-6.*

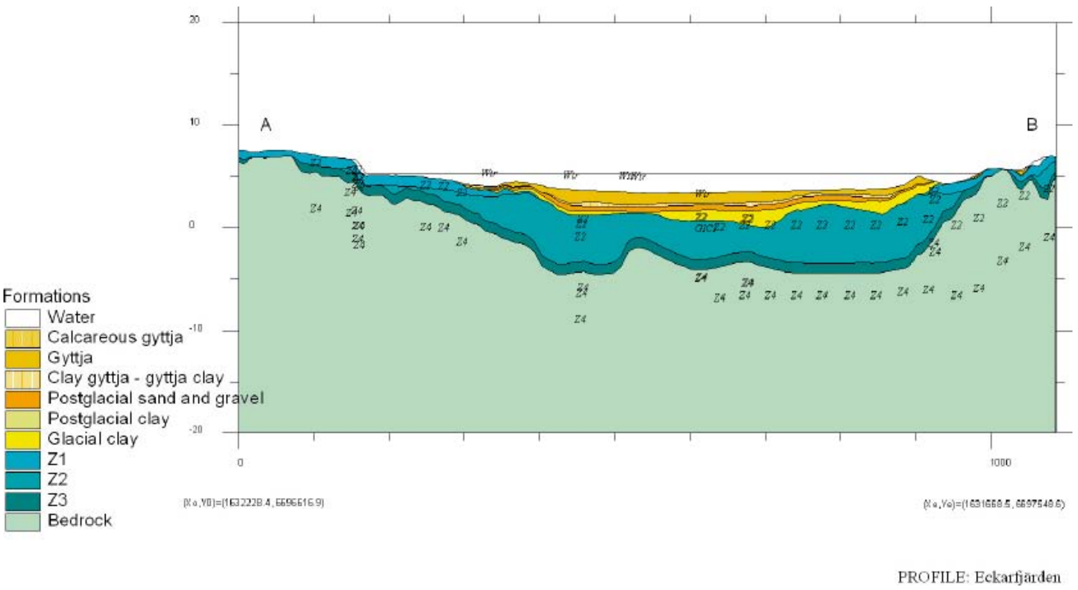


***Figure 4-4.** Lake sediments and total soil depth of Quaternary deposits along a profile through Lake Eckarfjärden. For location of the profile, see the Figure 4-3. The legend show the type of sediment presented in the profile, the formations Z1 to Z3 describe the Quaternary deposits. The letters shown in the profile formations refer to the lithology in observation points used to interpolate the layer surfaces /Vikström 2005/.*

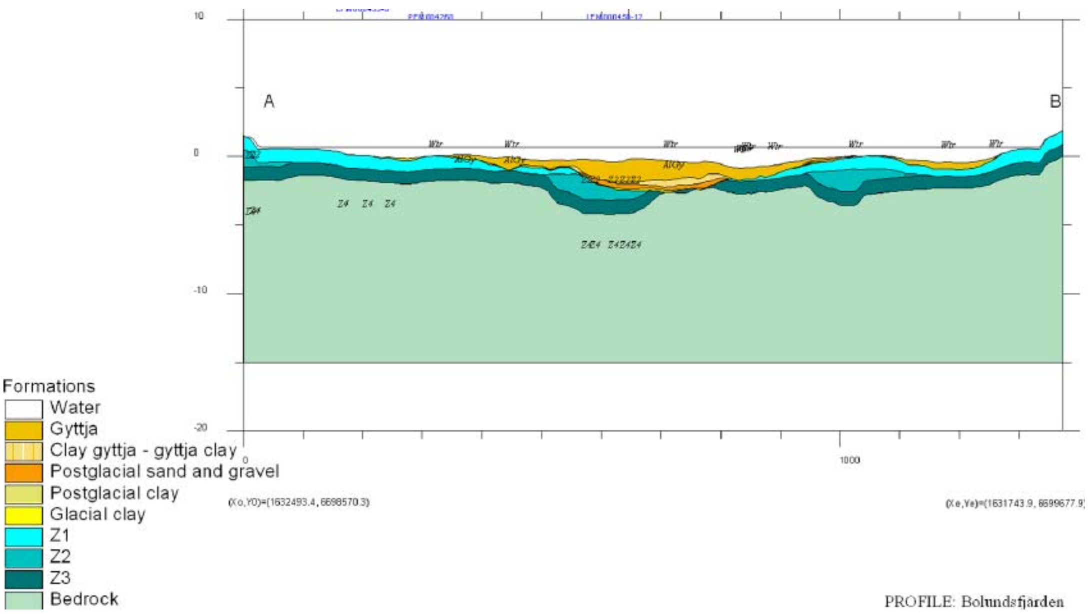


Figure 4-5. *Lake sediments and total soil depth of Quaternary deposits along a profile through Lake Bolundsfjärden. For location of the profile, see the Figure 4-3. The legend show the type of sediment presented in the profile, the formations Z1 to Z3 describe the Quaternary deposits. The letters shown in the profile formations refer to the lithology in observation points used to interpolate the layer surfaces /Vikström 2005/.*

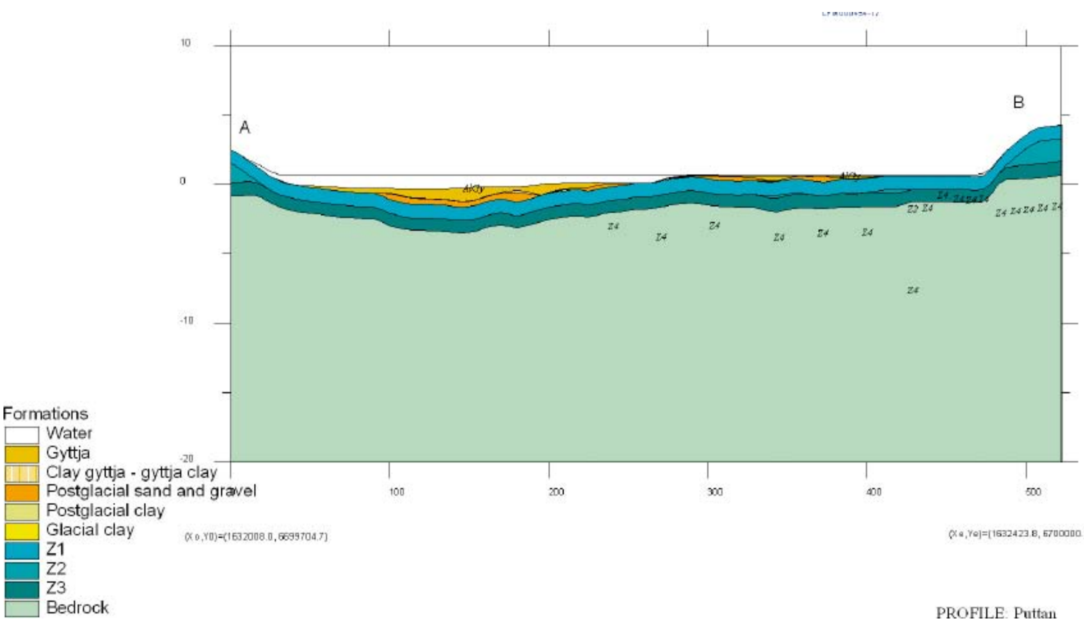


Figure 4-6. *Lake sediments and total soil depth of Quaternary deposits along a profile through Lake Puttan. For location of the profile, see the Figure 4-3. The legend show the type of sediment presented in the profile, the formations Z1 to Z3 describe the Quaternary deposits. The letters shown in the profile formations refer to the lithology in observation points used to interpolate the layer surfaces /Vikström 2005/.*

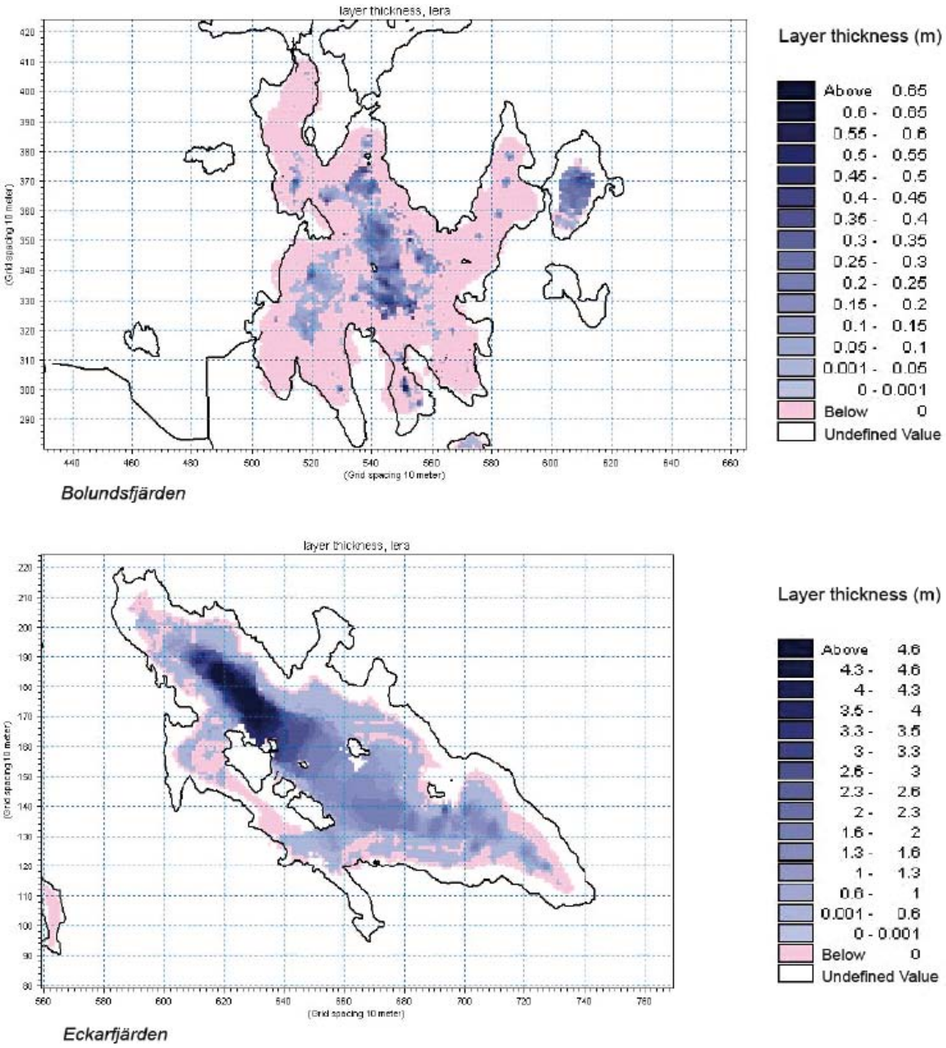


Figure 4-7. *Extension and layer thickness (m) of glacial clay sediment lenses under mires in Bolundsfjärden and Eckarfjärden.*

4.4 Input data for future wetlands

A number of modifications with respect to input data to the local models have been made to describe the development of mires in each catchment. The modifications refer to topography of the mire, vegetation on the peat surface, and the stage of development of the peat in the mires. This is further described in chapter 5.1.

5 Hydrological modelling and sensitivity analyses of future wetlands

The modelling of the assumed future wetlands has been performed as a sensitivity analysis where a number of parameters have been altered one at a time. The parameters that are studied are boundary conditions, such as location, vegetation and hydraulic properties according to development stages of the mires.

It should be noted that all simulations of local models describe hypothetical future wetlands with geological formations, hydraulic properties and boundary conditions from surrounding areas that differ from present conditions.

5.1 Input data

The basic model geology follows that described in chapter 4.4 and /Bosson 2005/. The local hypothetical models consist of seven geological layers, two types of peat, three layers of Quaternary deposits and two bedrock layers, as well as three sediment lenses.

5.1.1 Topography and overland flow of future wetlands

The topography of the mires is assumed to be flat, up to today's mean water level in each lake. To transport the surface runoff through the wetland, streams or channels are assumed to form within the peat. Further descriptions are given in chapter 5.4.

5.1.2 Vegetation on future wetlands

The overall vegetation has been divided into four vegetation groups: coniferous forest, deciduous forest, shrubs and water. The areas where no tree layer had been identified were classified as shrubs /Bosson 2005/.

The properties of each vegetation group are expressed in terms of the parameters Leaf Area Index (LAI), root depth, K_c-value, and the empirical parameters used in the Kristensen and Jensen model /Kristensen and Jensen 1975/. For description of parameters used in previous modelling, see /Bosson 2005/. These parameters have been used outside the assumed mires.

Three different types of vegetation in the mires have been defined; mesotrophic fen, sphagnum bog and alder-birch carrs/fens. Mesotrophic fen and spaghnum bog are the two types most likely to form /Kellner 2003/.

Table 5-1 show the variation of leaf area index and root depth over a one-year cycle.

Table 5-1. Leaf area index and root depth for different types of vegetation /Kellner 2001, Riutta T, Kim and Verma 1996, Aurela et al. 2001, Kutsch et al. 2004/.

Date	Leaf area index (–)			Root depth (m)		
	Mesotrophic fen	Spaghnum bog	Alder-birch carrs/fens	Mesotrophic fen	Spaghnum bog	Alder-birch carrs/fens
Jan 1	0	0.5	0	0.45	0.45	0.7
May 15	0	0.5	0	0.45	0.45	0.7
June 15	2	1	3.5	0.45	0.45	0.7
Sept 15	2	1	3.5	0.45	0.45	0.7
Oct 15	0	0.5	0	0.45	0.45	0.7
Jan 1	0	0.5	0	0.45	0.45	0.7

5.1.3 Stage of development for future wetlands

Three different types of peat that may occur at different stages of development have been defined. The content of fragments > 0.1 mm determines a division between the types Fibric (> 2/3), Hemic (1/3–2/3) and Sapric (< 1/3) peat /Farnham and Finney 1965/. The first type, fibric, is not fully decomposed and is assumed to always be present as an uppermost layer of at least 25 cm thickness above the more decomposed types hemic and sapric. The relation between the moisture potential, pF, and moisture content for the three types are shown in Figure 5-1 /Letts et al. 2000/.

The hydraulic properties in the saturated zone for the three defined types of peat are shown in Table 5-2.

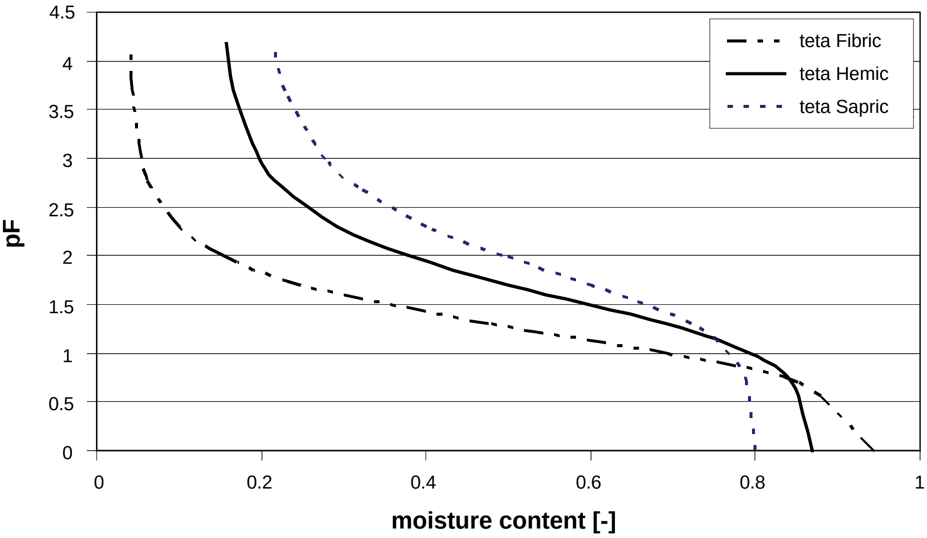


Figure 5-1. Relation between moisture potential, pF, and moisture content for the three different peat types; fibre, middle and amorphous.

Table 5-2. Hydraulic properties of the different types of peat /Letts et al. 2000/.

Type of peat	Ks, horisontal ($m \cdot s^{-1}$)	Ks, vertical ($m \cdot s^{-1}$)	Specific yield (–)	Storage coefficient (m^{-1})
Fibric	0.0002	0.0002	0.80	0.3
Hemic	2E–06	2E–06	0.49	0.05
Sapric	2E–08	2E–08	0.31	0.05

The effective porosity has been set equal to the specific yield for each type of peat. The effective porosity for the sediment lenses, Quaternary deposits and bedrock is described in /Bosson 2005/.

5.2 Boundaries

The regional groundwater model, as showed in Figure 5-2, produces time-varying boundaries for the saturated groundwater flow to the local hypothetical models within the regional model area. The lowest layer in the local models receives dynamic boundary conditions for the whole surface from the regional groundwater model. Remaining six layers receive results of a dynamic potential head at their outer boundaries.

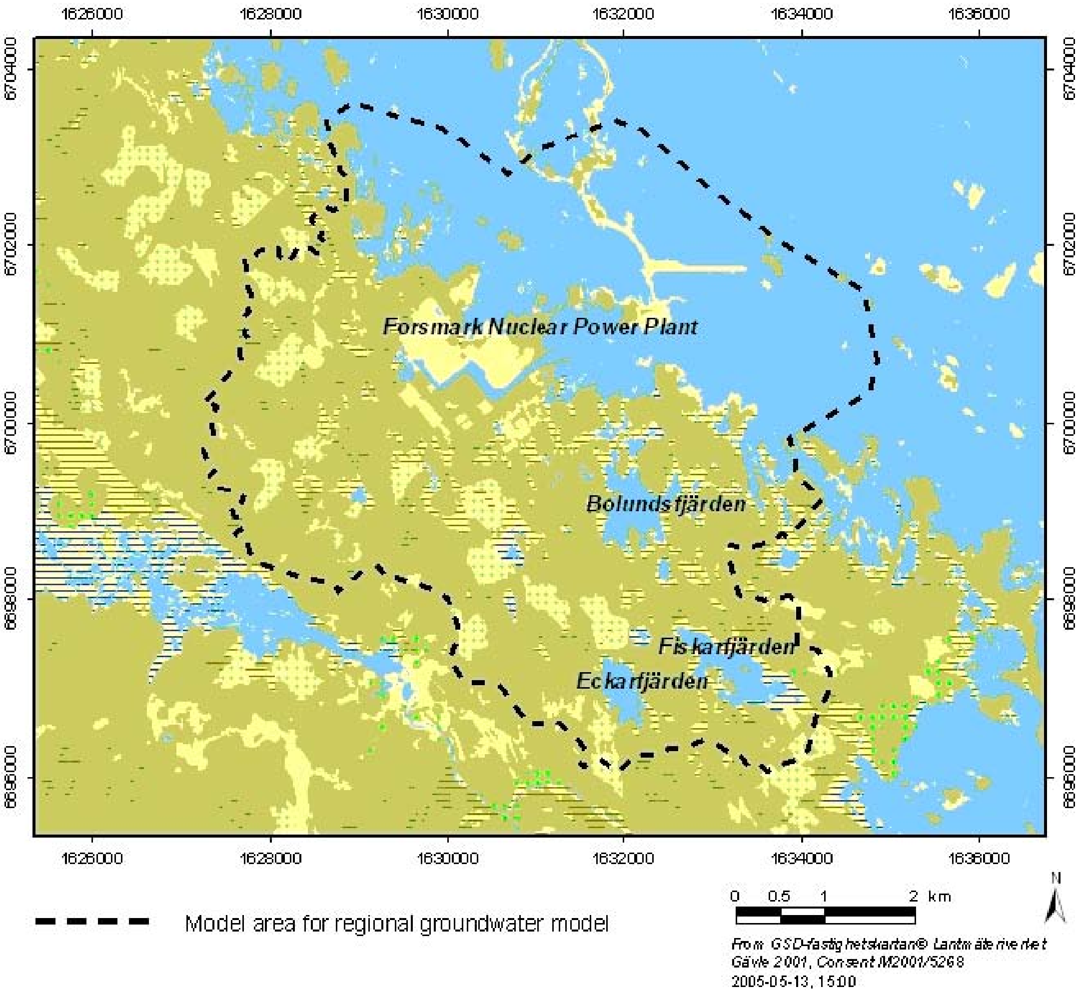


Figure 5-2. Model area for the regional groundwater model in Forsmark.

When mires develop, the groundwater head throughout the soil and bedrock profile may be affected of the hydraulics on the surface. The strength of recharge and discharge areas can also be affected. To handle this, the regional groundwater model was modified to include the mires in the future wetlands assumed to form at Bolundsfjärden, Eckarfjärden and Puttan. The MIKE 11 river model that transports water in existing water courses in the regional model /Bosson 2005/, was modified to correspond with streams described in the local models. This is described further in chapter 5.4.

The modified regional model was run two times for the period May 2003–May 2004 in order to reach a steady-state solution, with the first simulation as initial input to the second. Results from the second simulation are used as input and boundary conditions to the local models.

For present conditions, Bolundsfjärden, Eckarfjärden and Puttan are mainly discharge areas during an annual cycle.

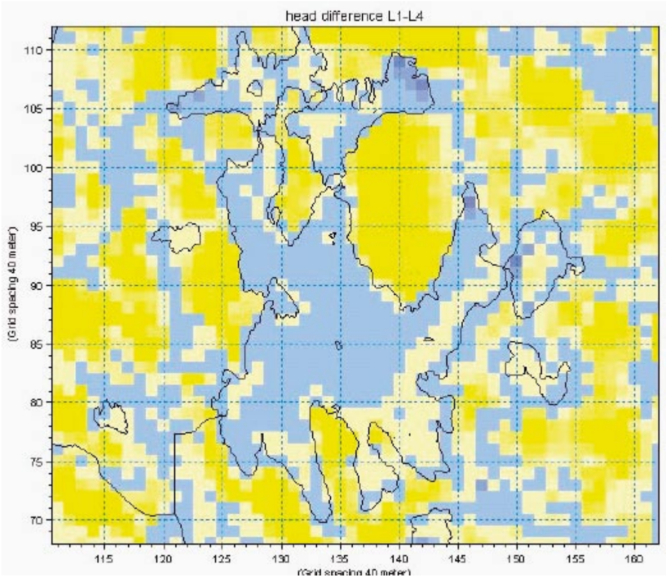
When the hypothetical mire forms and incoming runoff has to be transported on the surface or in small water courses, the depth of overland water affects the head elevations underneath the peat. Where there today are weak discharge areas, the change in overland water pressure can result in a weak recharge area.

Model results from the modified regional groundwater model with future mires show a larger recharge area for Bolundsfjärden and Eckarfjärden during the summer, with a discharge area around today's shorelines. During the winter, a weak discharge area occurs for both areas. Figure 5-3 show where there is recharge and discharge areas during the summer for Bolundsfjärden and Puttan, as a monthly mean in September. For future conditions with mires formed above the lake sediments, parts of the weak discharge area from present conditions have turned into a weak recharge area.

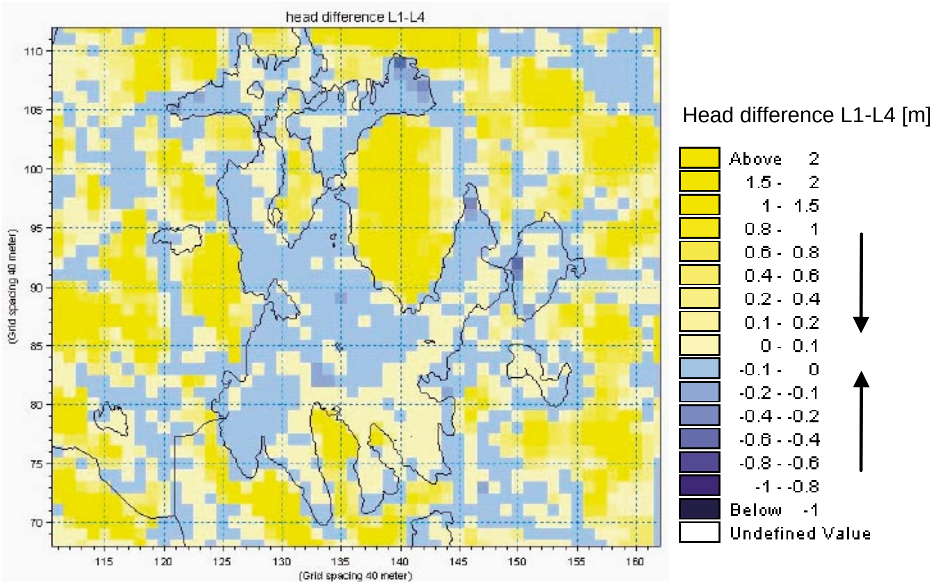
Figure 5-4 show where there are recharge and discharge areas during the winter for Bolundsfjärden and Puttan. A weak discharge area is formed during both present and future conditions.

Figure 5-5 illustrate a monthly mean in September of the calculated recharge and discharge areas both for present conditions and conditions with mires, and Figure 5-6 for the winter respectively. For Eckarfjärden, a monthly average during September show that a main recharge area forms for future conditions with mires. For the case with future mires, a weak discharge area is seen around today's shorelines. During the winter, a weak discharge area occurs for both cases.

As the results in Figure 5-3 to 5-6 illustrate, the conditions with respect to discharge and recharge areas have changed as the hypothetical mires are formed. A recharge area has formed during the summer, mainly for Bolundsfjärden, where there during present conditions are weak discharge areas. This can be explained by the increased head elevations in the mire (due to the amount of overland water that forms on the surface). However, the head elevations are not increased to the same extent in the bedrock which leads to a changed hydraulic gradient between the surface and the deeper layers.

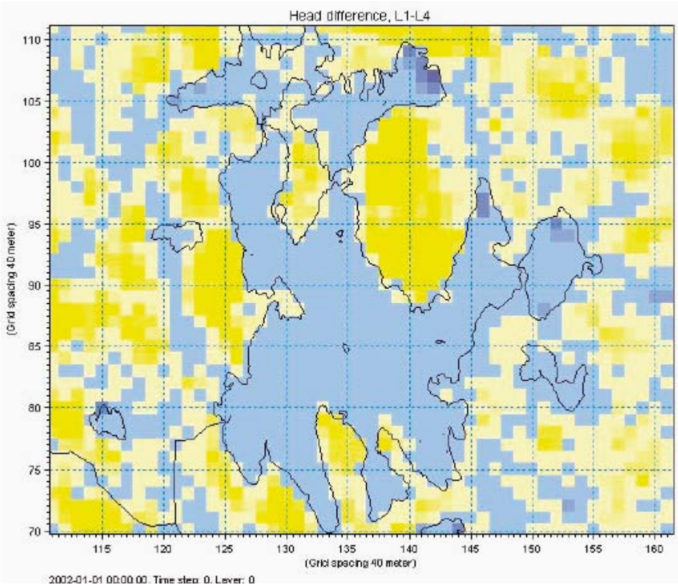


Bolundsfjärden and Puttan, present conditions, September mean

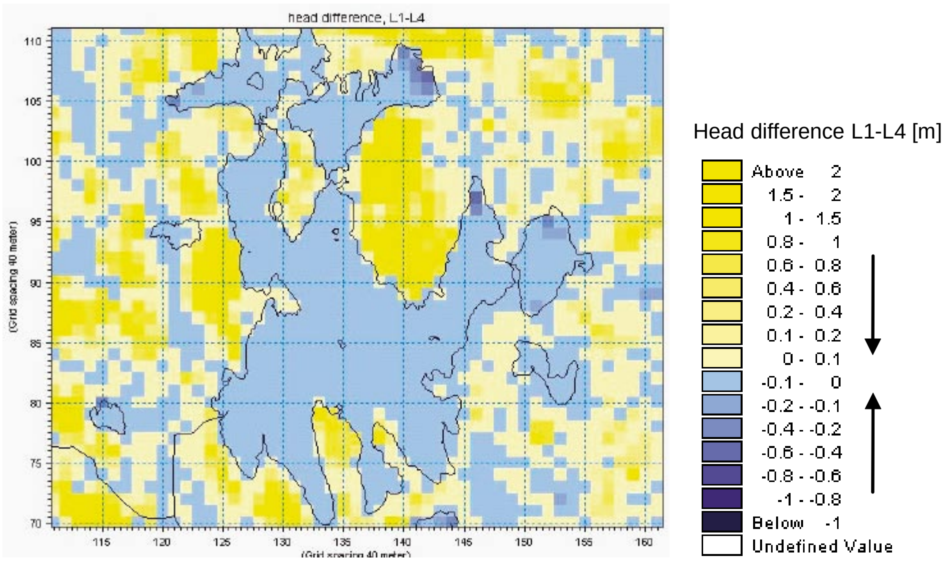


Bolundsfjärden and Puttan, future conditions with assumed peat formations up to today's mean water level, September mean

Figure 5-3. *Recharge and discharge area for Bolundsfjärden and Puttan for present conditions and with future assumed wetlands from the regional groundwater model as a mean value during September. Yellow colours show the strength of the recharge area, the light blue to dark blue the strength of the discharge area.*

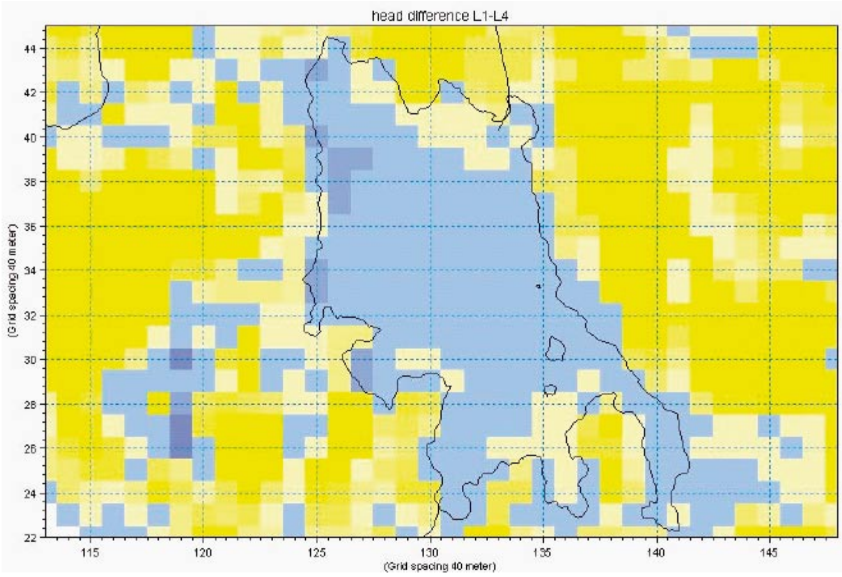


Bolundsfjärden and Puttan, present conditions, Dec. 31

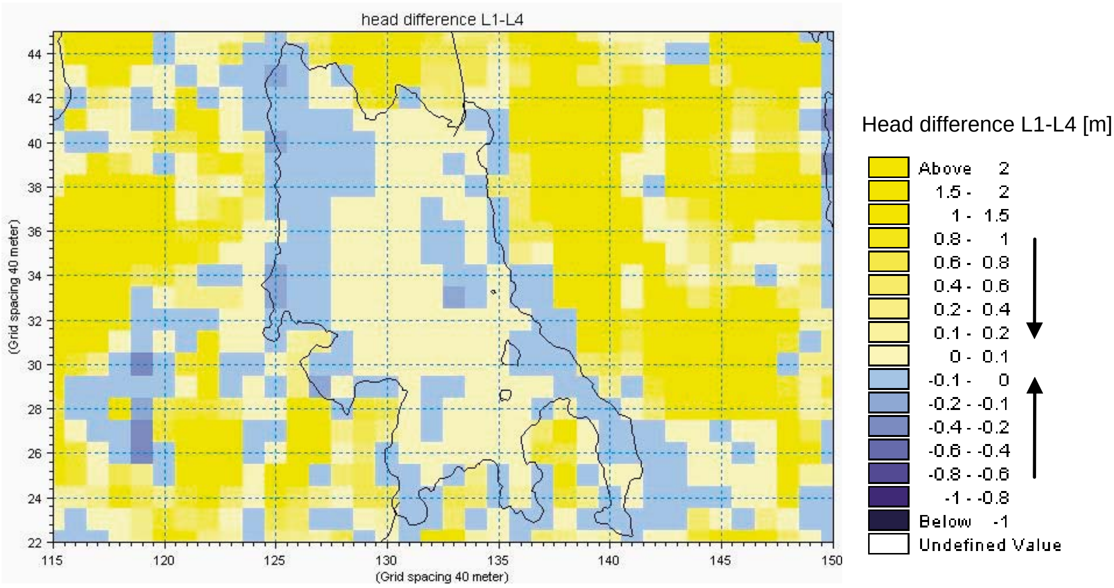


Bolundsfjärden and Puttan, future conditions with assumed mires up to today's mean water level, Dec 31.

Figure 5-4. *Recharge and discharge area for Bolundsfjärden and Puttan for present conditions and with future assumed wetlands from the regional groundwater model during a winter period (Dec 31). Yellow colours show the strength of the recharge area, the light blue to dark blue the strength of the discharge area.*

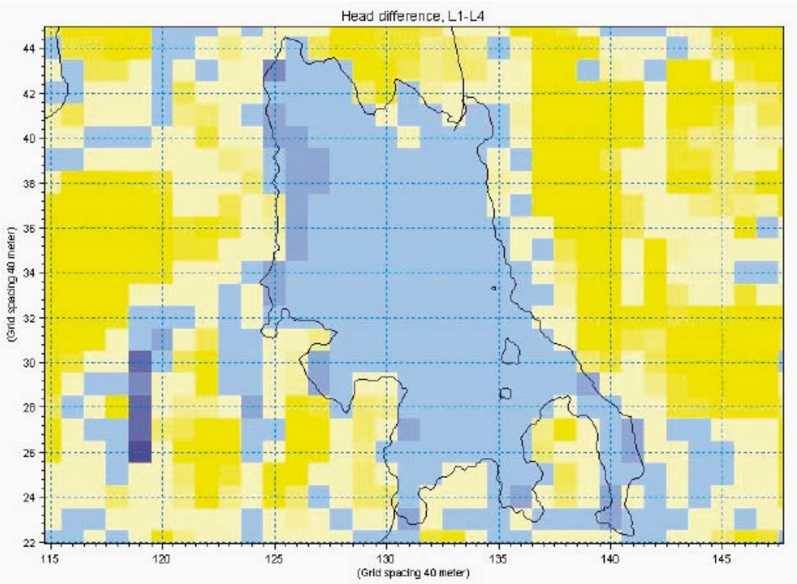


Eckarfjärden, present conditions, September mean

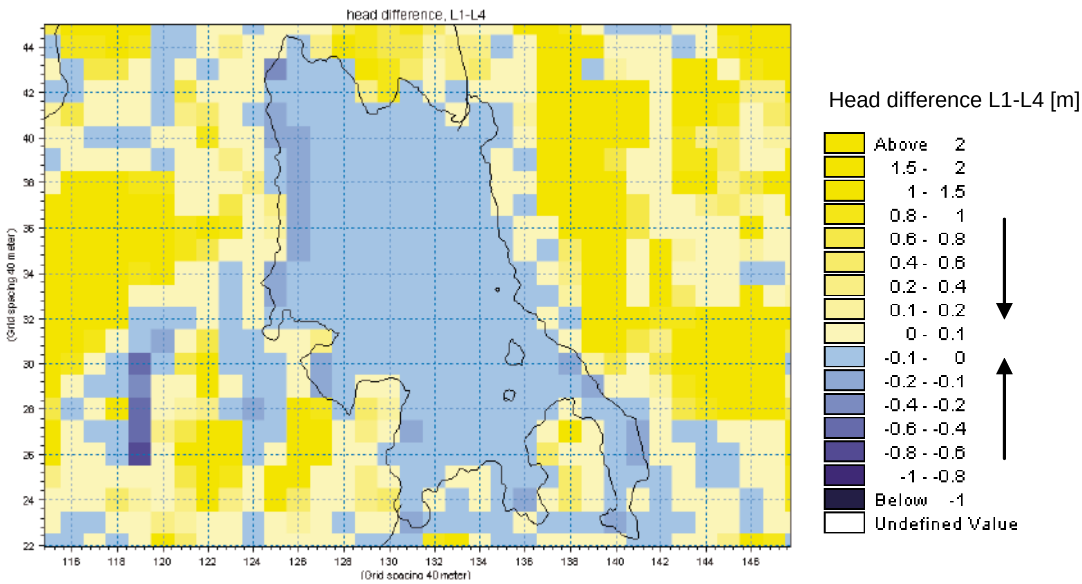


Eckarfjärden, future conditions with assumed peat formations up to today's mean water level, September mean

Figure 5-5. *Recharge and discharge area for Eckarfjärden for present conditions and with future assumed wetlands from the regional groundwater model as a mean value during September. Yellow colours show the strength of the recharge area, the light blue to dark blue the strength of the discharge area.*



Eckarfjärden, present conditions, Dec. 31



Eckarfjärden, future conditions with assumed mires up to today's mean water level, Dec. 31

Figure 5-6. *Recharge and discharge area for Eckarfjärden for present conditions and with future assumed wetlands from the regional groundwater model during a winter period (Dec 31). Yellow colours show the strength of the recharge area, the light blue to dark blue the strength of the discharge area.*

5.3 Numerical description of the local models

The model resolution of the local models is detailed, 10 m horizontally and varying vertically with a minimum of 1 m for the calculation layers. The calculation layers are separated from the thickness of the geological layers and lenses, which can be more detailed in the vertical resolution. Seven calculation layers are included in the model; one layer for the mire, one sediment layer (which comprises the geological layers gyttja, sand and glacial clay), three layers of Quaternary deposits and two layers of bedrock. Except for the peat layer, this corresponds to the layering in the regional model describing present conditions.

The simulation period is 2003-05-15 to 2004-05-15. A so called hotstart simulation is used to generate the initial conditions of each model simulation. The model is run until semi steady-state conditions are reached, that is, until the same conditions are reached at the end of the simulation as in the beginning.

5.4 Definition of cases for sensitivity analyses of future wetlands

The topography of the future mires is assumed to be flat, up to today's mean water level in each lake. To transport the surface runoff through the mire, streams or channels are assumed to form within the peat. The water courses follow today's natural streams where such are present. The runoff is described and transported as 2D-overland flow in MIKE SHE, as opposed to a 1D-river model with MIKE 11 in the regional groundwater model /Bosson 2005/. The effect of meandering that often occurs in wet-lands is included in the description of the water courses, as the model resolution is 10 m horizontally and an equivalent Manning number of 10 is applied in the water course.

The width and depth of the water courses were chosen with respect to the size of the upstream inflow, in order not to get too extreme depths of overland water during the wintertime. For Bolundsfjärden, a wider water course is applied, due to the large amount of water that is transported through the wetland. Figures 5-7 to 5-9 illustrate the water courses in the three local catchments.

The main water course in Bolundsfjärden is 30 m wide and 1 m deep. The two tri-butaries in Bolundsfjärden were set to a width of 10 m and depth 1 m. The Manning number was set to 10 in the water courses, assuming a high degree of meandering and vegetation in the stream, and 3 on the remaining surface. For Eckarfjärden and Puttan, the water courses were set to a width of 10 m and depth 0.4 m.

The properties for vegetation, the unsaturated and the saturated zone, have been altered in three ways, as described in chapter 5.1.

Table 5-3 show the simulation cases defined for the sensitivity analyses.

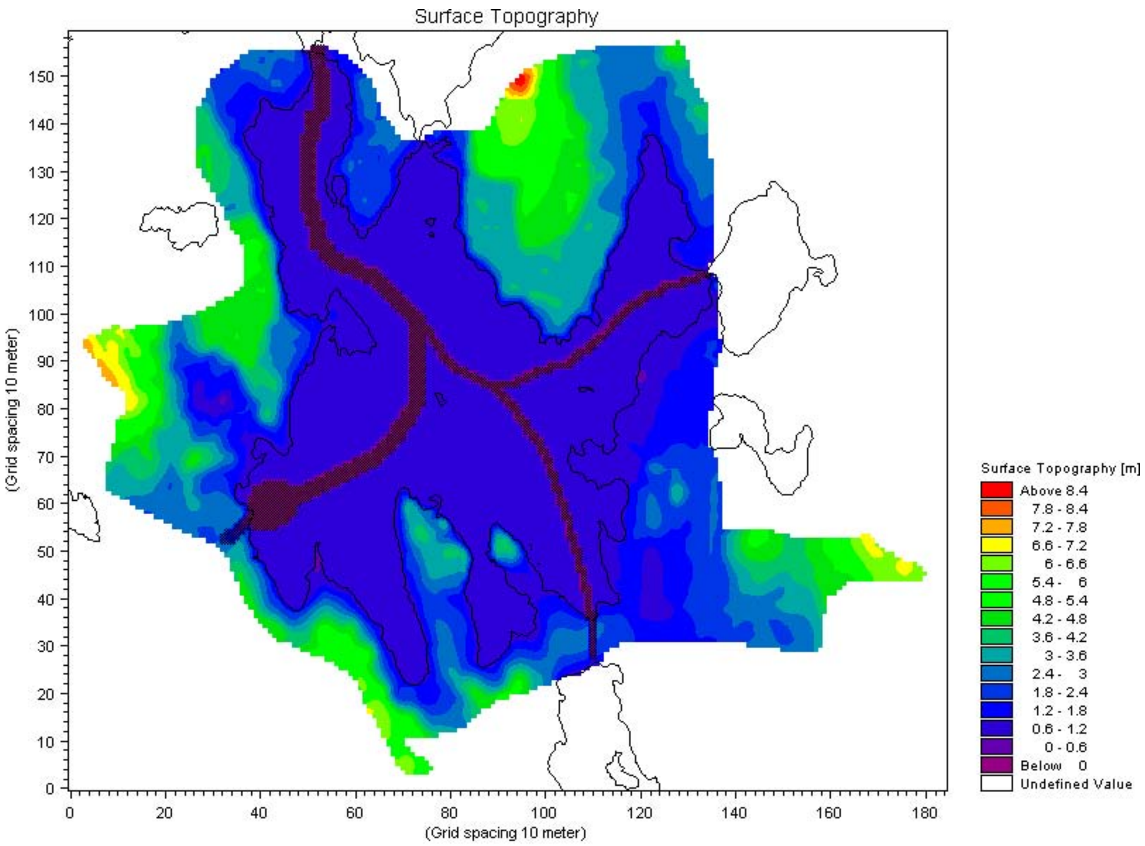


Figure 5-7. *Model catchment, surface topography (metre above see level) and location of ware courses to transport surface water for Bolundsfjärden. An area of open water is formed at the largest inflow. The peat surface is situated 0.64 m above see level.*

Table 5-3. Simulation cases for sensitivity analyses of future wetlands.

Simulation parameter	**Simulation case**						
	1	2	3	4	5	6	7
Catchment	Bolundsfj.	Eckarfj.	Bolundsfj.	Bolundsfj.	Bolundsfj.	Bolundsfj.	Puttan
Peat development							
Upper 25 cm	Fibric	Fibric	Fibric	Fibric	Fibric	Fibric	Fibric
Below 25 cm	Hemic	Hemic	Sapric	Sapric	Sapric	Fibric	Hemic
Vegetation type	Mesotrophic fen	Mesotrophic fen	Mesotrophic fen	Mesotrophic fen	Alder-Birch carrs/fens	Sphagnum bog	Mesotrophic fen

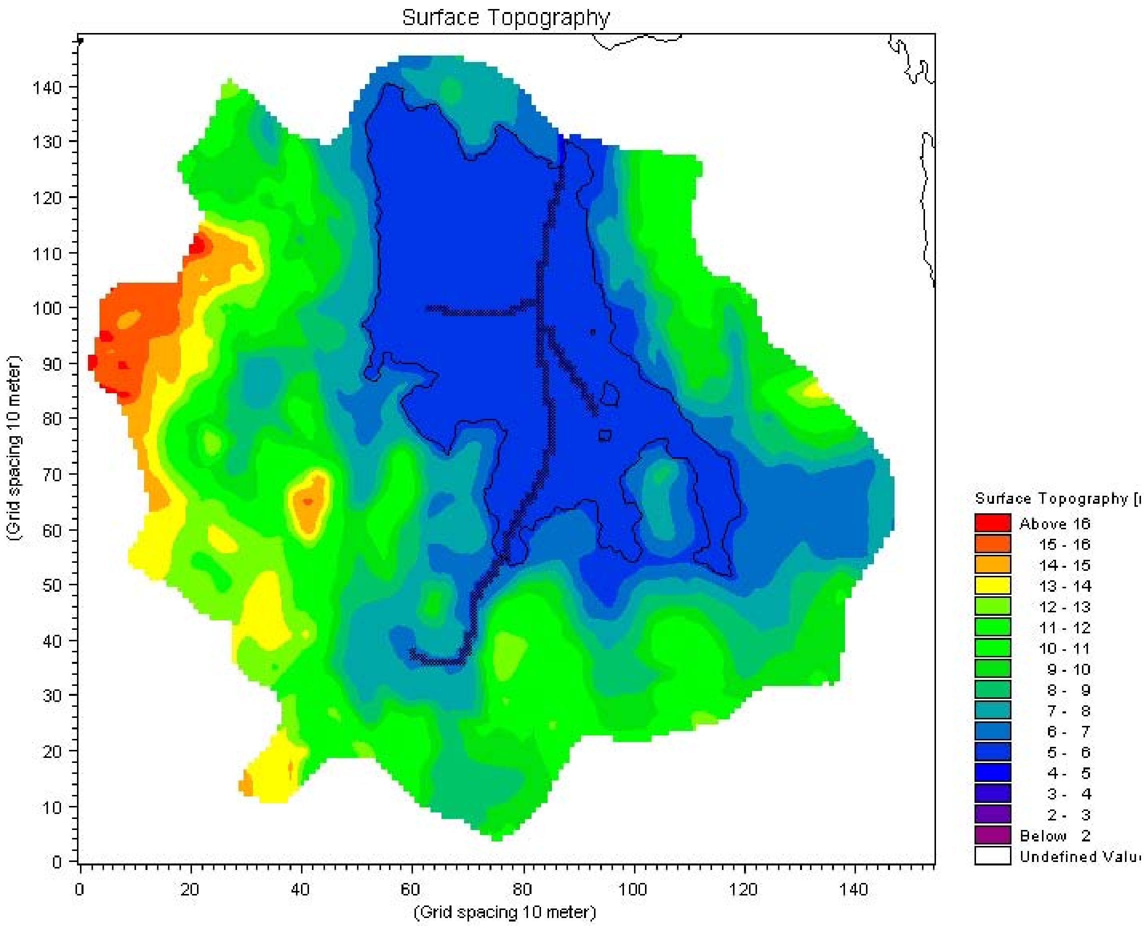


Figure 5-8. *Model catchment, surface topography (metre above see level) and location of water courses to transport surface water for Eckarfjärden. The peat surface is situated 5.37 m above see level.*

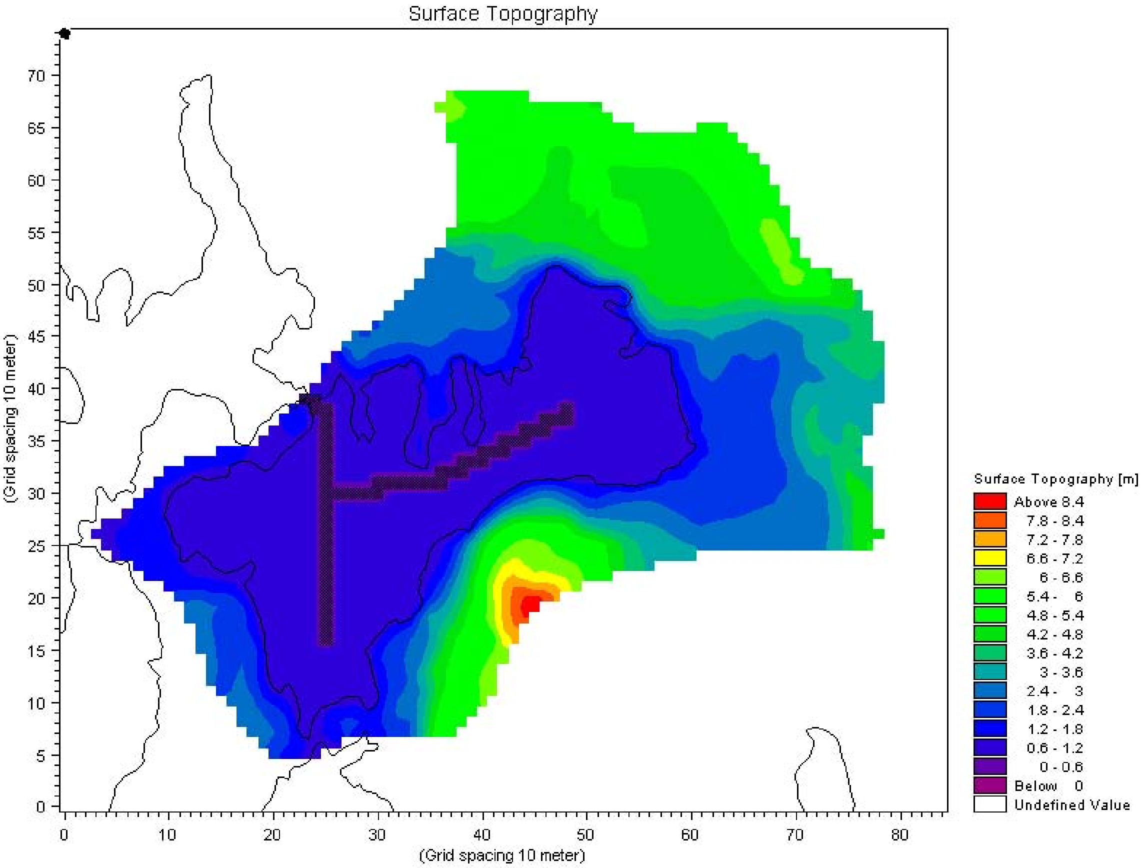


***Figure 5-9.** Model catchment, surface topography (metre above see level) and location of water courses to transport surface water for Puttan. The peat surface is situated 0.63 m above see level.*

5.5 Results of sensitivity analyses of future wetlands

Results from the hydrological modelling of the hypothetical wetlands are presented in this chapter with respect to water balance, groundwater flow pattern and depth of overland water on the peat surface.

5.5.1 Water balance for future wetlands

Figure 5-10, 5-12 and 5-14 show the total water balance for one year simulation over the mire for case 1, Bolundsfjärden (hemic peat and mesotrophic fen vegetation), case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation), and case 7, Puttan (hemic peat and mesotrophic fen vegetation). The accumulated potential evaporation during the period is 534 mm.

The different terms in the water balance summary in Figure 5-10, 5-12 and 5-14 include a number of processes. The evapotranspiration term include interception of rainfall by the canopy, drainage from the canopy to the soil surface, evaporation from the canopy surface, evaporation from ponded water and/or the soil surface, and uptake of water by plant roots and its transpiration. The term infiltration including evapotranspiration from the saturated zone includes the processes of recharge from the unsaturated to the saturated zone, evaporation from the saturated zone, in- and outflow from the saturated flow to the overland component and precipitation added directly to the saturated zone.

Figure 5-11, Figure 5-13 and Figure 5-15 presents a schematic water balance of the overland water body and the saturated zone water body respectively (the actual numbers for overland and saturated zone should not be analysed together). The numbers give the relative origin of water in each component.

Case 1, Bolundsfjärden

Figure 5-10 show that 71% of the precipitation is emitted through evapotranspiration. Figure 5-11 show that out of the inflowing surface water, 17% is infiltrated to groundwater and 83% is transported out over the boundary as overland flow. The saturated zone receives 75% of its water from infiltration and 25% by horizontal groundwater flow from surrounding areas.

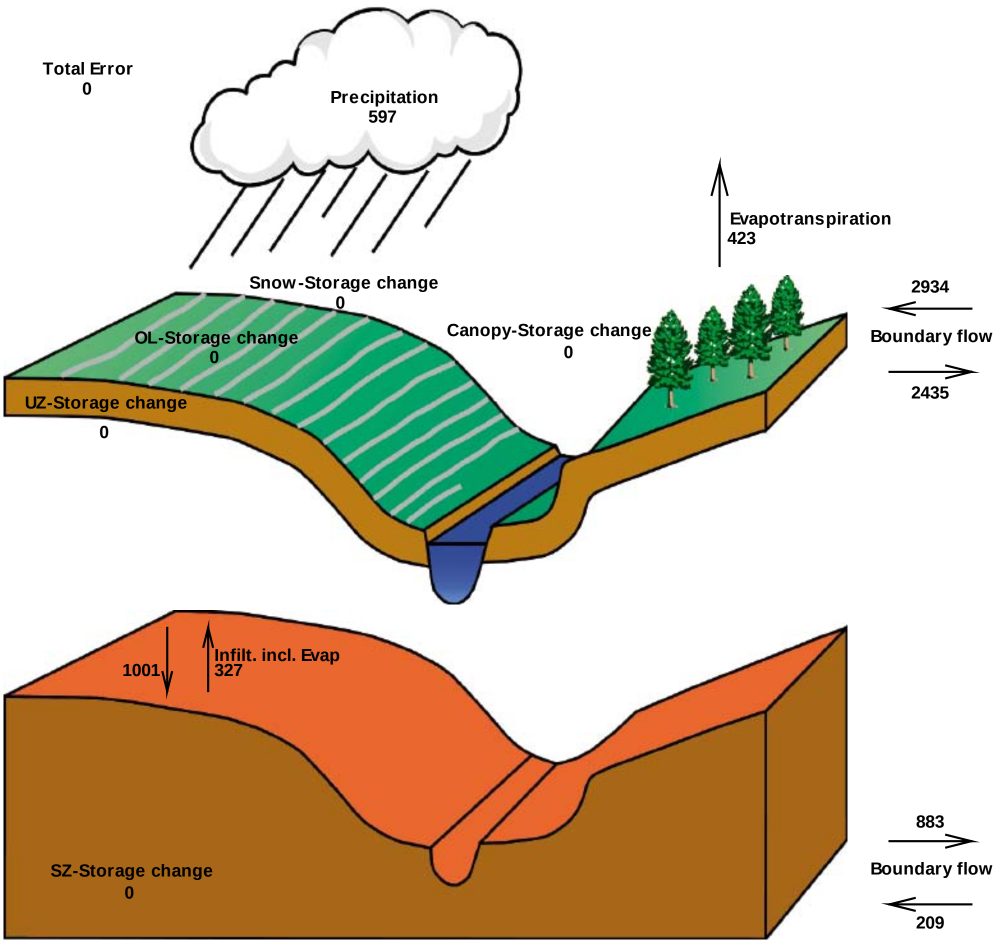


Figure 5-10. *Total water balance for case 1, Bolundsfjärden (hemic peat and mesotrophic fen vegetation).*

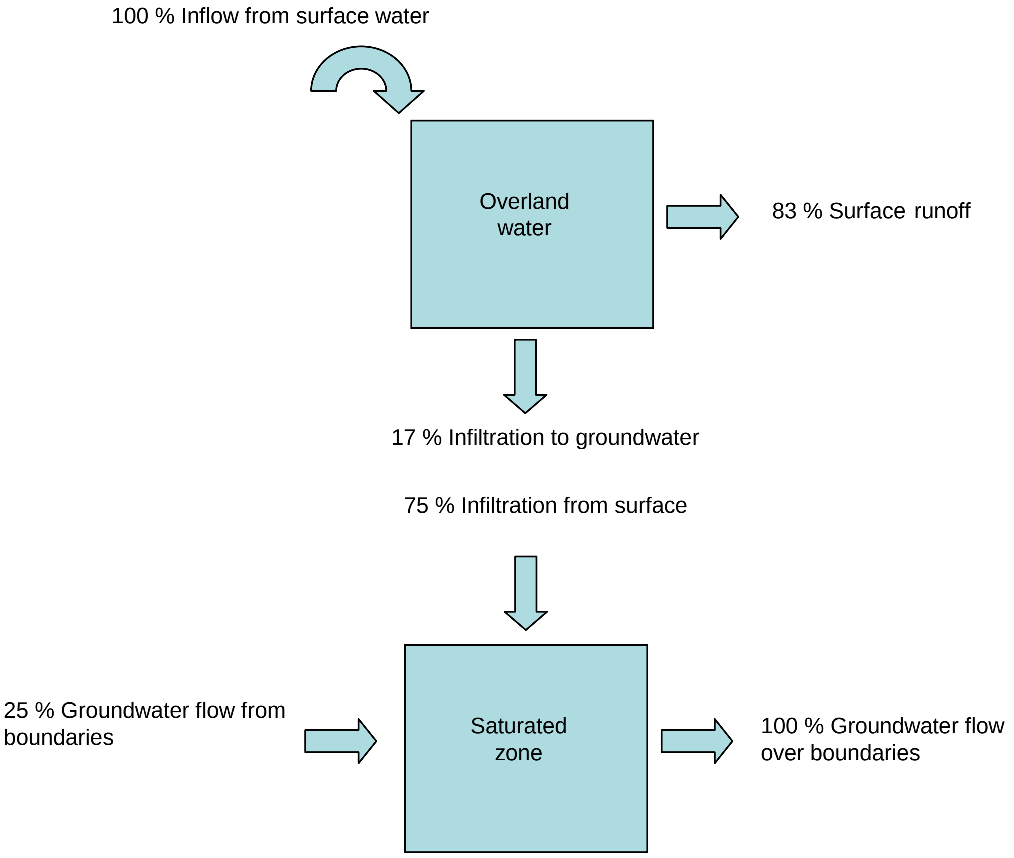


Figure 5-11. *A schematic water balance of the overland water flow and the saturated zone. The figure illustrates the relative origin of water in each component. Case 1, Bolundsfjärden (hemic peat and mesotrophic fen vegetation).*

This means that out of the total infiltration, only 25% comes from net precipitation over the mire, the rest comes from inflowing surface water. All this means that Bolundsfjärden is mainly a recharge area on a yearly average.

Case 2, Eckarfjärden

Figure 5-12 show the total water balance for case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation). 75% of the precipitation is emitted through evapotranspiration. Figure 5-13 presents a schematic water balance of the overland water body and the saturated zone water body in the same way as for Figure 5-11.

Eckarfjärden is slightly different with varying conditions of recharge and discharge over a year. 10% of the overland outflow is created inside the mire through net precipitation and groundwater discharge. This means that out of the total net precipitation only 26% is effectively infiltrating. In the case of Bolundsfjärden, all of the net precipitation was infiltrated, and in addition, 70% of the surface water inflow. As only 26% of the net precipitation is infiltrating at the mire at Eckarfjärden, the saturated zone under the mire at Eckarfjärden only receives 25% from infiltration and the rest from the surrounding area by horizontal groundwater flow.

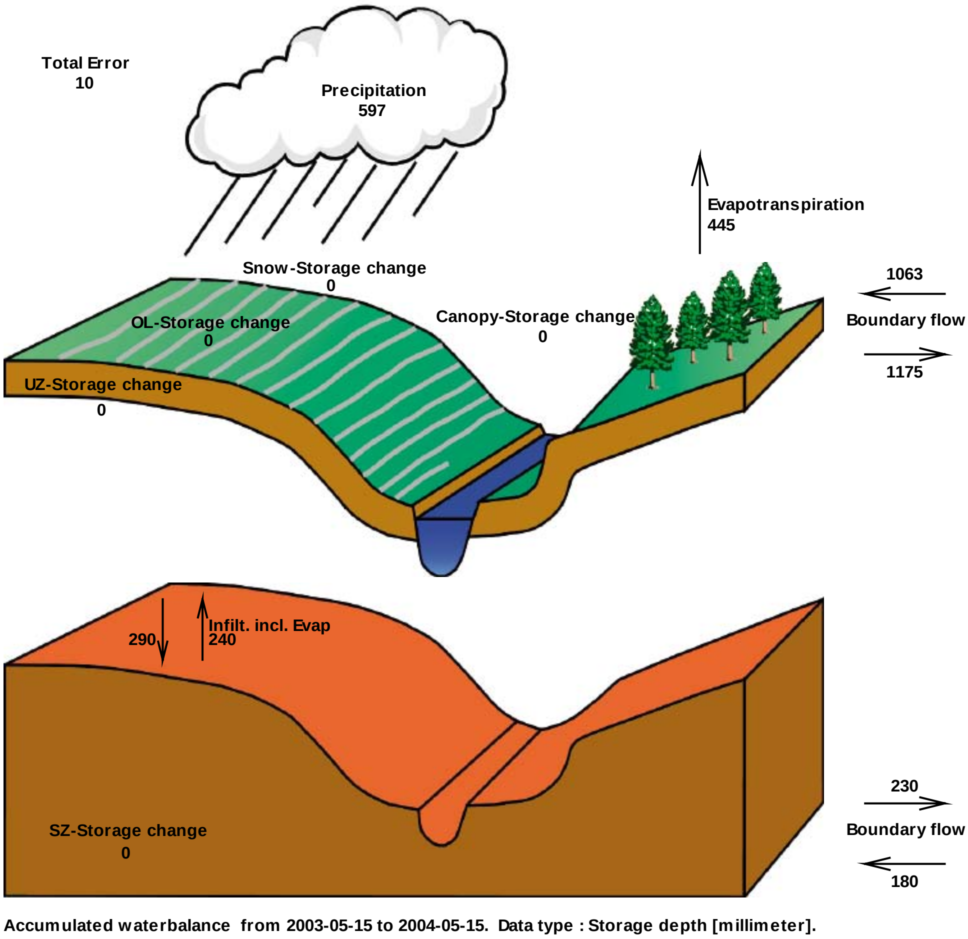


Figure 5-12. *Total water balance for case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation).*

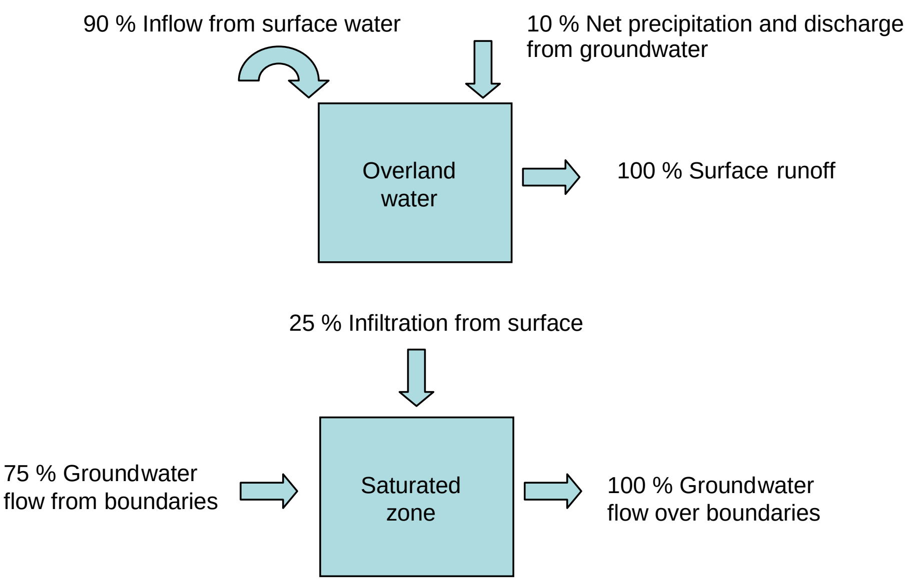


Figure 5-13. *A schematic water balance of the overland water body and the saturated zone water body. The figure illustrates the relative origin of water in each component. Case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation).*

Case 7, Puttan

The conditions for Puttan are the opposite compared to Bolundsfjärden, as it mainly is a discharge area with 90% of the overland outflow produced by groundwater discharge and net precipitation. Figure 5-14 show the total water balance for case 7, Puttan (hemic peat and mesotrophic fen vegetation).

Figure 5-15 presents a schematic water balance of the overland water body and the saturated zone water body in the same way as for Figure 5-11.

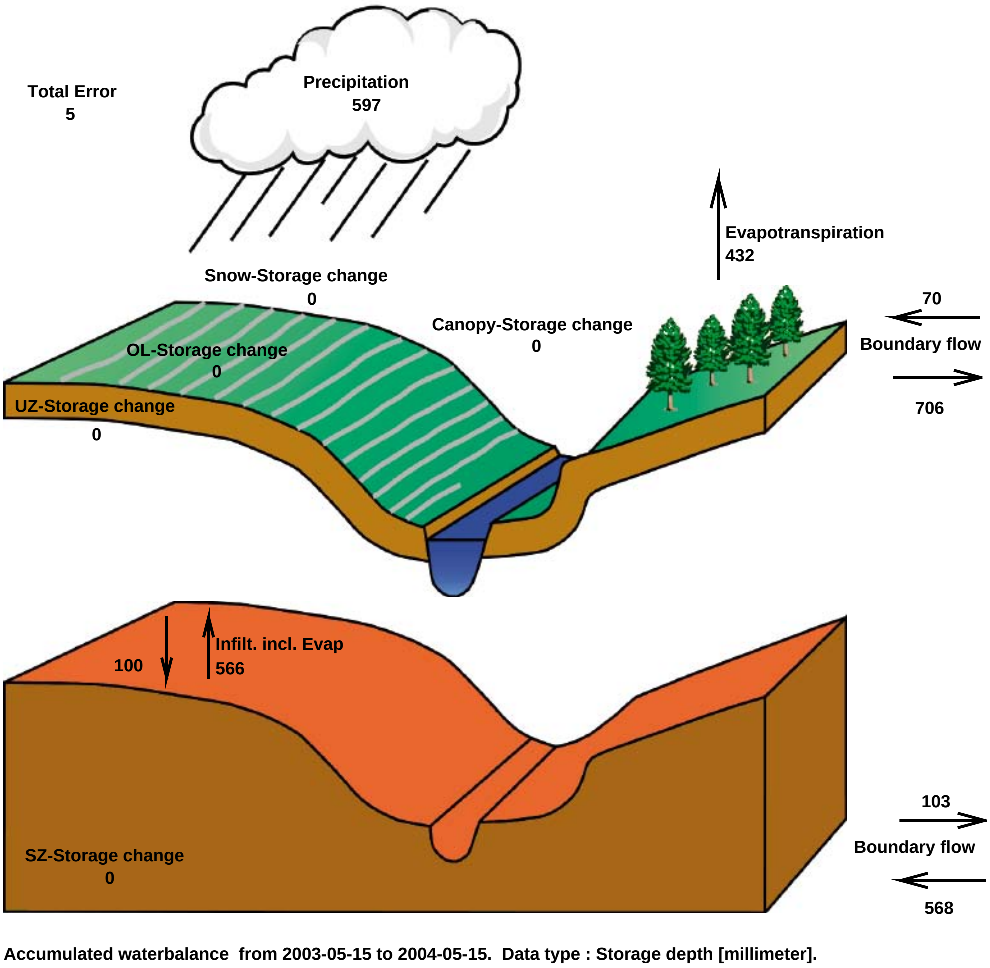


***Figure 5-14.** Total water balance for case 7, Puttan (hemic peat and mesotrophic fen vegetation).*

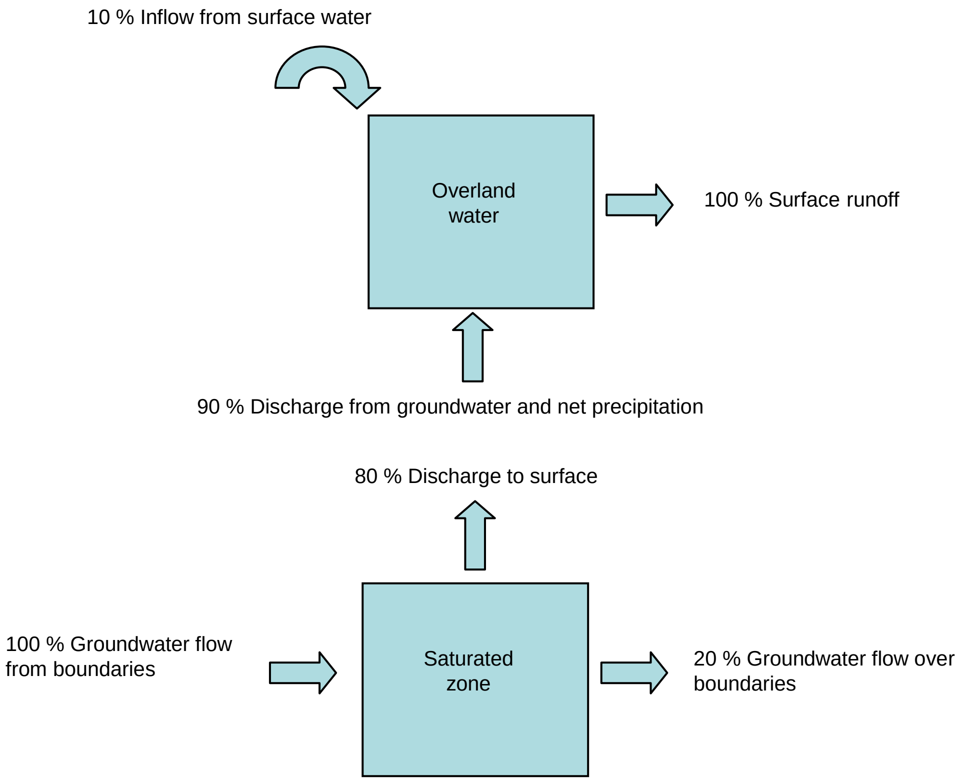


Figure 5-15. *A schematic water balance of the overland water flow and the saturated zone, evapotranspiration not included. The figure illustrates the relative origin of water in each component. Case 7, Puttan (hemic peat and mesotrophic fen vegetation).*

Summary of all cases

Total water balances over the peat formations for each simulation case are shown in Table 5-4.

Case 5 for Bolundsfjärden (sapric peat and alder-birch carrs/fens) show a high evapotranspiration compared to the other simulations. This is a result of the type of vegetation, alder-birch carrs/fens, which covers the mire. The sapric peat has a low conductivity and allows for water to remain reachable for evapotranspiration.

Case 6 for Bolundsfjärden (fibric peat and sphagnum bog) on the other hand show a small evapotranspiration due to the sphagnum bog growing on the surface in combination with high conductivities in the fibric peat that allows water to infiltrate.

Case 3 and 5 for Bolundsfjärden (sapric peat and mesotrophic fen/alder-birch carrs)has a smaller infiltration of overland water due to the low conductivities in the sapric mire, which results in a larger overland outflow and a smaller groundwater outflow.

Table 5-4. Total accumulated water balances over mires for each simulation case (mm).

Simulation case	Precipi-tation	Evapo-transpiration	Overland Storage Change	Overland Boundary Inflow	Overland Boundary Outflow	Groundwa-ter Storage Change	Groundwater Boundary Inflow	Groundwater Boundary Outflow	Error	Infiltration to groundwater
Case 1, Bolundsfjärden Peat type: Hemic Vegetation: Mesotrophic fen	597.0	–422.5	0.4	2,934.5	–2,434.9	0.0	208.7	–883.0	0.1	675
Case 3, Bolundsfjärden Peat type: Sapric Vegetation: Mesotrophic fen	597.0	–426.8	–47.0	3,065.4	–2,701.4	–3.4	192.6	–676.8	–0.5	484
Case 4, Bolundsfjärden Peat type: Fibric Vegetation: Mesotrophic fen	597.0	–423.0	–6.2	2,924.9	–2,408.1	–1.1	209.4	–893.5	–0.6	685
Case 5, Bolundsfjärden Peat type: Sapric Vegetation: Alder-Birch carrs/fens	597.0	–534.0	–45.7	3,044.5	–2,622.7	–3.3	214.1	–627.2	1.2	413
Case 6, Bolundsfjärden Peat type: Fibric Vegetation: Sphagnum bog	597.0	–336.8	–56.0	2,932.6	–2,430.5	–11.3	206.1	–901.2	–0.2	695
Case 2, Eckarfjärden Peat type: Hemic Vegetation: Mesotrophic fen	597.0	–444.9	–0.2	1,063.4	–1,175.2	0.0	179.8	–230.3	–0.3	50
Case 7, Puttan Peat type: Hemic Vegetation: Mesotrophic fen	597.0	–432.1	0.0	70.2	–705.8	0.1	567.7	–102.5	–5.4	–466

5.5.2 Overland flow

Bolundsfjärden has a relatively large surface inflow, which has been assumed not to reduce as the mire is developed. A large amount of water, previously forming a quite large lake, has to be transported through the wetland. The first simulations of the local models were made with a uniform flat peat surface over the whole lake bottom. This resulted in a very high depth of overland water forming on the peat surface due to the large inflows from upstream catchments. This indicates that such a formation (with a fully uniform flat surface) would not develop in the case of Bolundsfjärden. Instead, it is assumed that the large inflows from upstream catchments will keep quite large water courses open where the velocities are higher, while the actual mire develops around the main stream where the velocities are smaller.

The width and depth of the water courses were determined in an iterative process in order to get acceptable and likely depths of overland water on the peat surfaces. The main water course is defined to be 30 m wide and 1 m deep, two tributaries are 10 m wide with a depth of 1 m. A low Manning number of 10 were used in the water courses, assuming a high degree of meandering and vegetation in the stream. Typical values for natural rivers are between 20 and 40. The Manning number for the remaining peat surface was set as low as 3. i.e. according to a highly vegetated surface.

Figure 5-16 shows the spatial distribution of the mean water level on the peat surface in each grid point over one year of simulation, as well as the overland water depth during the summer (1 Sept) and the winter (31 Dec).

A mean value of 30 cm is calculated over an annual cycle. During high surface runoff in the winter, a mean water level of around 50 cm occurs. A water pressure gradient develops over the peat surface with a depth of overland water close to zero near the outlet.

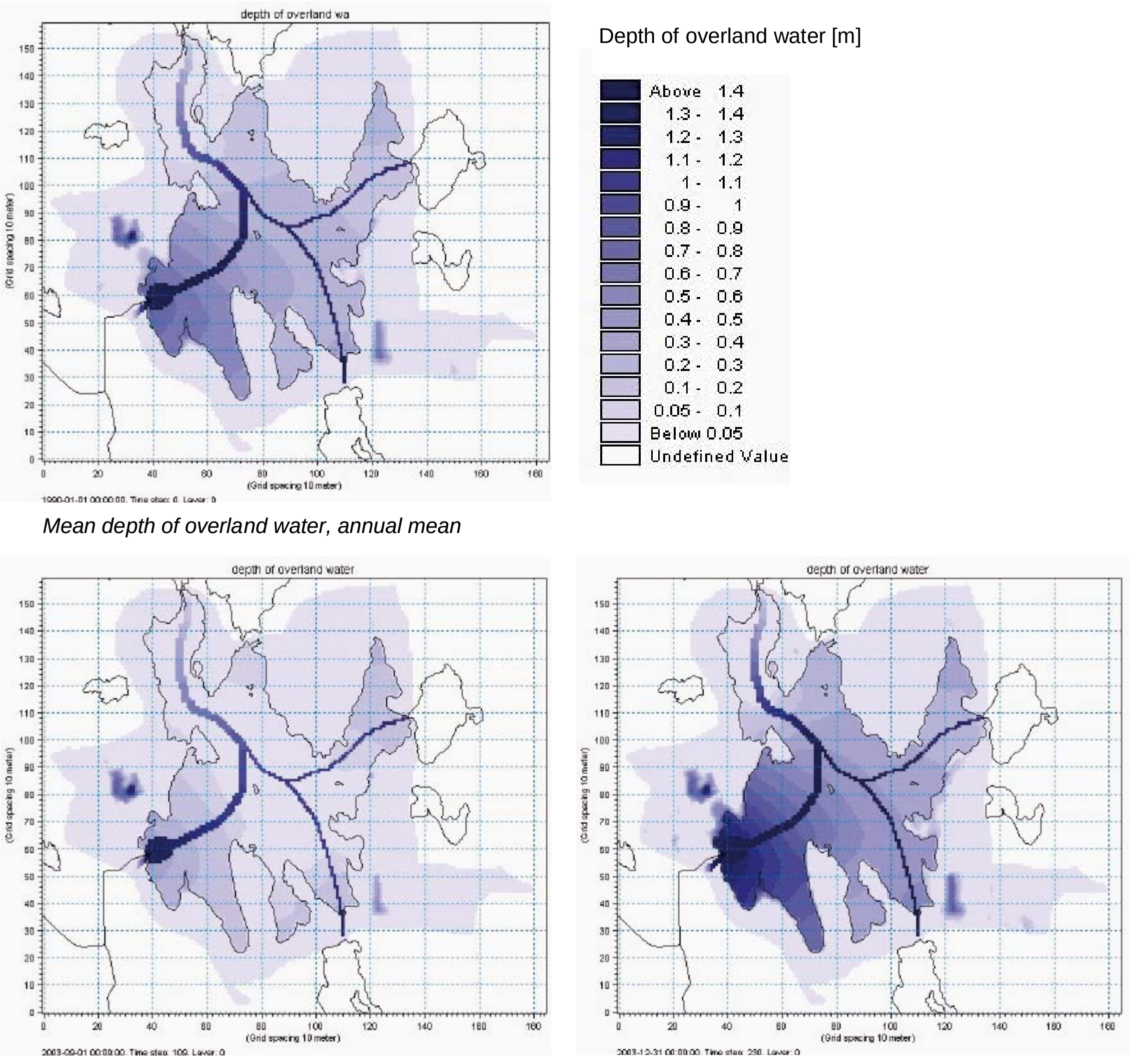
Eckarfjärden is situated in the uppermost part of the regional model area and has a relatively small inflow from surface runoff. The water courses are set to 10 m wide and 0.4 m deep. The main water course follows the natural stream that leads to Eckarfjärden during present conditions. The two tributaries are assumed to transport surface runoff from the mire itself.

For the future mire at Eckarfjärden, a mean value of 10 cm is calculated over an annual cycle. During higher runoff in the winter, a mean water level of around 20 cm occurs. A water pressure gradient develops over the peat surface with a depth of overland water close to zero near the outlet, see Figure 5-17.

Puttan is situated in the uppermost part of the regional model area and has a relatively small inflow from surface runoff. The water courses are 10 m wide and 0.4 m deep. As there is no natural stream of significant size with an outflow in Puttan during present conditions, the water courses that are assumed to form in the future mire are located within the formation itself.

For the future mire at Puttan, a mean value on the depth of overland water of 6 cm is calculated over an annual cycle. A water pressure gradient develops over the peat surface with a depth of overland water close to zero near the outlet, see Figure 5-18.

Table 5-5 presents the mean water level on the surface for each simulation case, water in the watercourses not included.



Mean depth of overland water, annual mean

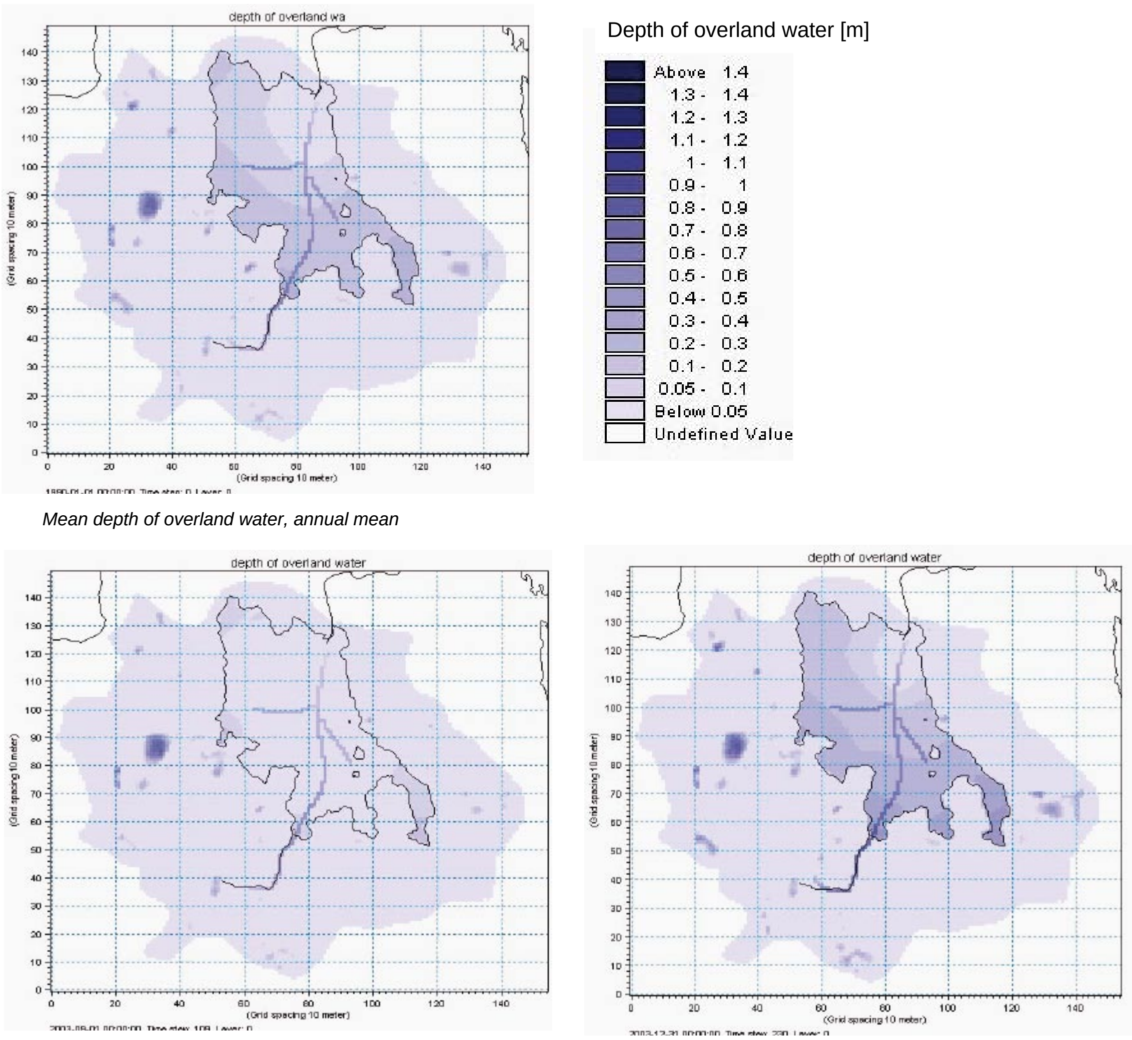
Depth of overland water, 1 September

Depth of overland water, 31 December

Figure 5-16. *Mean depth of overland water (m) during one year of simulation, depth of overland water during the summer and depth of overland water during the winter for Bolundsfjärden, case 1 (hemic peat and mesotrophic fen vegetation). See Table 5-5 for mean depths of overland water on the peat surface.*

Table 5-5. Mean depth of overland water on peat surface for each simulation case (water courses not included), (m).

Period	Mean water level Bolunds-fjärden, case 1 (m)	Mean water level Bolunds-fjärden, case 3 (m)	Mean water level Bolunds-fjärden, case 4 (m)	Mean water level Bolunds-fjärden, case 5 (m)	Mean water level Bolunds-fjärden, case 6 (m)	Mean water level Eckar-fjärden, case 2 (m)	Mean water level Puttan, case 7 (m)
Annual mean	0.29	0.31	0.28	0.30	0.29	0.10	0.06
1 Sept	0.08	0.11	0.08	0.06	0.09	0.02	0.06
31 Dec	0.47	0.50	0.46	0.49	0.46	0.18	0.11



Mean depth of overland water, annual mean

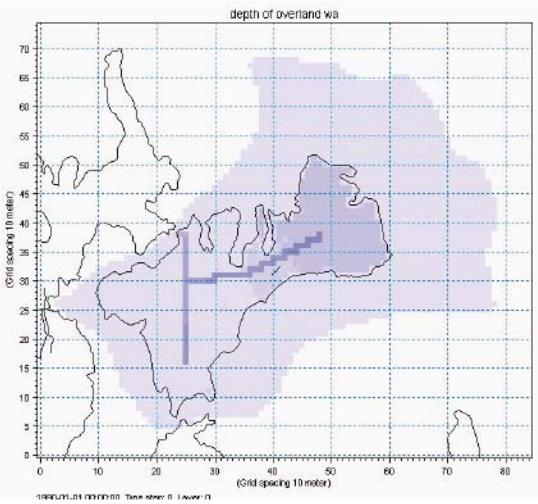
Depth of overland water, 1 September

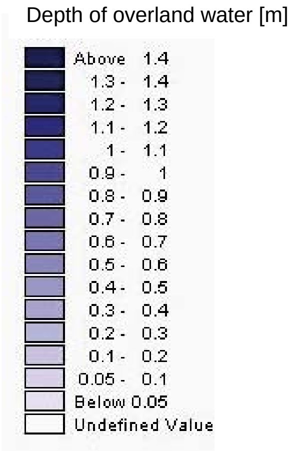
Depth of overland water, 31 December

Figure 5-17. *Mean depth of overland water (m) during one year of simulation, depth of overland water during the summer and depth of overland water during the winter for Eckarfjärden, case 2 (hemic peat and mesotrophic fen vegetation). See Table 5-5 for mean depths of overland water on the peat surface.*

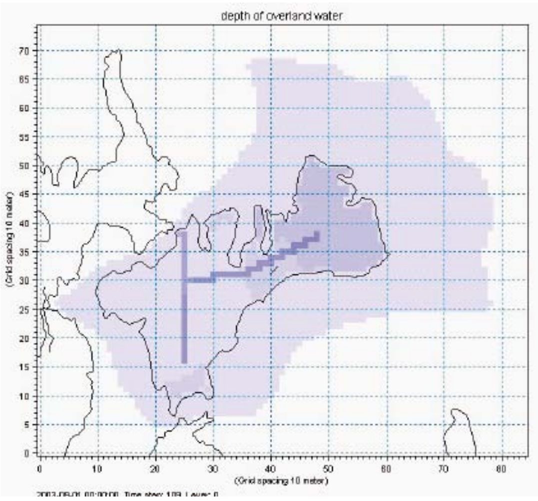
The depth of overland water on the assumed peat surface is relatively constant with different hydraulic properties of the peat, and is to a high degree affected by the amount of water that enters the formation through surface runoff. For the future mire at Bolundsfjärden, a mean value of 30 cm is calculated over an annual cycle. During high runoff during the winter, a mean water level of around 50 cm occurs. A water pressure gradient develops over the peat surface with a depth of overland water close to zero near the outlet. Eckarfjärden and Puttan have considerably lower runoff which results in lower depth of overland water and a smaller water pressure gradient over the peat surfaces.

The depth of overland water on the peat surfaces and the water pressure gradient that forms affects the groundwater head elevations and may contribute to the development of recharge areas where there during present conditions are discharge areas, see chapter 5.5.3.

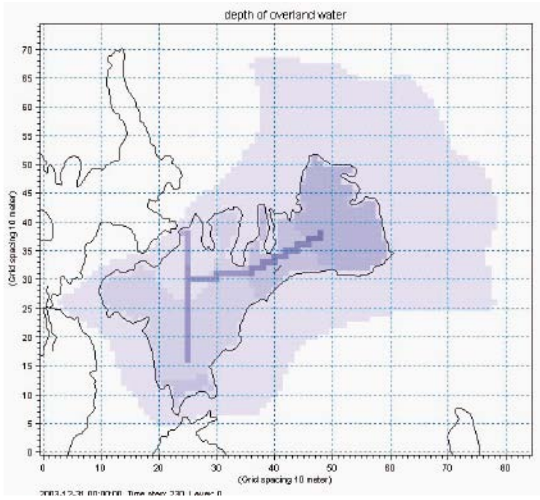




Mean depth of overland water, annual mean



Depth of overland water, 1 September



Depth of overland water, 31 December

Figure 5-18. *Mean depth of overland water (m) during one year of simulation, depth of overland water during the summer and depth of overland water during the winter for Puttan, case 7 (hemic peat and mesotrophic fen vegetation). See Table 5-5 for mean depths of overland water on the peat surface.*

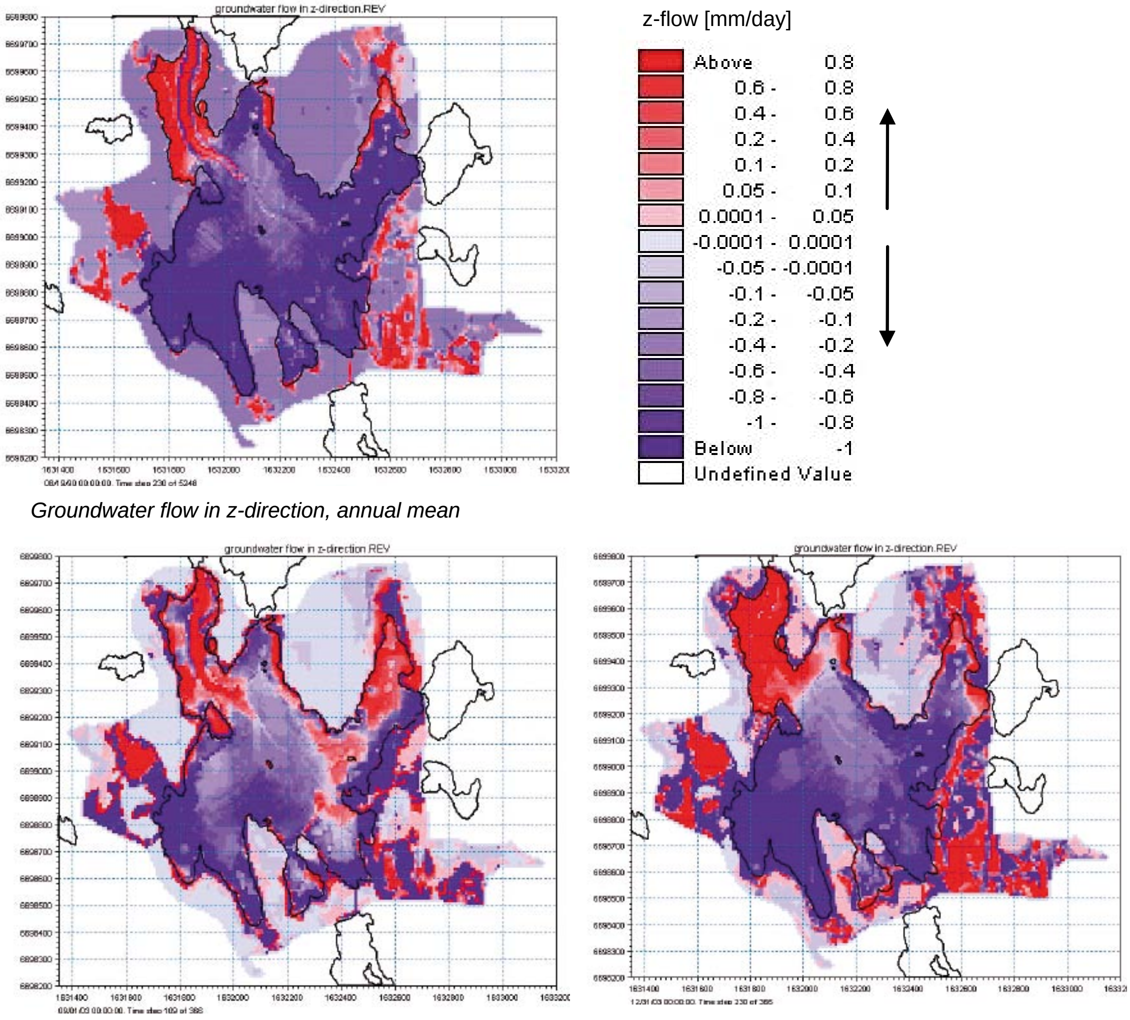
5.5.3 Groundwater flow pattern

Figure 5-19 illustrates the vertical groundwater flow for calculation layer two in Bolunds-fjärden, case 1 (hemic peat and mesotrophic fen). The flow velocities represent the actual groundwater flow to and from the mire, and defines the discharge and recharge areas of the model. Figure 5-20 and 5-21 show the vertical groundwater flow in calculation layer two for case 2, Eckarfjärden, and case 7, Puttan both cases with hemic peat and mesotrophic fen vegetation.

The vertical flow velocities into the mires are affected by the pressure of overland water, the presence of sediment barriers and the local boundaries.

Notable is that the discharge area in Bolundsfjärden during present condition has developed into a recharge area due to the increased overland water pressure on the mire. Close to the outlet of the mire, a discharge area is still present. The pressure from overland water on the peat surface is considerably lower in this area. In the western part of the catchment, a strong discharge area is found. A natural mire is situated in this area during present conditions, and thus remains a discharge area with the future assumed conditions, see Figure 5-19.

The same conditions forms for Eckarfjärden where the discharge area from present condition has developed into a recharge area due to the increased overland water pressure on the mire. A discharge area is still present around the shorelines near the outlet, see Figure 5-20.

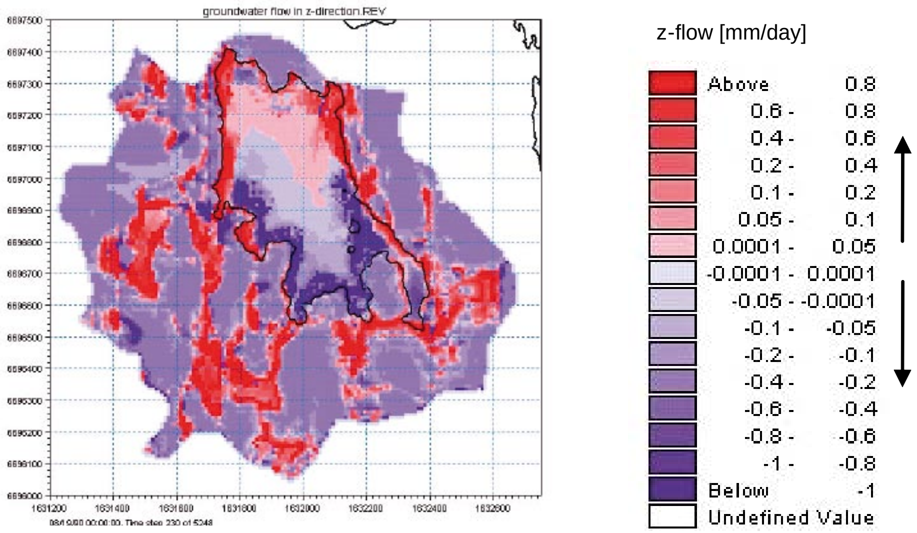


Groundwater flow in z-direction, annual mean

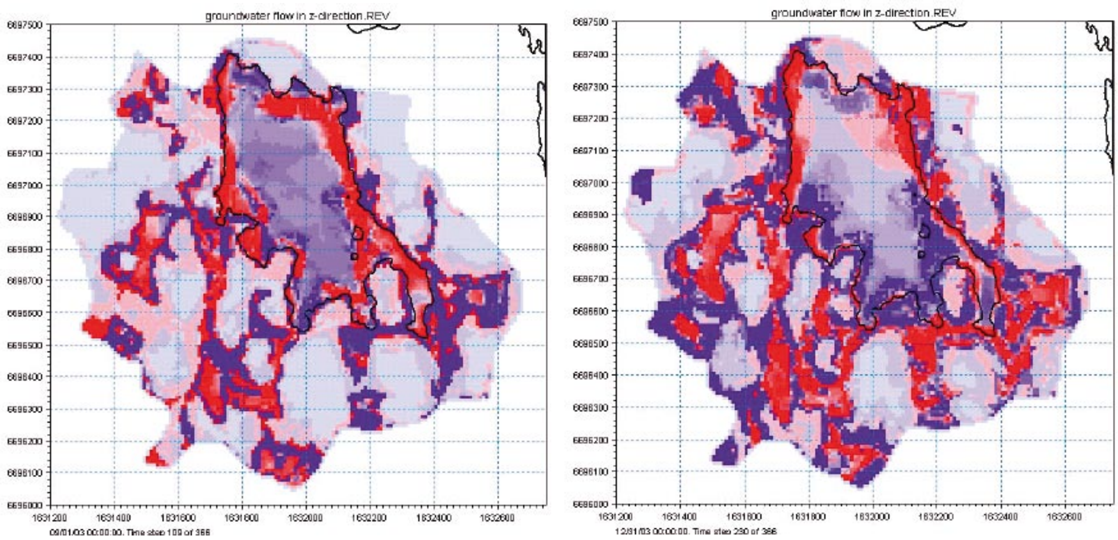
Groundwater flow in z-direction, 1 September

Groundwater flow in z-direction, 31 December

Figure 5-19. *Vertical groundwater flow (mm/day) in calculation layer two, e.i. strength of discharge and recharge area, case 1, Bolundsfjärden (hemic peat and mesotrophic fen vegetation). A blue colour tone represent a downwards groundwater flow (recharge area), a red colour tone represent an upwards groundwater flow (discharge area).*



Groundwater flow in z-direction, annual mean



Groundwater flow in z-direction, 1 September

Groundwater flow in z-direction, 31 December

Figure 5-20. *Vertical groundwater flow (mm/day) in calculation layer two, e.i. strength of discharge and recharge area, case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation). A blue colour tone represent a downwards groundwater flow (recharge area), a red colour tone represent an upwards groundwater flow (discharge area).*

The conditions differ for the future mire at Puttan which after the peat development still is a discharge area due to its naturally strong discharge position close to the sea, see Figure 5-21.

Figure 5-22 to 5-24 show the potential head elevations in calculation layer three, the uppermost layer of Quaternary deposits, with horizontal flow direction of the groundwater flow for case 1, Bolundsfjärden, case 2, Eckarfjärden and case 7, Puttan, all cases with hemic peat and mesotrophic fen vegetation.

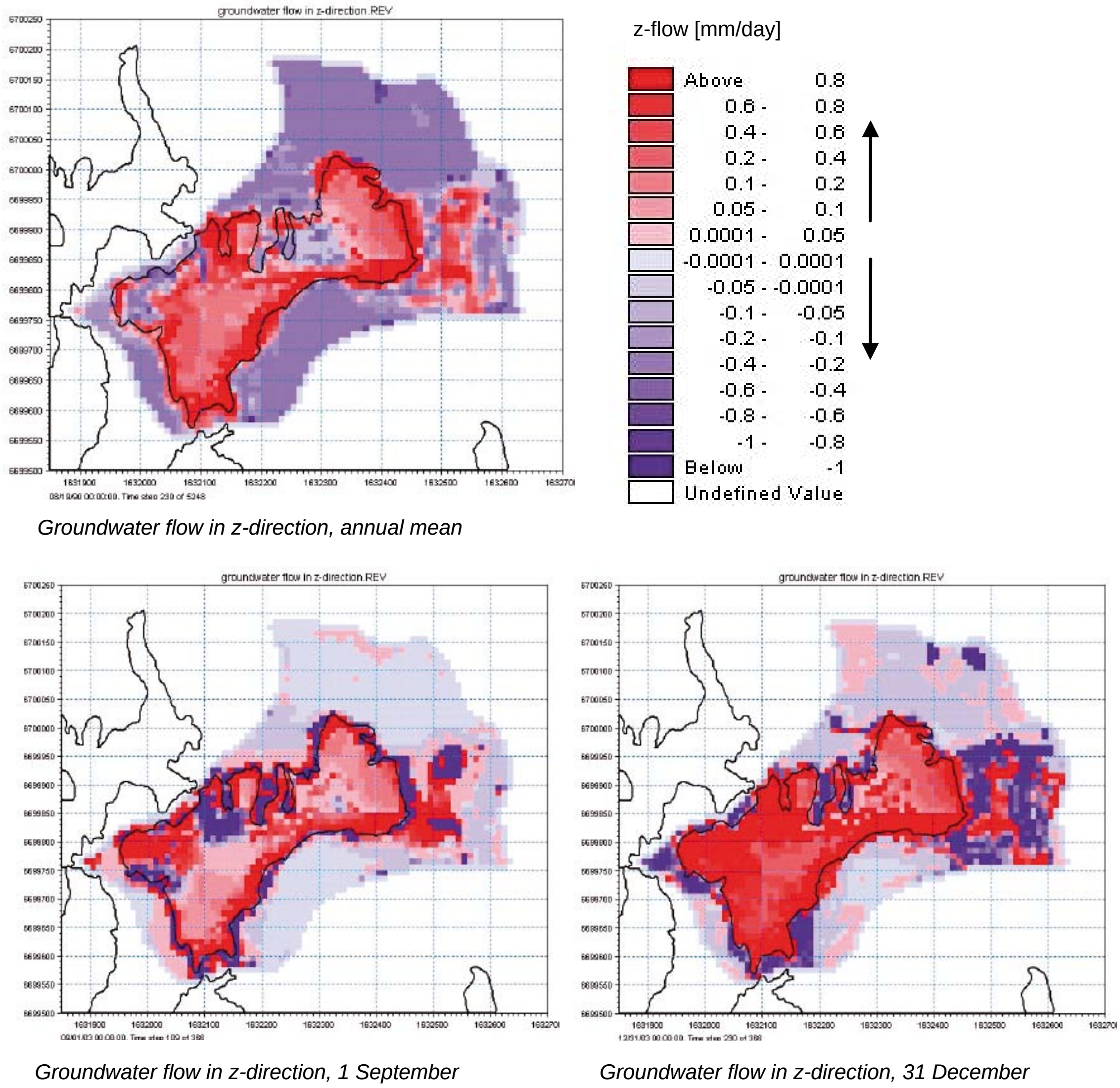
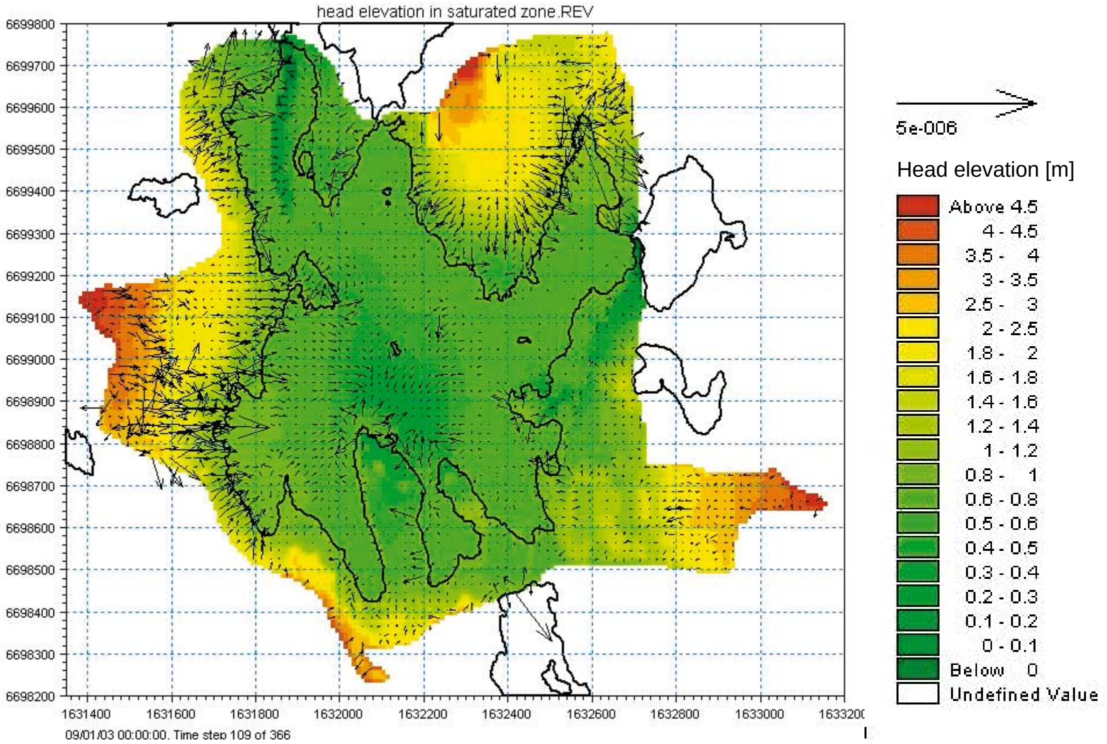


Figure 5-21. *Vertical groundwater flow (mm/day) in calculation layer two, e.i. strength of discharge and recharge area, case 7, Puttan (hemic peat and mesotrophic fen vegetation). A blue colour tone represent a downwards groundwater flow (recharge area), a red colour tone represent an upwards groundwater flow (discharge area).*

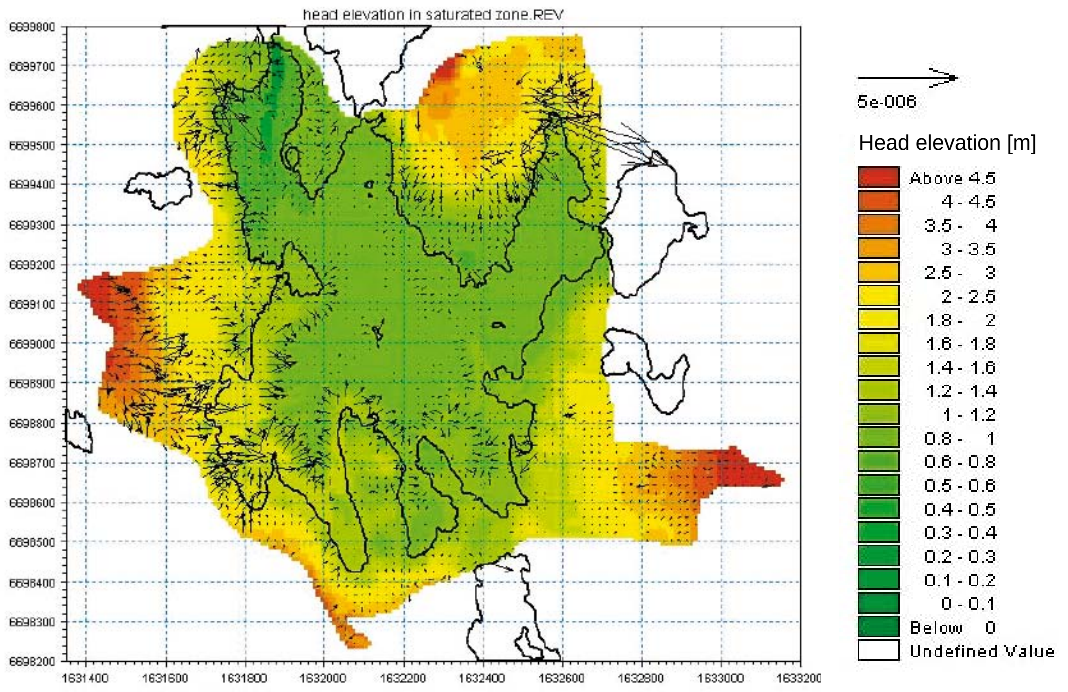
The flow direction is mainly vertical underneath the mire at Bolundsfjärden with very small horizontal flow velocities, see Figure 5-22. Higher horizontal velocities can be noted outside of the actual mire with a flow direction towards the peat.

The flow direction is mainly vertical underneath the mire at Eckarfjärden with small horizontal flow velocities in the centre of the formations and somewhat higher velocities around the shorelines. Outside of the mire, the velocities are generally higher with a direction towards the peat, see Figure 5-23.

For the mire at Puttan, no barrier in the form of a clay sediment layer is present, and the flow pattern shows more horizontal velocities than for Bolundsfjärden and Eckarfjärden. The high velocities by the northern shoreline of the mire is due to the relatively steep topography, see Figure 5-24.

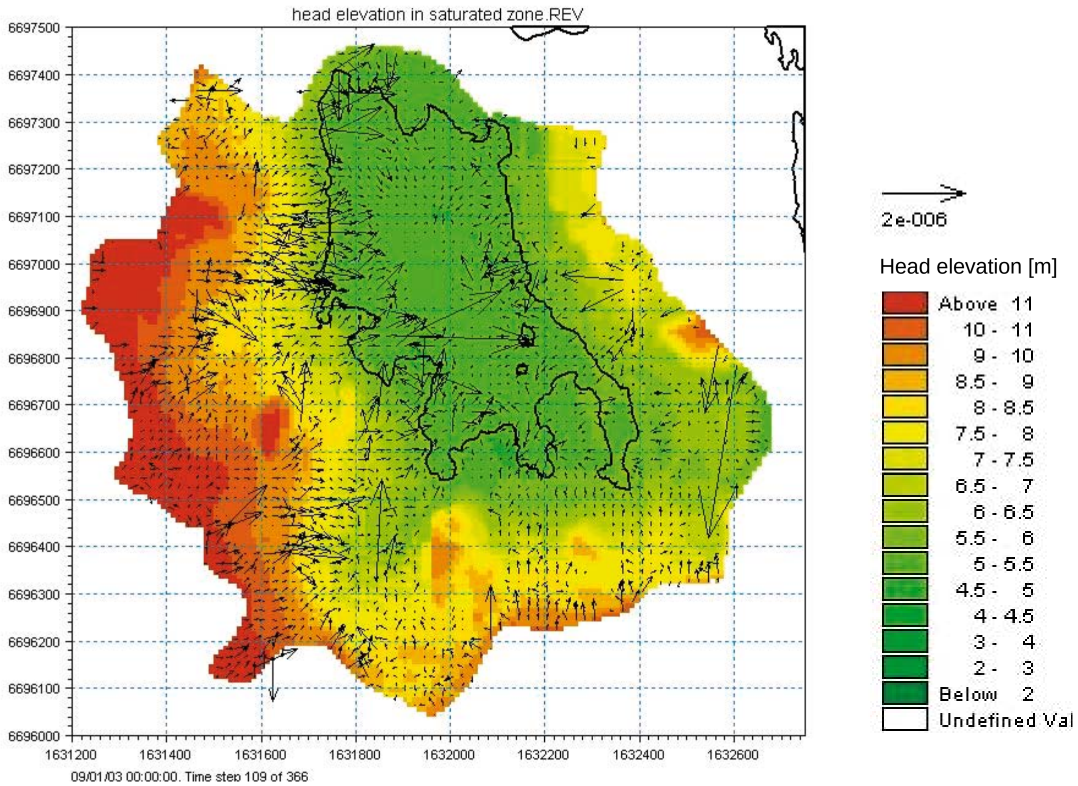


Head elevation and horizontal flow direction, 1 September

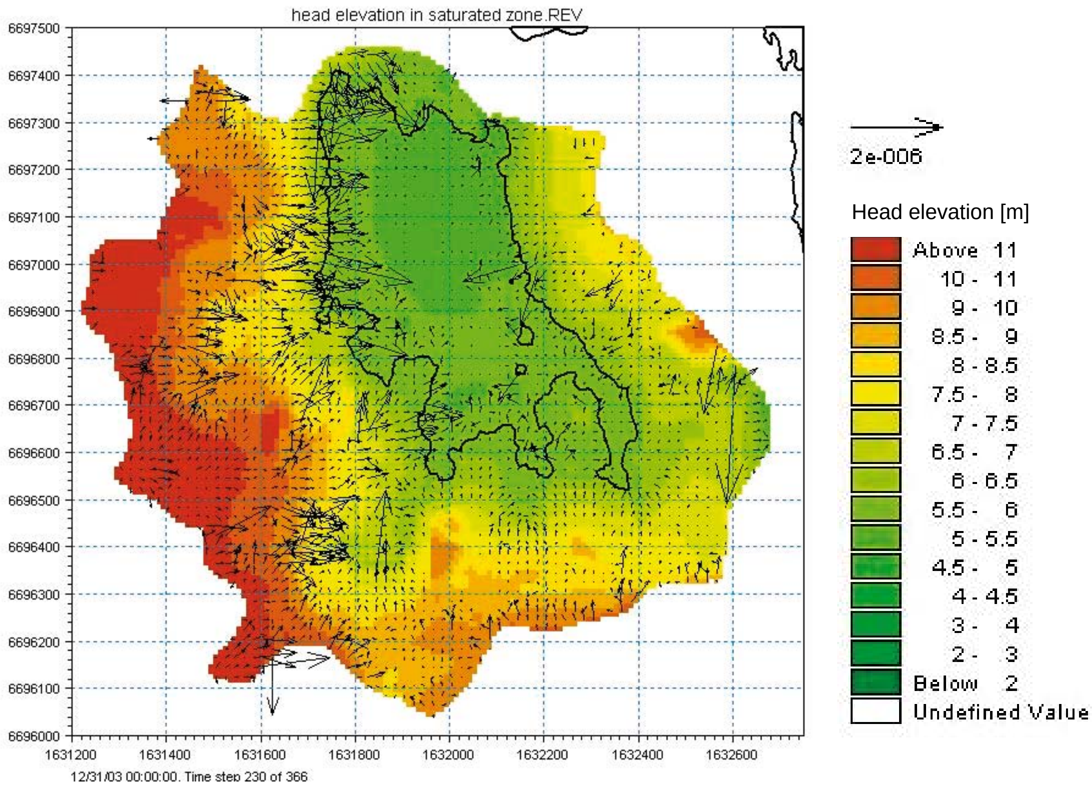


Head elevation and horizontal flow direction, 31 December

Figure 5-22. *Head elevation (m) and horizontal flow vectors (mm/day) in calculation layer three, case 1, Bolundsfjärden (hemic peat and mesotrophic fen vegetation).*

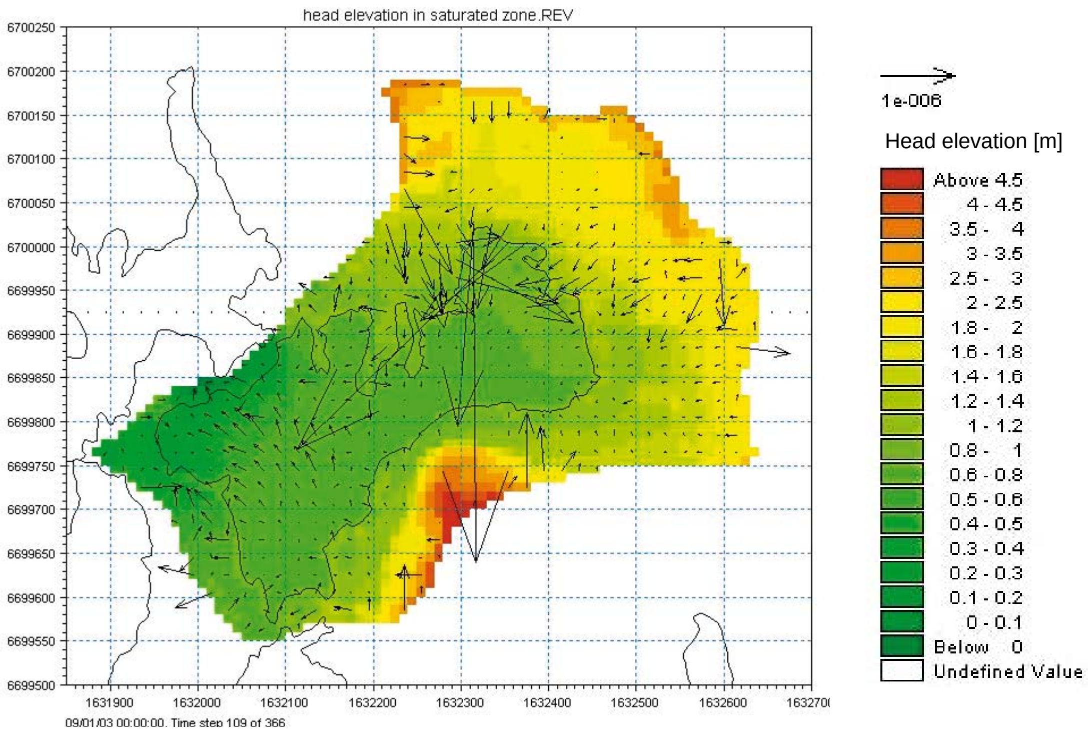


Head elevation and horizontal flow direction, 1 September

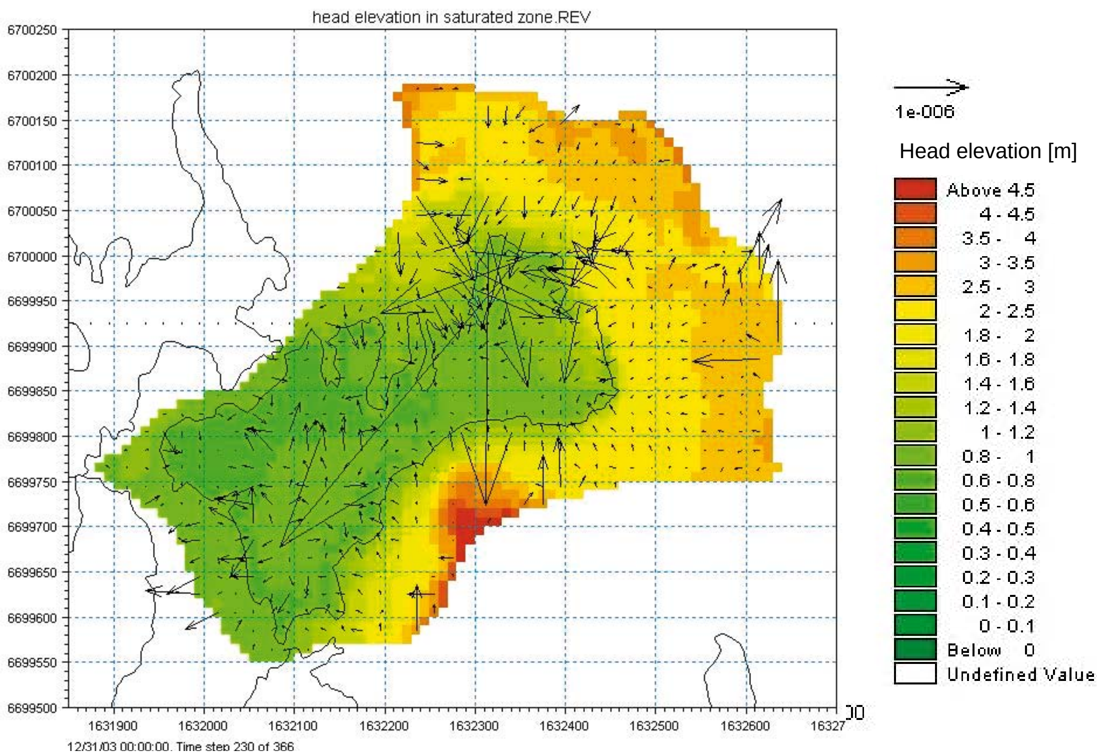


Head elevation and horizontal flow direction, 31 December

Figure 5-23. *Head elevation (m) and horizontal flow vectors (mm/day) in calculation layer three, case 2, Eckarfjärden (hemic peat and mesotrophic fen vegetation).*



Head elevation and horizontal flow direction, 1 September



Head elevation and horizontal flow direction, 31 December

Figure 5-24. *Head elevation (m) and horizontal flow vectors (mm/day) in calculation layer three, case 7, Puttan (hemic peat and mesotrophic fen vegetation).*

6 Transport modelling

To evaluate the effect on the wetlands of a radionuclide being transported from the deep repository, transport modelling has been performed on a number of the defined simulation cases.

The solute is assumed to enter the model through the bottom layer, simulating the effect of an upward transport through the bedrock. A surface source is assumed to enter the peat through the local stream inflows, simulating the effect of a pollutant that has already reached the surface in the upstream areas.

Three types of processes are included in the transport modelling; advection, dispersion, and sorption.

The simulation period was set to 100 years, from 2003 to 2103. Flow results from the one year water movement simulation were cycled from 2003-15-15 to 2004-05-15.

6.1 Solute transport in groundwater

The transport of solutes in the saturated zone is governed by the advection-dispersion equation, which for a porous medium with uniform porosity distribution is formulated as follows:

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x_i}(cv_i) + \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right) + R_c \quad i, j = 1,2,3$$

where

c concentration of the solute (mass·m^{-3}),

R_c represents sources or sinks (mass·m^{-3}·s^{-1}),

D_{ij} dispersion coefficient tensor (m^{-2}·s^{-1}),

v_{i} velocity tensor (m·s^{-1}).

The advective transport is determined by the water fluxes (Darcy velocities) calculated by the groundwater flow model. In order to determine the groundwater velocity the Darcy velocity is divided by the effective porosity:

$$v_i = \frac{q_i}{\theta}$$

where

q_i Darcian velocity vector (m·s^{-1}),

θ effective porosity of the medium (–).

The mathematical formulation of the dispersion of the solutes follows the traditional formulations generalised to three dimensions. This formula was developed under the assumption that the dispersion coefficient is a linear function of the mean velocity of the solutes. In the three-dimensional case of arbitrary flow-direction in an anisotropic aquifer the dispersion tensor, D_{ij} ($m^{-2} \cdot s^{-1}$), contains 9 elements which depend on 36 'dispersivities'. The dispersion tensor is often simplified into:

$$D_{xx} = \left[\alpha_T \left(V_y^2 + V_z^2\right) + \alpha_L V_x^2\right] / U$$
$$D_{yy} = \left[\alpha_T \left(V_x^2 + V_z^2\right) + \alpha_L V_y^2\right] / U$$
$$D_{zz} = \left[\alpha_T \left(V_x^2 + V_y^2\right) + \alpha_L V_z^2\right] / U$$
$$D_{xy} = \left(\alpha_L - \alpha_T\right) V_x V_y / U = D_{yx}$$
$$D_{xz} = \left(\alpha_L - \alpha_T\right) V_x V_z / U = D_{zx}$$
$$D_{yz} = \left(\alpha_L - \alpha_T\right) V_y V_z / U = D_{zy}$$

where α_L (m) and α_T (m) are the longitudinal and transversal dispersivities respectively of the porous medium.

The dispersion term in the advection-dispersion equation accounts for the spreading of solutes that is not accounted for by the simulated mean flow velocities i.e. the advection. Therefore, it is obvious that the more accurate you describe the spatial variability in the hydrogeological regime and if the grid is sufficiently fine (i.e. the variations in the advective velocity) the smaller dispersivities you need to apply in the model. This is the general equation for dispersion coefficients in an isotropic medium for arbitrary mean flow direction, which is being used in the simulations performed here.

The source/sink term R_c may contain changes in concentration due to geochemical reactions between the solute and the soil matrix or chemical reactions between different solutes (in case of multi-species transport simulation). Often geochemical reactions are described by macro parameters such as retardation coefficients and degradation (decay) constants. Such parameter values are often found in the literature for specific solutes under different soil conditions, but may be subject for calibration if concentration measurements have been carried out. Often K_d and log K_{ow} may be used to determine retardation factors.

For further description, see /DHI 2003b/.

6.2 Sorption

Sorption processes cover a number of geochemical and chemical reactions such as adsorption of solutes to the aquifer material surface by electrostatic forces (called cation exchange). If these processes occur sufficiently fast compared to the water flow velocity they can be described by an equilibrium sorption isotherm.

MIKE SHE AD includes three of the most commonly applied isotherms; the linear, Freundlich and Langmuir equilibrium sorption isotherms.

Sorption processes that do not occur sufficiently fast compared to the water flow velocities have to be described by a kinetic sorption isotherm. In MIKE SHE AD, the three equilibrium sorption isotherms have been extended to include a kinetically controlled sorption process so that a certain part of the sorbed matter is "transferred" to another part of the soil material.

The linear sorption isotherm is mathematically the simplest isotherm and can be described as a linear relationship between the amount of solute sorbed onto the soil material and the aqueous concentration of the solute:

$$c^*_i = K_d c$$

where K_d is known as the distribution coefficient ($m^3 \cdot mass^{-1}$).

A commonly used term is the retardation factor, R, which is the ratio between the average water flow velocity, v, and the average velocity of the solute plume, v_c, can be given as:

$$R = \frac{v}{v_c} = 1 + \frac{\rho_b}{\theta} K_d$$

where

ρ_b bulk density ($mass \cdot m^{-3}$),

θ effective porosity of the medium (–).

For further description, see /DHI 2003b/.

6.3 Definition of evaluation cases of future wetlands

Two of the hypothetical cases defined in chapter 5.2 have been modelled with respect to transport of solutes; case 1 for Bolundsfjärden and case 7 for Puttan. For each case, different dispersivities and sorption conditions are simulated, see Table 6.1.

Two different solutes have been defined, one entering the model at the very bottom calculation layer (at a depth of 10 m from the peat surface), and one at the surface in the main water course for Bolundsfjärden. Puttan, is only charged with solutes in the bottom layer. The source strength was set to a constant value of 1,000 units expressed as $g \cdot m^{-3}$, evenly distributed over the bottom layer.

Table 6-1 shows the simulation cases for the transport modelling.

The overland source was only introduced in simulation case Bolund 1-high. No dispersion on the surface is applied on the overland source.

Table 6-1. Simulation cases for sensitivity analyses of transport processes in future wetlands.

Simulation parameter	Simulation case – sensitivity analysis					
	Bolund1-high	Bolund2-low	Bolund3-sorption	Puttan4-high	Puttan5-low	Puttan6-sorption
Dispersivity: Longitudinal/Transversal	2/0.1	0.2/0.01	0.2/0.01	2/0.1	0.2/0.01	0.2/0.01
Adsorption for soil, K_d ($m^3 \cdot g^{-1}$)	–	–	1e–7	–	–	1e–7
Adsorption for bedrock, K_d ($m^3 \cdot g^{-1}$)	–	–	1e–10	–	–	1e–10
Bulk density ($kg \cdot m^{-3}$)			1,600			1,600

6.4 Results from transport modelling in future wetlands

Results from the transport modelling are presented with respect to spatial and vertical extension of the pollutants at different times and depths from ground surface.

6.4.1 Transport of pollutant from bottom layer source

Results for the future mire at Bolundsfjärden

Figure 6-1 to 6-3 show the concentration in the saturated zone for case 1, Bolundsfjärden for a solute introduced in the bottom layer (at a depth of 10 m from the peat surface), using high dispersivities. The source was set to a constant value of 1,000 arbitrary units, in this case expressed as $g \cdot m^{-3}$.

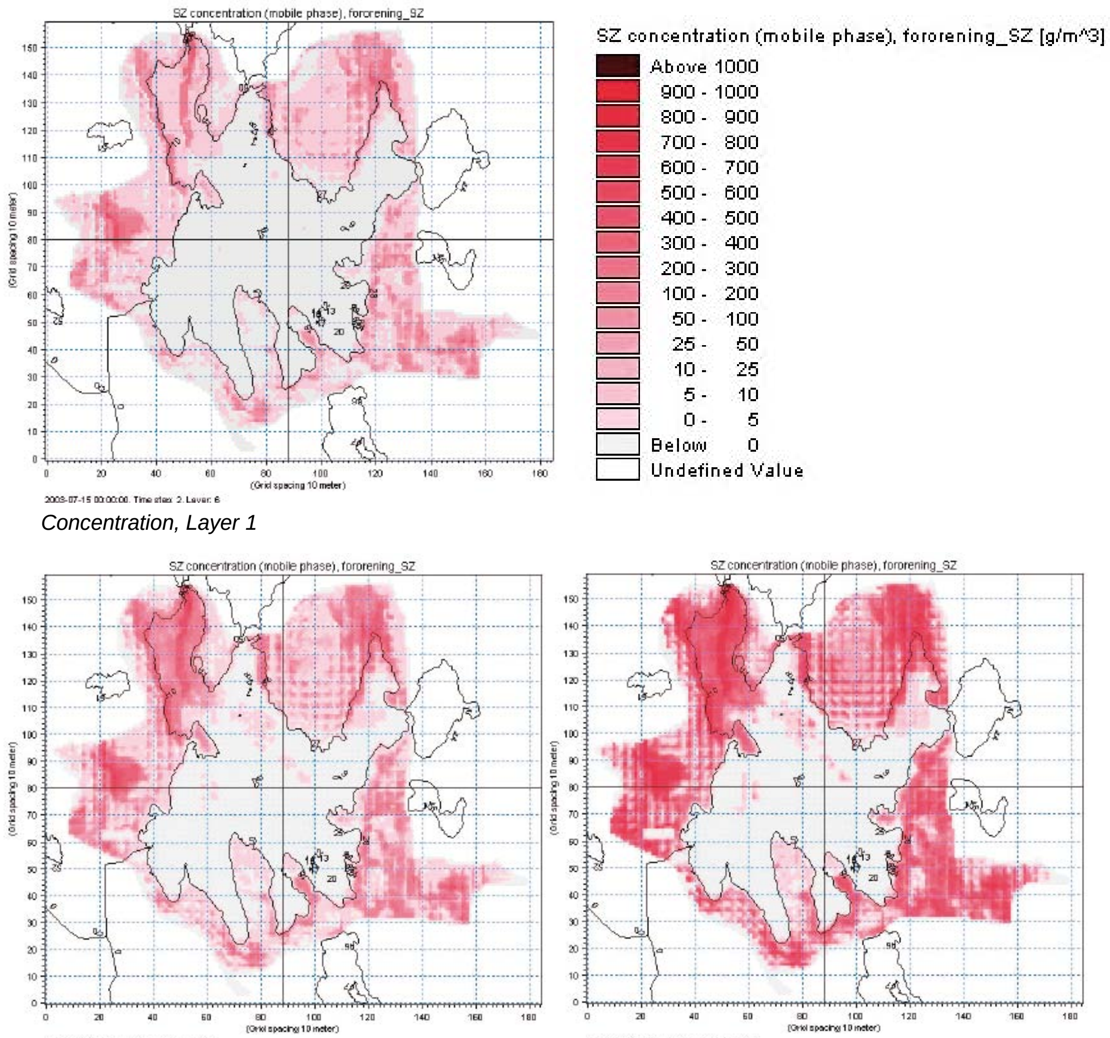


Figure 6-1. *Concentrations (arbitrary units, in the figure expressed as $g \cdot m^{-3}$) after 2 months, case 1, Bolundsfjärden, using high dispersivities. See Table 6-2 for a summary of approximate solute concentrations in different areas of the mire.*

After two months from the solute introduction in the bottom layer of the model, the concentrations are low in larger parts of the mire. Close to the outlet, where there is an upward going flow pattern and no clay sediment, the concentrations reach around 500 units (expressed as g·m^{-3}) in calculation layer 5 and around 1 units (g·m^{-3}) in the uppermost calculation layer. The concentrations are higher west of the mire by the natural wetland, see Figure 6-1.

After one year from the solute introduction in the bottom layer of the model, the concentrations are low near the inlet to the mire, where there is a downward going flow and a high pressure from overland water. Close to the outlet, the concentrations reach around 600 units (g·m^{-3}) in calculation layer 5 and around 150 units (g·m^{-3}) in the uppermost calculation layer (the watercourse not included), see Figure 6-2.

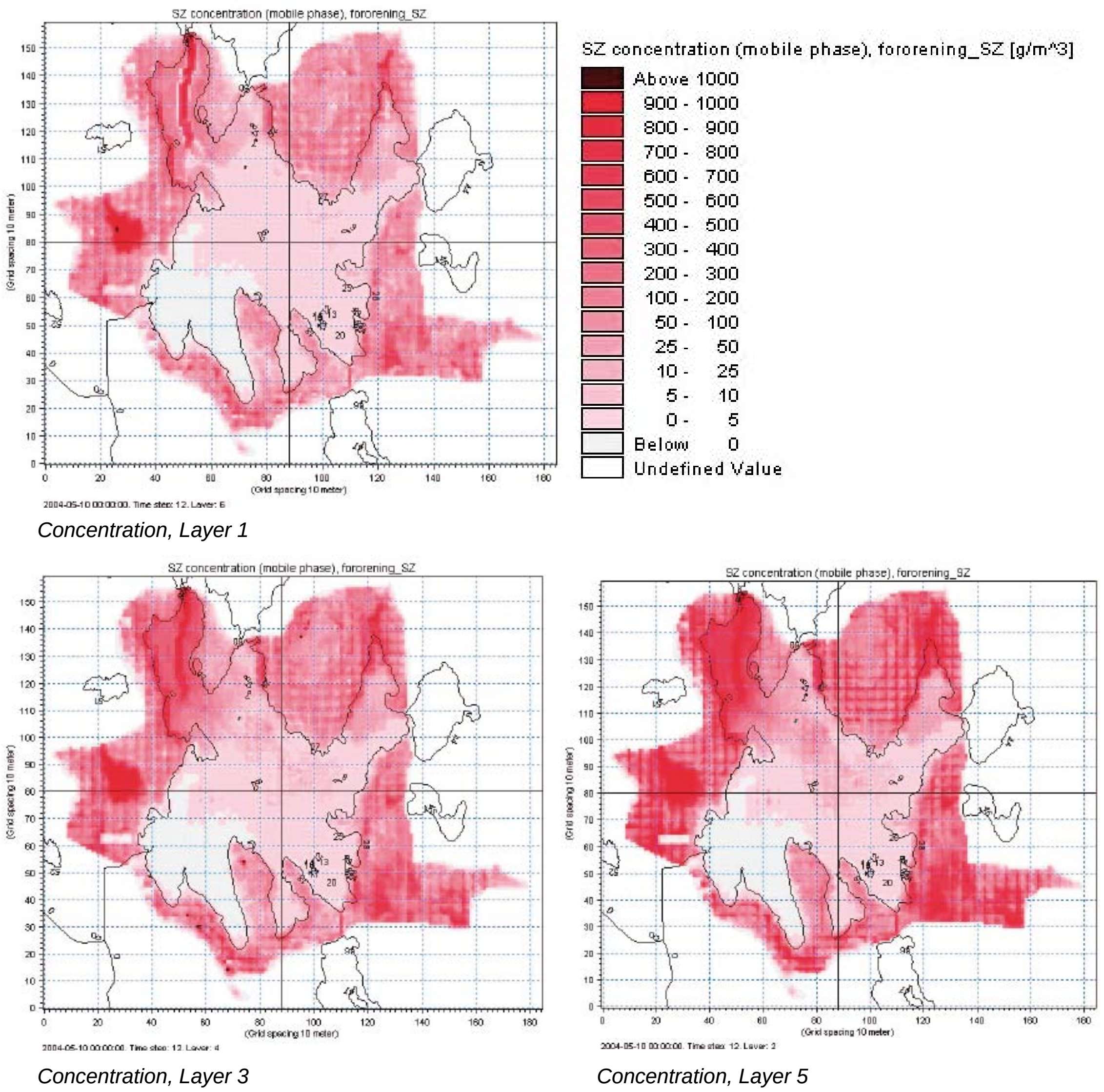


Figure 6-2. *Concentrations (arbitrary units, in the figure expressed as g·m^{-3}) after 1 year, case 1, Bolundsfjärden, using high dispersivities. See Table 6-2 for a summary of approximate solute concentrations in different areas of the mire.*

After ten years from the solute introduction in the bottom layer of the model, the concentrations are still low near the inlet to the mire, where there is a downward going flow and a high pressure from overland water. Close to the outlet, the concentrations reach around 850 units ($g \cdot m^{-3}$) in calculation layer 5 and around 600 units ($g \cdot m^{-3}$) in the uppermost calculation layer (the watercourse not included). For the natural wetland west of the mire, source concentration is reached at all depths, see Figure 6-3.

The results show that the concentrations are transported quickly towards the surface in discharge areas. For the recharge area that develops in large parts of the mire, the solute is mainly transported through horizontal dispersion, which results in low concentrations. The solute concentration is at the lowest where the overland water pressure is at the highest close to the south western inlet.

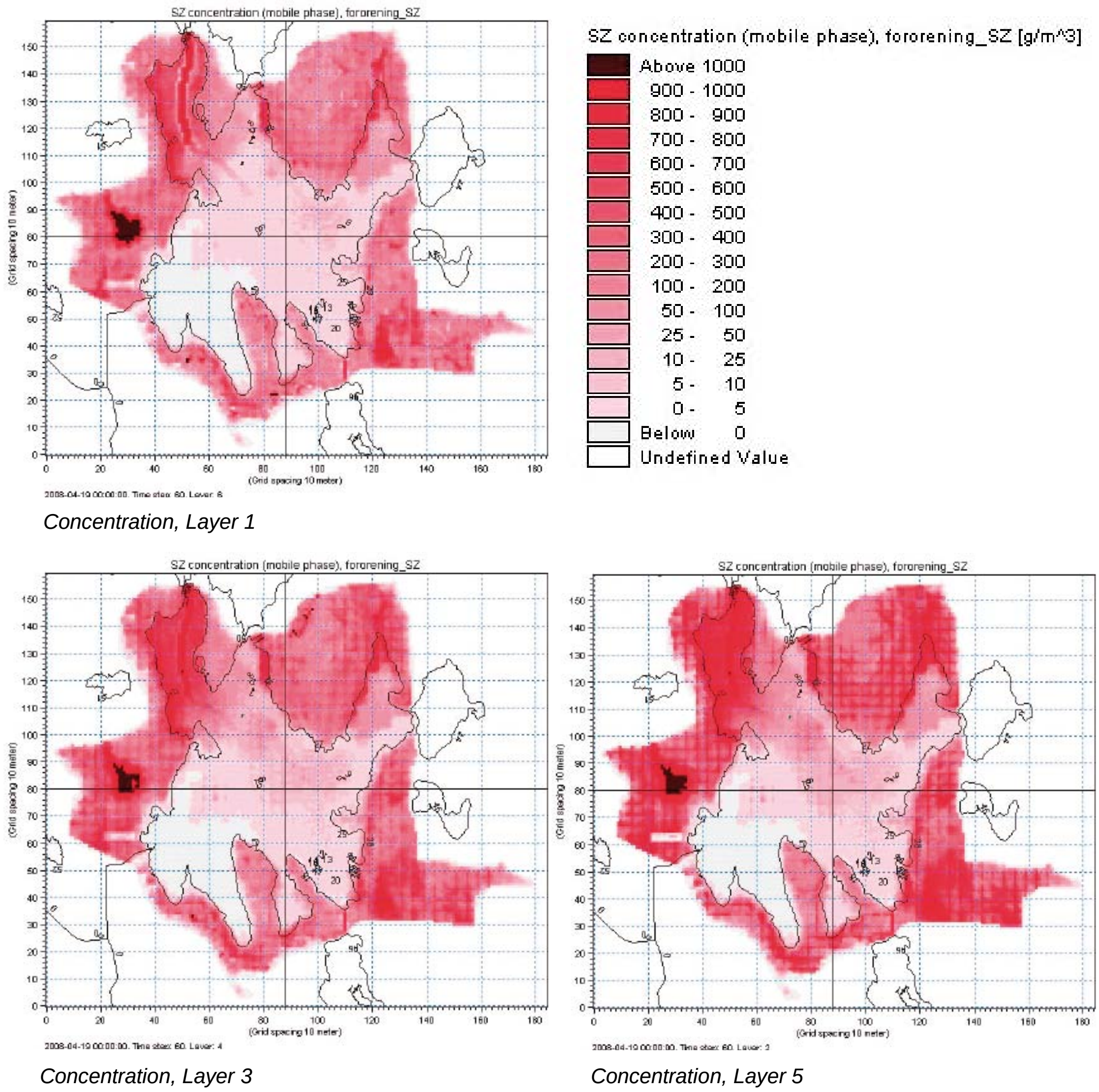


Figure 6-3. *Concentrations (arbitrary units, in the figure expressed as $g \cdot m^{-3}$) after 10 years, case 1, Bolundsfjärden, using high dispersivities. See Table 6-2 for a summary of approximate solute concentrations in different areas of the mire.*

After about two months, the concentration at the uppermost layer near the outlet is around 1 units (g·m^{-3}). In the middle part the concentration is zero. West of the hypothetical mire, a natural wetland that exist also during present conditions show a concentration of around 200 units (g·m^{-3}).

Figure 6-4 shows three areas from which average solute concentrations are presented in Table 6-2. The figure also show the location of two grid cells from which detailed results are shown in Figures 6-5 to 6-7.

Table 6-2 shows the approximate solute concentrations at the three areas shown in Figure 6-4 for different calculation layers after 2 months, 1 year and 10 years after introduction of the solute.

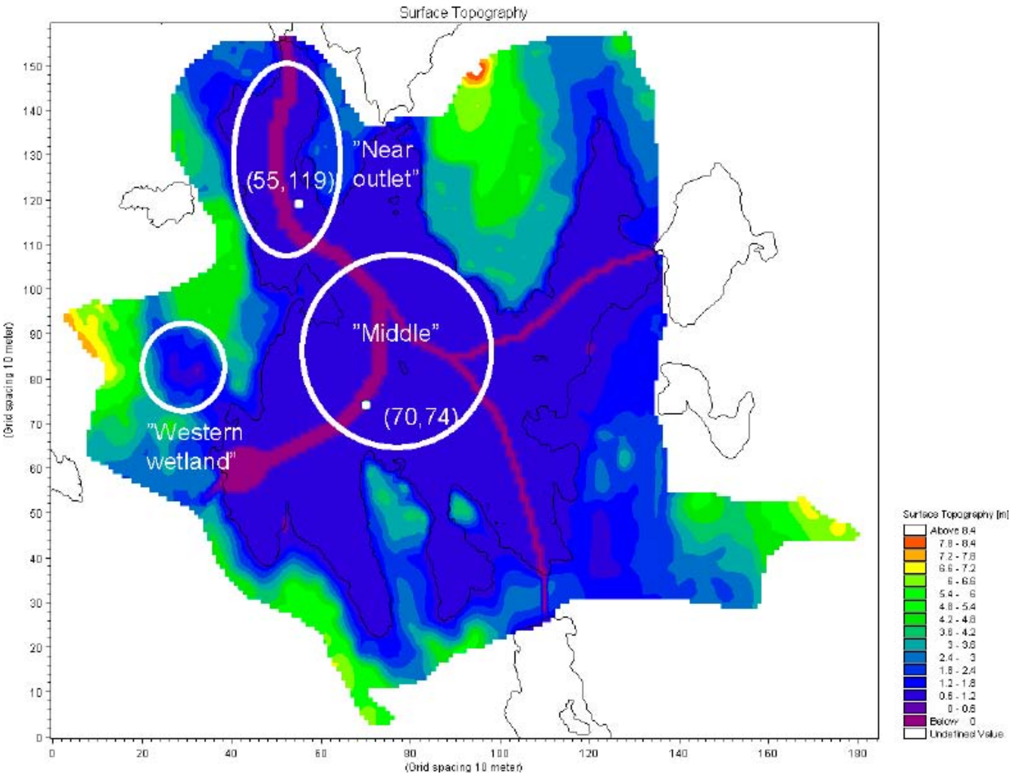


Figure 6-4. *White dots show the location of grid cell (70,74) and (55,119) and white circles the location of areas for approximate solute concentration in Table 6-2.*

Table 6-2. Approximate solute concentration in different areas of the future mire at Bolundsfjärden (arbitrary units, in the table expressed as g·m^{-3}). For location of areas, see Figure 6-4.

Time since solute introduction	Near outlet, L1	Near outlet, L3	Near outlet, L5	Middle, L1	Middle, L3	Middle, L5	Western wetland, L1	Western wetland, L3	Western wetland, L5
2 months	1	70	500	0	0	0	200	400	650
1 year	150	300	600	0.5	1	2	900	900	980
10 years	600	750	850	1	3	5	1,000	1,000	1,000

Figure 6-5 show the concentrations at three calculation layers for grid cell (70,74), situated in a strong recharge area. This area of the mire has an underlying barrier as the sediments consist of both gyttja and clay. A stationary condition is reached after around 10 years.

Grid point (55,119) is situated in the northern part of Bolundsfjärden at a considerably stronger discharge area. Figure 6-6 presents the concentrations at three calculation layers. A stationary condition is reached after around 10 years.

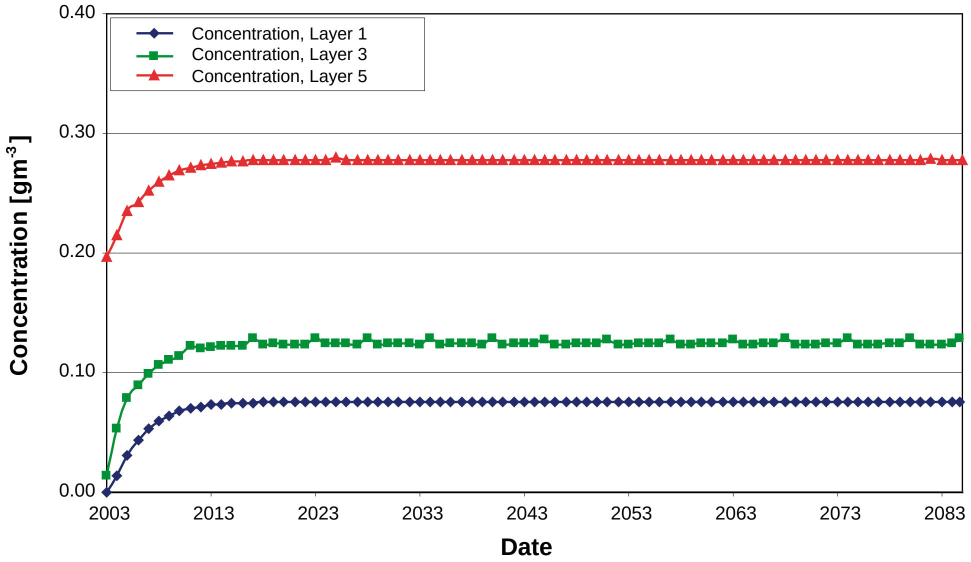


Figure 6-5. *Annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) at calculation layer 1, 3 and 5 for cell (70,74), Bolundsfjärden, using high dispersivities. For location of the cell, see Figure 6-4.*

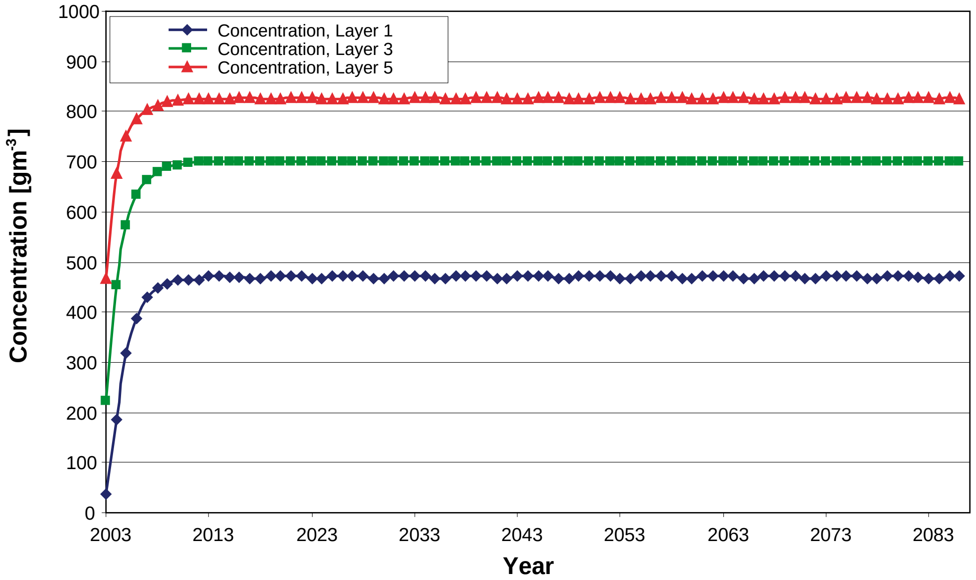


Figure 6-6. *Annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) at calculation layer 1, 3 and 5 for cell (55,119), Bolundsfjärden, using high dispersivities. For location of the cell, see Figure 6-4.*

Figure 6-7 show the results from the sensitivity analyses of dispersion and sorption coefficients for cell (70,74), located in a recharge area with underlying sediment barriers, in layer three. The vertical flow velocities are very low in this area, and the highest concentrations are reached with high dispersivities that transport the solute by horizontal dispersion from neighbouring discharge areas.

Figure 6-8 show the results from the sensitivity analyses of dispersion and sorption coefficients for cell (55,119), located in a discharge area with no underlying sediment barriers, in layer three. The low dispersivities results in the highest concentrations in this area as the

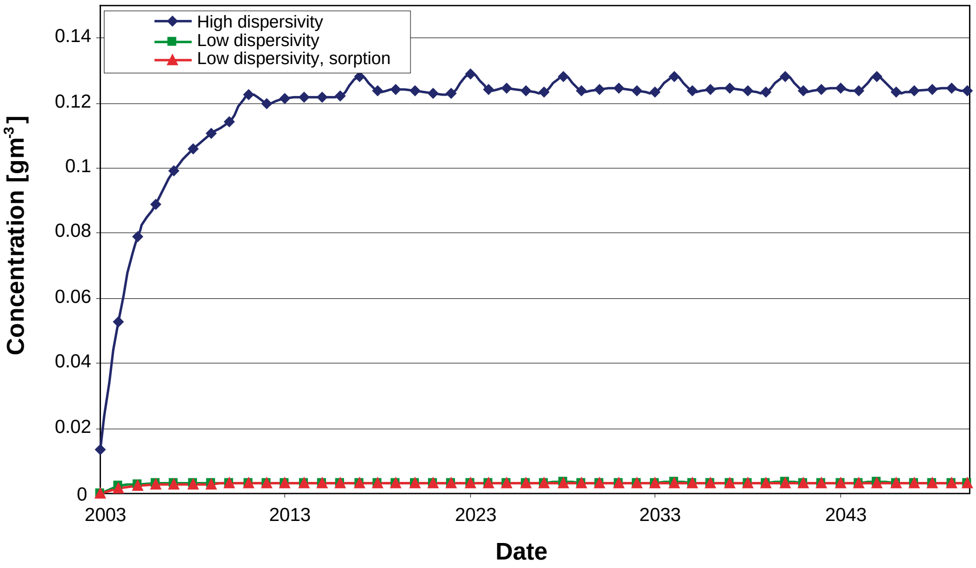


Figure 6-7. *Comparison of annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) in cell (70,74,3) for the different dispersion and sorption parameters, Bolundsfjärden. For location of the cell, see Figure 6-4.*

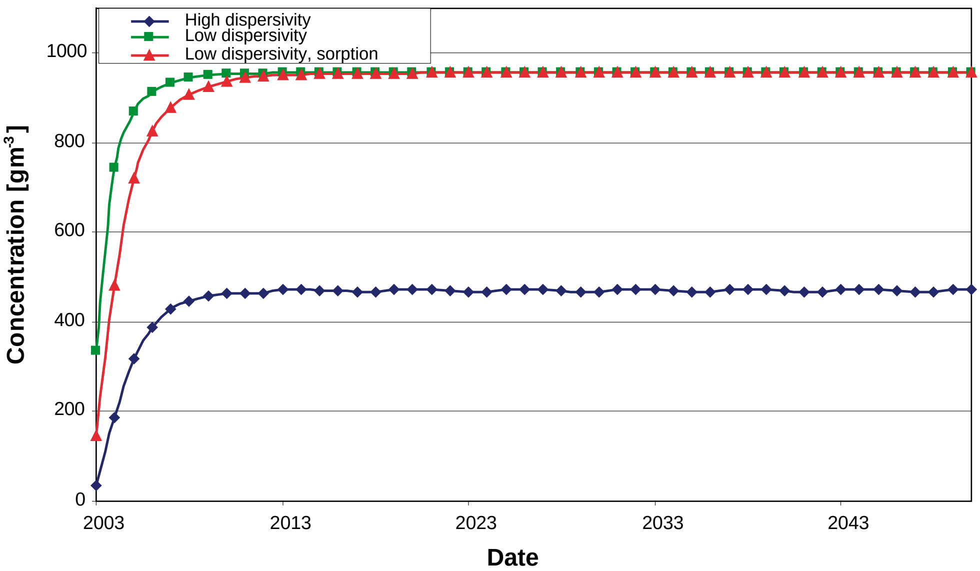


Figure 6-8. *Comparison of annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) in cell (55,119,3) for the different dispersion and sorption parameters, Bolundsfjärden. For location of the cell, see Figure 6-4.*

solute transport is mainly advective (velocity driven). At higher dispersivities, there is a horizontal loss of solute concentration in lower layers. When sorption is taken into account, the initial horizontal loss of concentration results in lower solute concentration in calculation layer three and the maximum levels are reached after a longer period.

The storage capacity and sorption is higher in the beginning of the simulation and equals zero when stationary concentration conditions are reached in the whole model domain. Figure 6-9 show the accumulated sorption and the accumulated sorption in relation to accumulated solute input for the mire at Bolundsfjärden. The sorption process is effective in the beginning of the simulation and decreases with time. A stationary condition when no further solute is sorbed to the soil is reached after about 20 years for the whole model area.

The sorbed solute concentration after 80 years of simulation is shown in Figure 6-10. The highest amount of sorbed concentration is found in calculation layer 3, the uppermost layer of Quaternary deposits. The K_d values are set to $1e^{-7}$ $m^3 \cdot g^{-1}$ for both the mire and the Quaternary deposits, and $1e^{-10}$ for the lower bedrock which leads to a lower sorption in calculation layer 5.

The retardation or sorption is also affected by the effective porosity of each layer, a higher effective porosity giving a lower retardation. The peat used in the solute transport simulations has an effective porosity of 0.8 for the fibric peat and 0.49 for the hemic peat, the uppermost layer of Quaternary deposits has an effective porosity of 0.15 under Bolundsfjärden. With the presence of Sapric peat that has a lower effective porosity, the retardation would increase.

The sorption in the actual mire is lower than in the uppermost Quaternary deposits due to the large amount of solute that is sorbed before it enters the mire and the effect of the effective porosity.

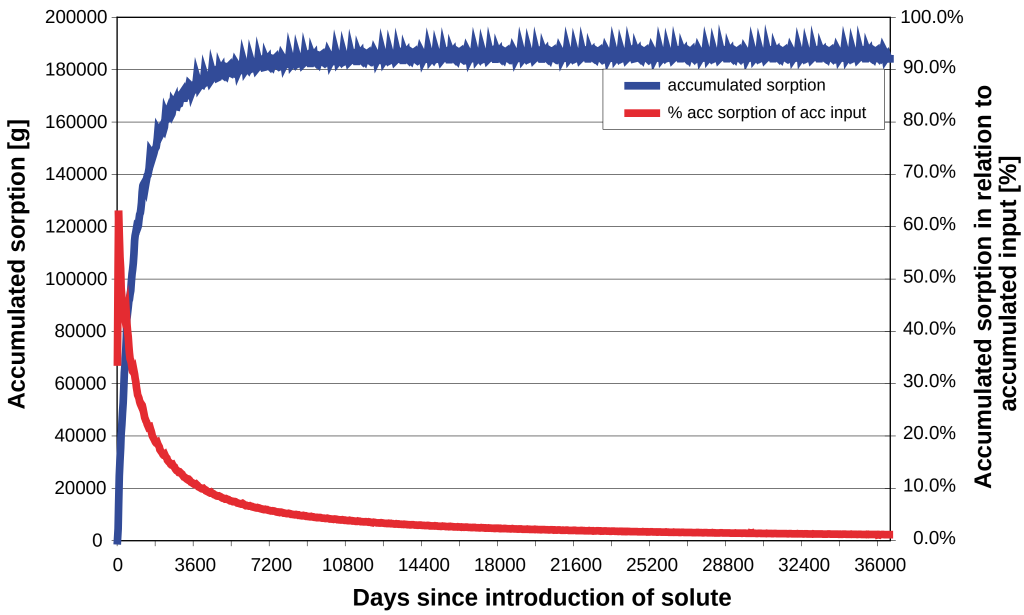
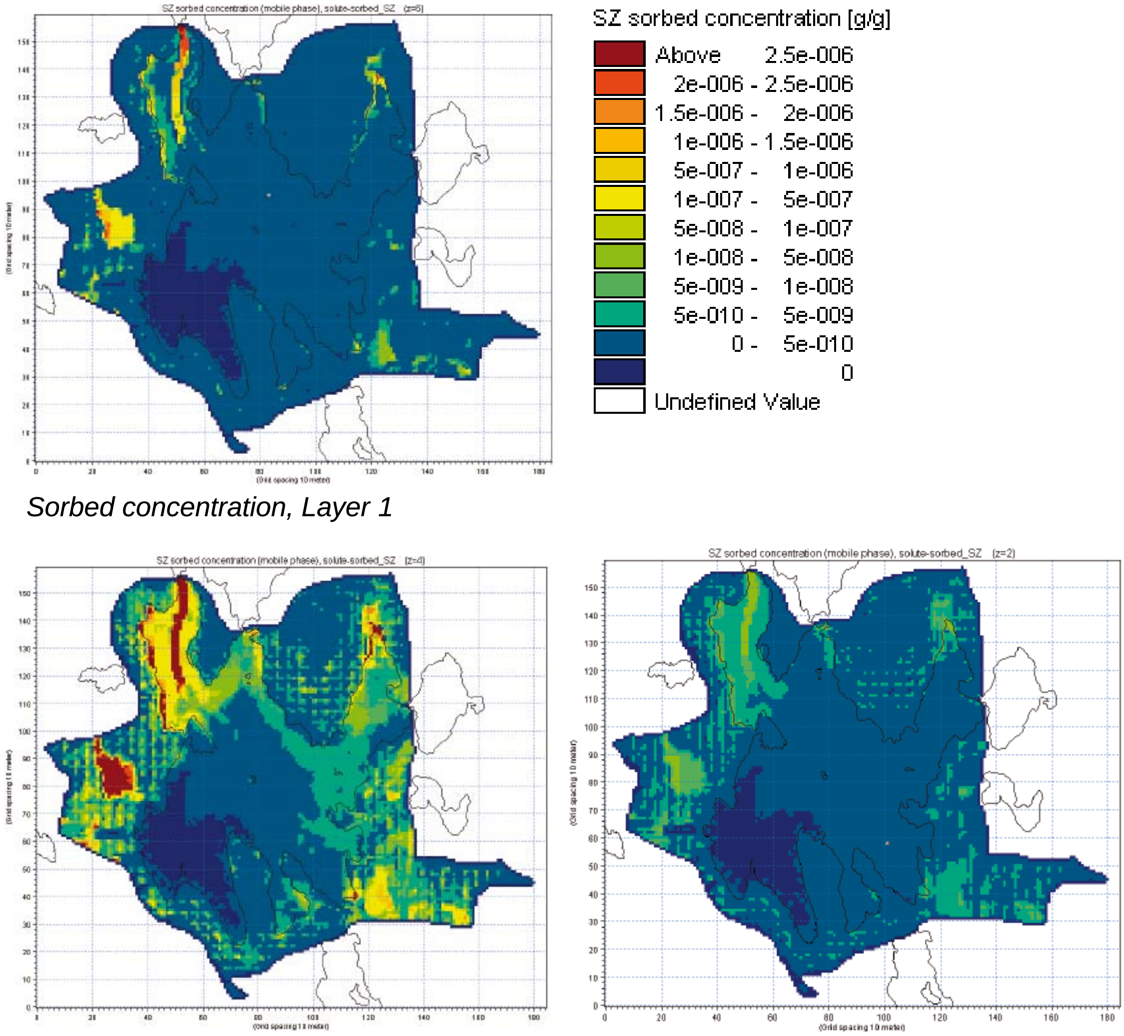


Figure 6-9. *Accumulated sorption and accumulated sorption in relation to accumulated solute input for the mire at Bolundsfjärden, case 3.*



Sorbed concentration, Layer 1

Sorbed concentration, Layer 3

Sorbed concentration, Layer 5

Figure 6-10. *Sorbed concentrations (arbitrary units, in the figure expressed as g/g) after 80 years, case 3, Bolundsfjärden, using low dispersivities and sorption.*

Figure 6-11 presents a schematic annual mass balance at three times for the different dispersivities used in the transport simulations for the future mire at Bolundsfjärden. The mass balances represent the total model areas and not only the mires.

As the annual periods that are presented in the figures differ slightly in actual dates, the net input from the bedrock differs somewhat within one description of dispersivities and sorption.

The storage capacity and sorption is higher in the beginning of the simulation and equals zero when stationary concentration conditions are reached in the whole model domain. With high dispersivities this occurs after approximately 10 years, with low dispersivities after 5 years and with sorption after 10 years, see Figure 6-8. The transport to upper layers and the surface increase as the storage and sorption decrease.

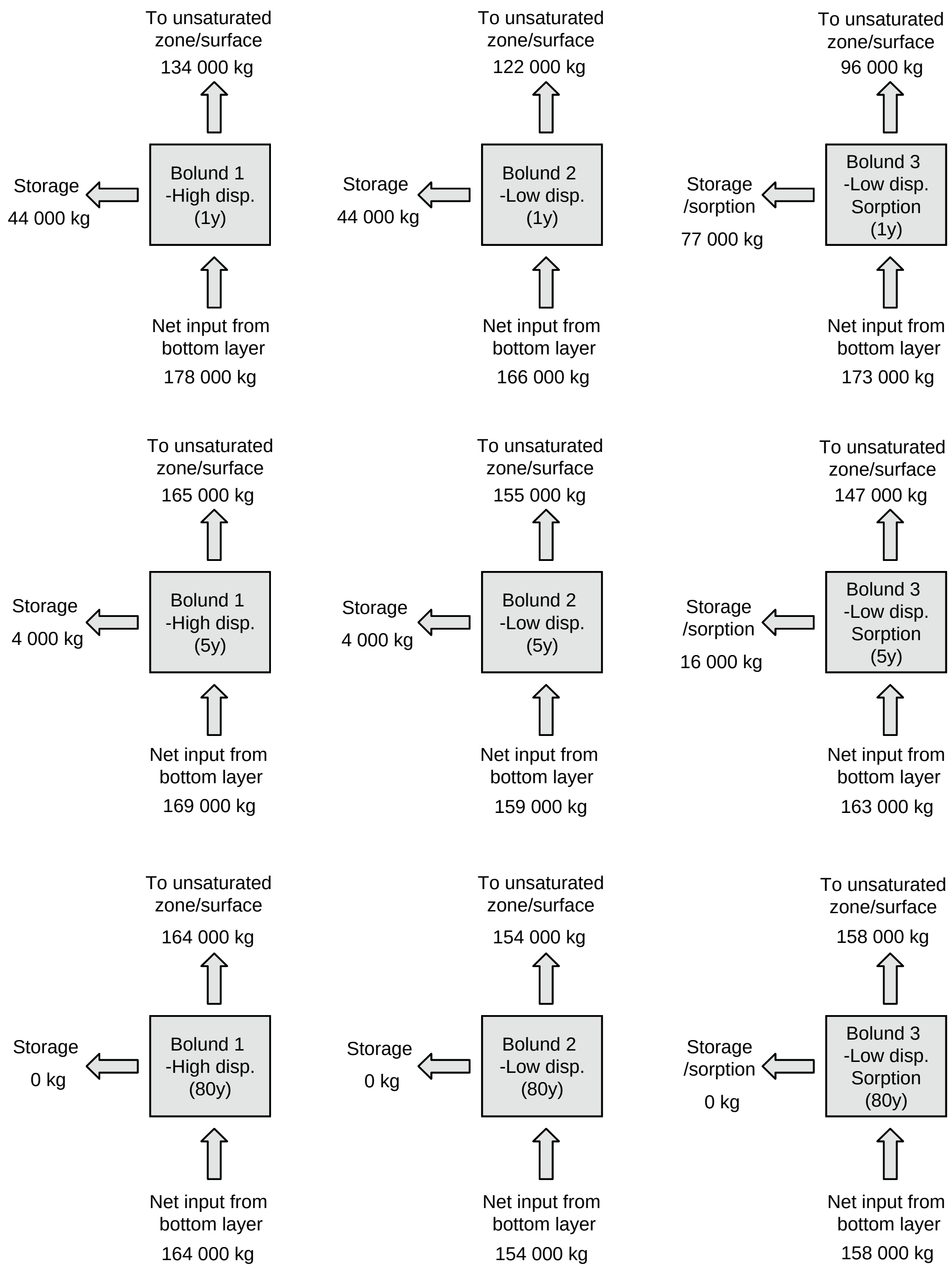


Figure 6-11. *Annual schematic mass balances after 1 year, 5 years and 80 years from introduction of the solute in the bedrock for different dispersivities and sorption for the total model area of Bolundsfjärden.*

Results for the future mire at Puttan

The future mire at Puttan has a vertical flow pattern that differs from the mire at Bolundsfjärden. The pressure from water on the peat surface is considerably lower and for a major part of the year Puttan is a discharge area with an upwards flow direction.

Figure 6-12 to 6-14 show concentrations in the saturated zone for case 4, Puttan for a solute introduced in the bottom layer (at a depth of 10 m from the peat surface), using high dispersivities. After two months from the solute introduction in the bottom layer of the model, the concentrations are quite evenly distributed over the mire. Lower concentrations are found near the outlet. Mean concentrations reach around 250 units (expressed as $g \cdot m^{-3}$) in calculation layer 5 and around 10 units ($g \cdot m^{-3}$) in the uppermost calculation layer, see Figure 6-12.

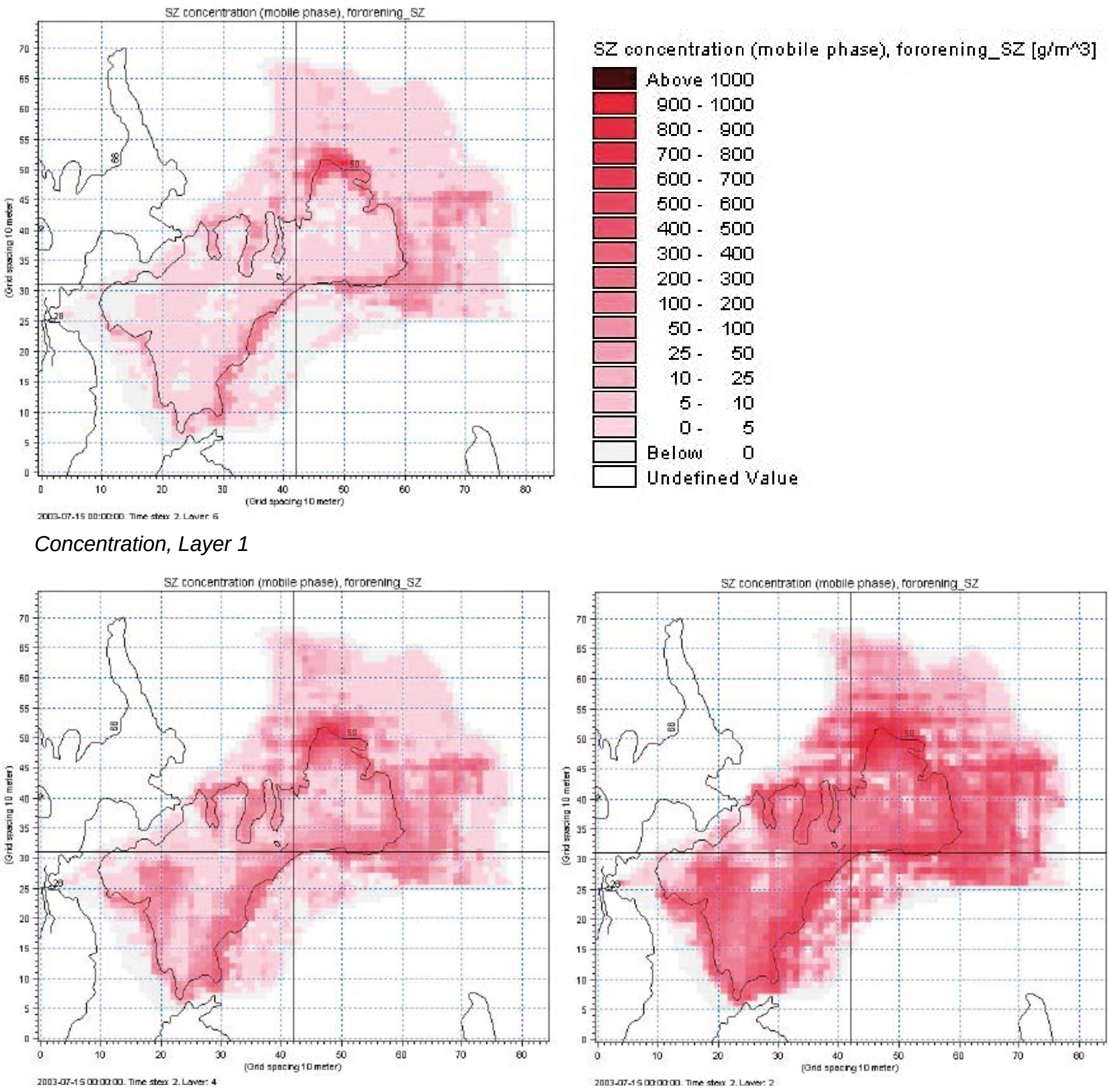


Figure 6-12. *Concentrations (arbitrary units, in the figure expressed as $g \cdot m^{-3}$) after 2 months, case 4, Puttan, using high dispersivities. See Table 6-3 for a summary of average solute concentrations in the mire.*

After one year from the solute introduction in the bottom layer of the model, the concentrations are quite evenly distributed over the mire in the lower layers. In the uppermost calculation layer, higher concentrations are found around the shorelines. Mean concentrations reach around 500 units (g·m^{-3}) in calculation layer 5 and around 100 units (g·m^{-3}) in the uppermost calculation layer, see Figure 6-13.

After ten years from the solute introduction in the bottom layer of the model, the same distribution of concentrations is found, with higher concentrations around the shorelines. Mean concentrations reach around 700 units (g·m^{-3}) in calculation layer 5 and around 400 units (g·m^{-3}) in the uppermost calculation layer, see Figure 6-14.

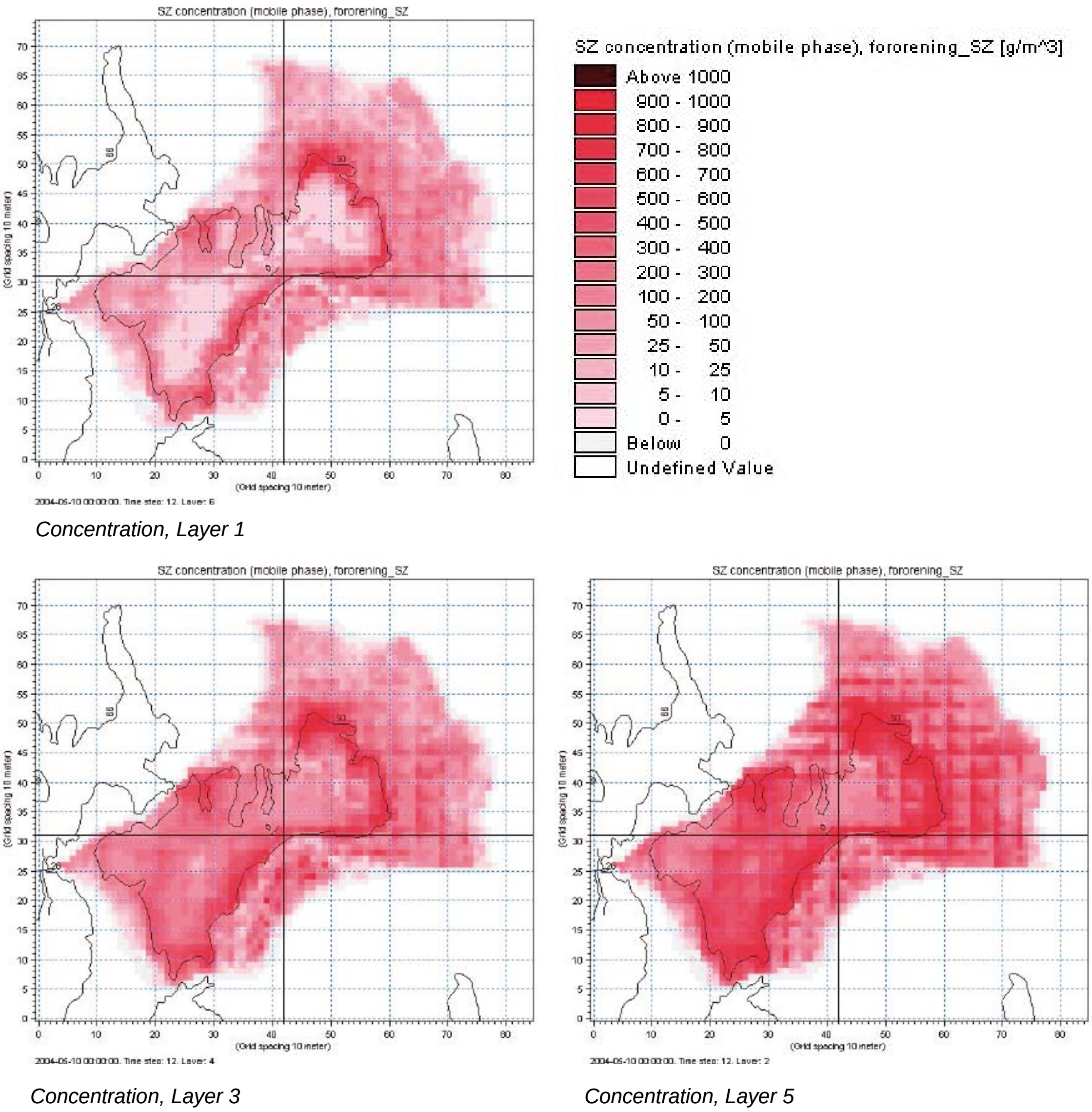
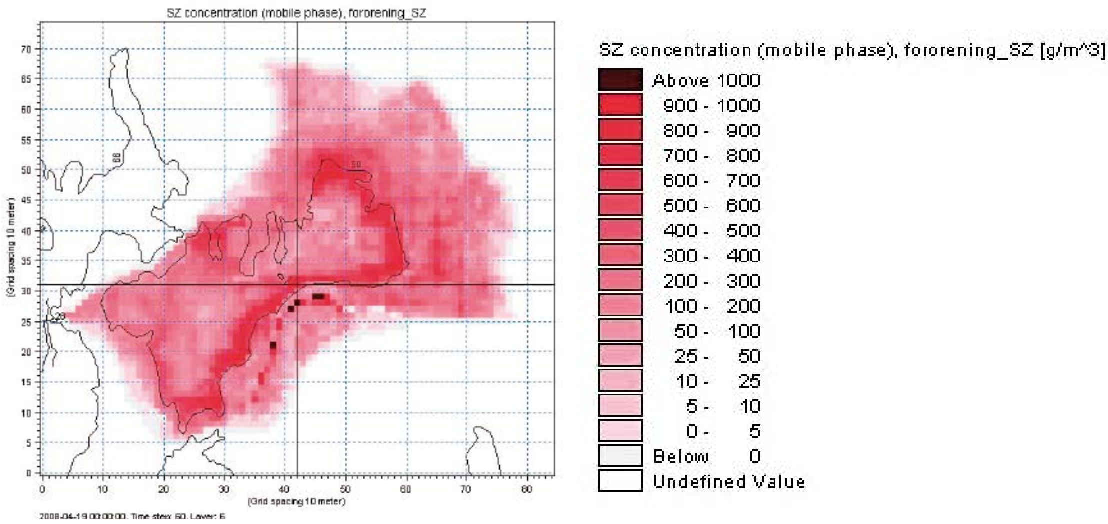
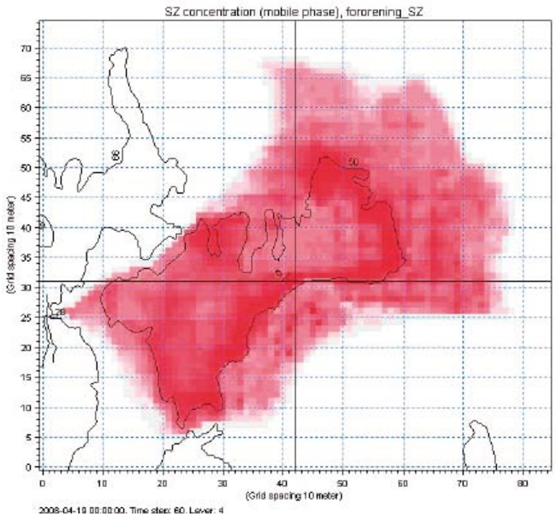


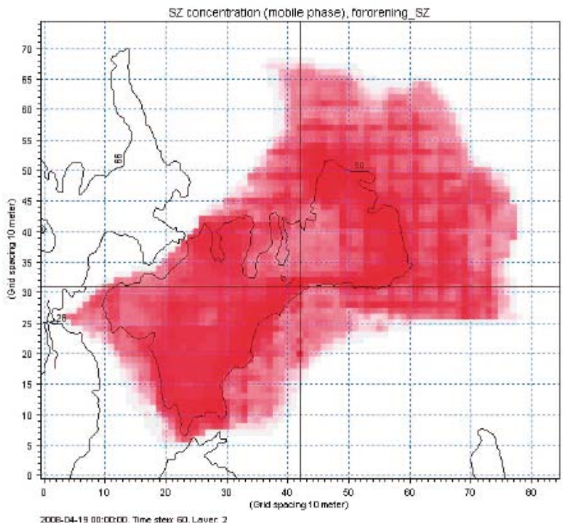
Figure 6-13. *Concentrations (arbitrary units, in the figure expressed as g·m^{-3}) after 1 year, case 4, Puttan, using high dispersivities. See Table 6-3 for a summary of average solute concentrations in the mire.*



Concentration, Layer 1



Concentration, Layer 3



Concentration, Layer 5

Figure 6-14. *Concentrations (arbitrary units, in the figure expressed as g·m^{-3}) after 10 years, case 4, Puttan, using high dispersivities. See Table 6-3 for a summary of average solute concentrations in the mire.*

The spatial distribution of solutes for the mire at Puttan is more even over the surface than for the mire at Bolundsfjärden, but higher concentrations are found around today's shoreline which is a strong discharge area. Lower concentrations are found where the discharge area is weaker.

After about two months, the mean concentration at the uppermost layer is around 10 units (g·m^{-3}). Table 6-3 show average solute concentrations over the mire for different calculation layers after 2 months, 1 year and 10 years after introduction of the solute.

Table 6-3. Average solute concentration over the future mire in Puttan (arbitrary units, in the table expressed as g·m^{-3}).

Time since solute introduction	Layer 1	Layer 3	Layer 5
2 months	10	65	260
1 year	115	280	480
10 years	400	595	700

Figure 6-15 show the location gridcell (28,27) from which detailed results are shown in Figures 6-16 and 6-17.

Figure 6-16 show the concentrations at three calculation layers for cell (28,27) in Puttan. A stationary condition is reached after around 20 years.

Figure 6-17 show the results from the sensitivity analyses of dispersion and sorption coefficients for cell (28,27), located in a discharge area with no underlying sediment barriers except for gyttja, in layer three.

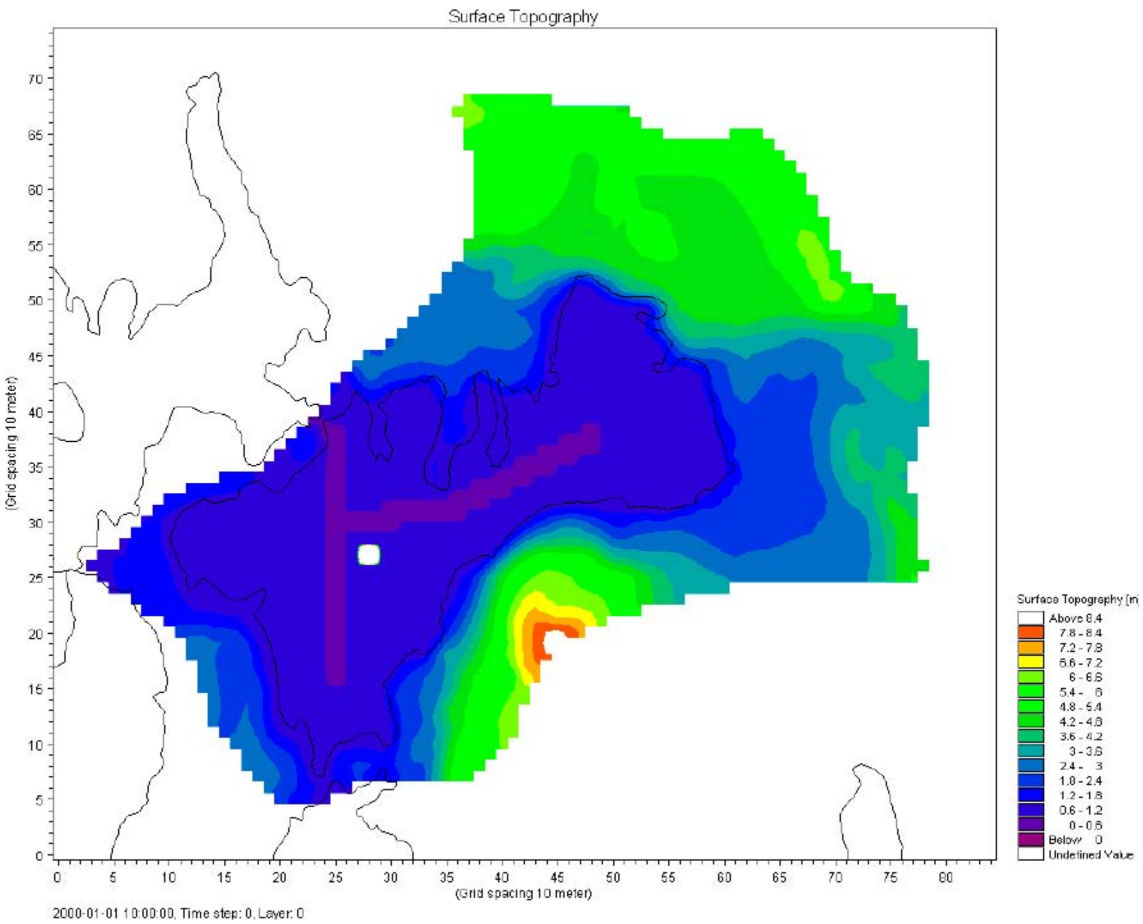


Figure 6-15. *White dots show the location of grid cell (28,27) from which detailed results are shown in Figure 6-16 and 6-17.*

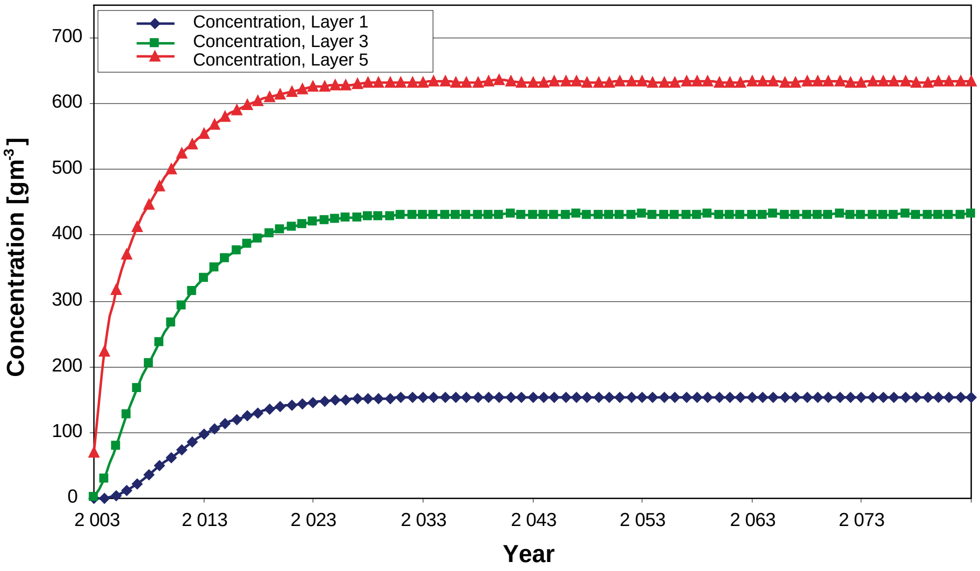


Figure 6-16. *Annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) at calculation layer 1, 3 and 5 for cell (28,27), Puttan, using high dispersivities. For location of the cell, see Figure 6-13.*

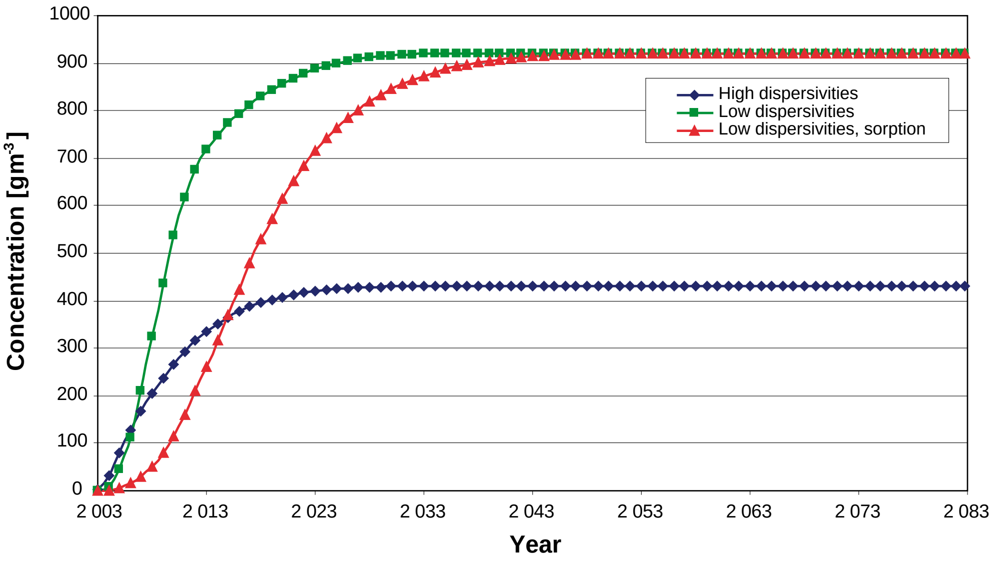


Figure 6-17. *Comparison of annual mean concentrations (arbitrary units, in the figure expressed as g·m^{-3}) in cell (28,27,3) for the different dispersion and sorption parameters, Puttan. For location of the cell, see Figure 6-13.*

As for the discharge area in Bolundsfjärden, the low dispersivities results in the highest concentrations in this area as the solute transport is mainly velocity driven. At higher dispersivities, there is a horizontal loss of solute concentration in lower layers. When sorption is taken into account, the initial horizontal loss of concentration results in lower solute concentration in calculation layer three and the maximum levels are reached after a longer period.

The storage capacity and sorption is higher in the beginning of the simulation and equals zero when stationary concentration conditions are reached in the whole model domain. Figure 6-18 show the accumulated sorption and the accumulated sorption in relation to accumulated solute input for the mire at Puttan. The sorption process is effective in the beginning of the simulation and decreases with time. A stationary condition when no further solute is sorbed to the soil is reached after about 30 y for the whole model area.

The sorbed solute concentration after 80 years of simulation is shown in Figure 6-19. The highest amount of sorbed concentration is found in calculation layer 3, the uppermost layer of Quaternary deposits. The K_d values are set to $1e^{-7}$ $m^3 \cdot g^{-1}$ for both the mire and the Quaternary deposits, and $1e^{-10}$ for the lower bedrock which leads to a lower sorption in calculation layer 5.

The retardation or sorption is also affected by the effective porosity of each layer, a higher effective porosity giving a lower retardation. The peat used in the solute transport simulations has an effective porosity of 0.8 for the fibric peat and 0.49 for the hemic peat, the uppermost layer of Quaternary deposits has an effective porosity of 0.15 under Bolundsfjärden. With the presence of Sapric peat that has a lower effective porosity, the retardation would increase.

The sorption in the actual mire is lower than in the uppermost Quaternary deposits due to the large amount of solute that is sorbed before it enters the mire and the effect of the effective porosity.

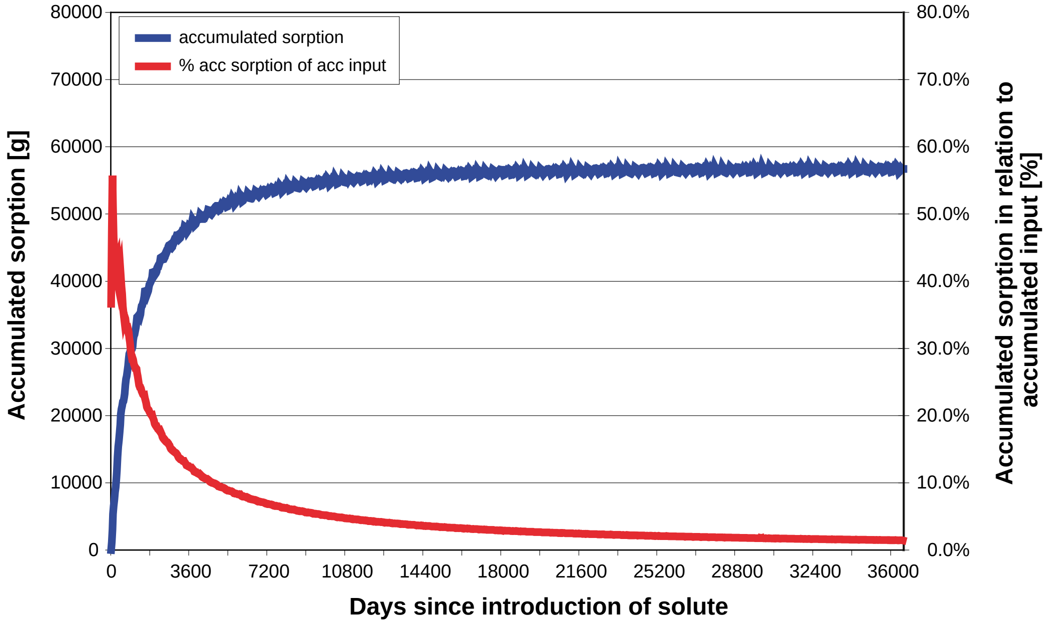
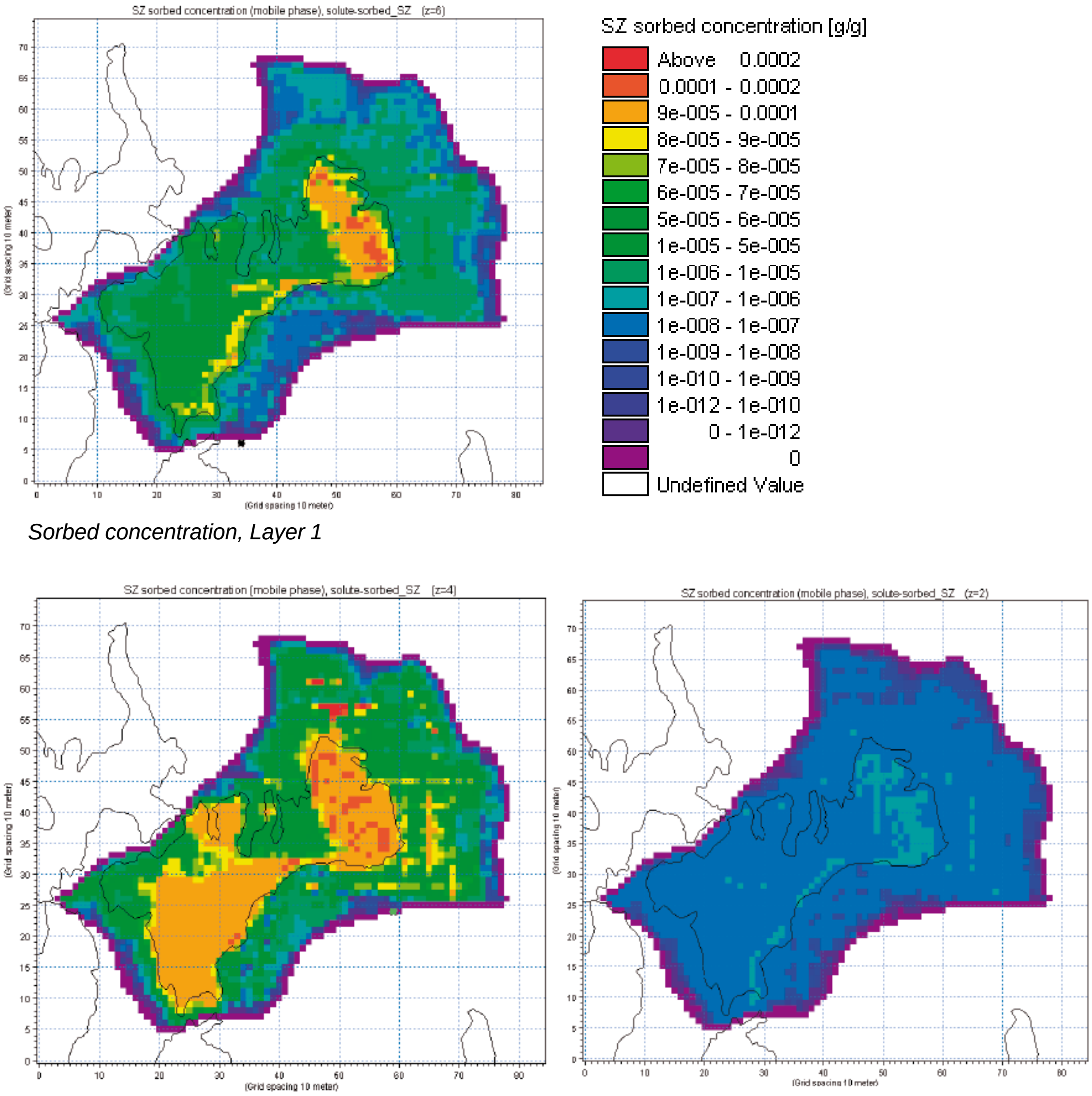


Figure 6-18. *Accumulated sorption and accumulated sorption in relation to accumulated solute input for the mire at Puttan, case 6.*



Sorbed concentration, Layer 1

Sorbed concentration, Layer 3

Sorbed concentration, Layer 5

Figure 6-19. *Sorbed concentrations (arbitrary units, in the figure expressed as g/g) after 80 years, case 6, Puttan, using low dispersivities and sorption.*

Figure 6-20 presents a schematic annual mass balance at three times for the different dispersivities used in the transport simulations for the future mire at Puttan. The mass balances represent the total model areas and not only the mires.

As the annual periods that are presented in the figures differ slightly in actual dates, the net input from the bedrock differs somewhat within one description of dispersivities and sorption.

The storage capacity and sorption is higher in the beginning of the simulation and equals zero when stationary concentration conditions are reached in the whole model domain. With high dispersivities this occurs after approximately 20 years, with low dispersivities after 25 years and with sorption after 40 years, see Figure 6-15. The transport to upper layers and the surface increase as the storage and sorption decrease.

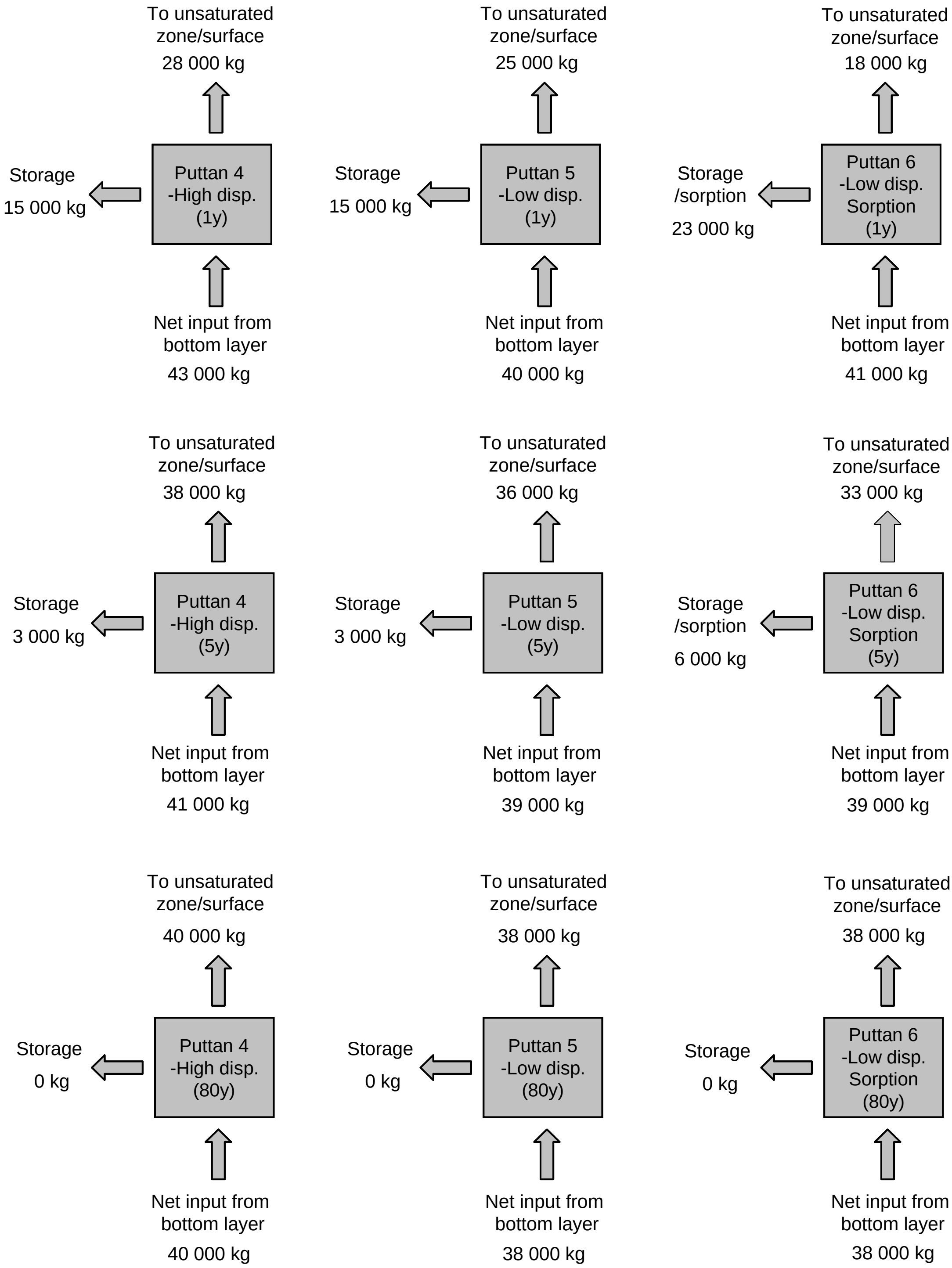


Figure 6-20. *Annual schematic mass balances after 1 year, 5 years and 80 years from introduction of the solute in the bedrock for different dispersivities and sorption for the total model area of Puttan.*

6.4.2 Transport of pollutants from overland source

For the mire at Bolundsfjärden, an overland source of pollution was introduced in the largest inflow in the south western part of the model, where a water course transports surface water through the wetland. The source was set to a constant value of 1,000 arbitrary units, expressed as $g \cdot m^{-3}$.

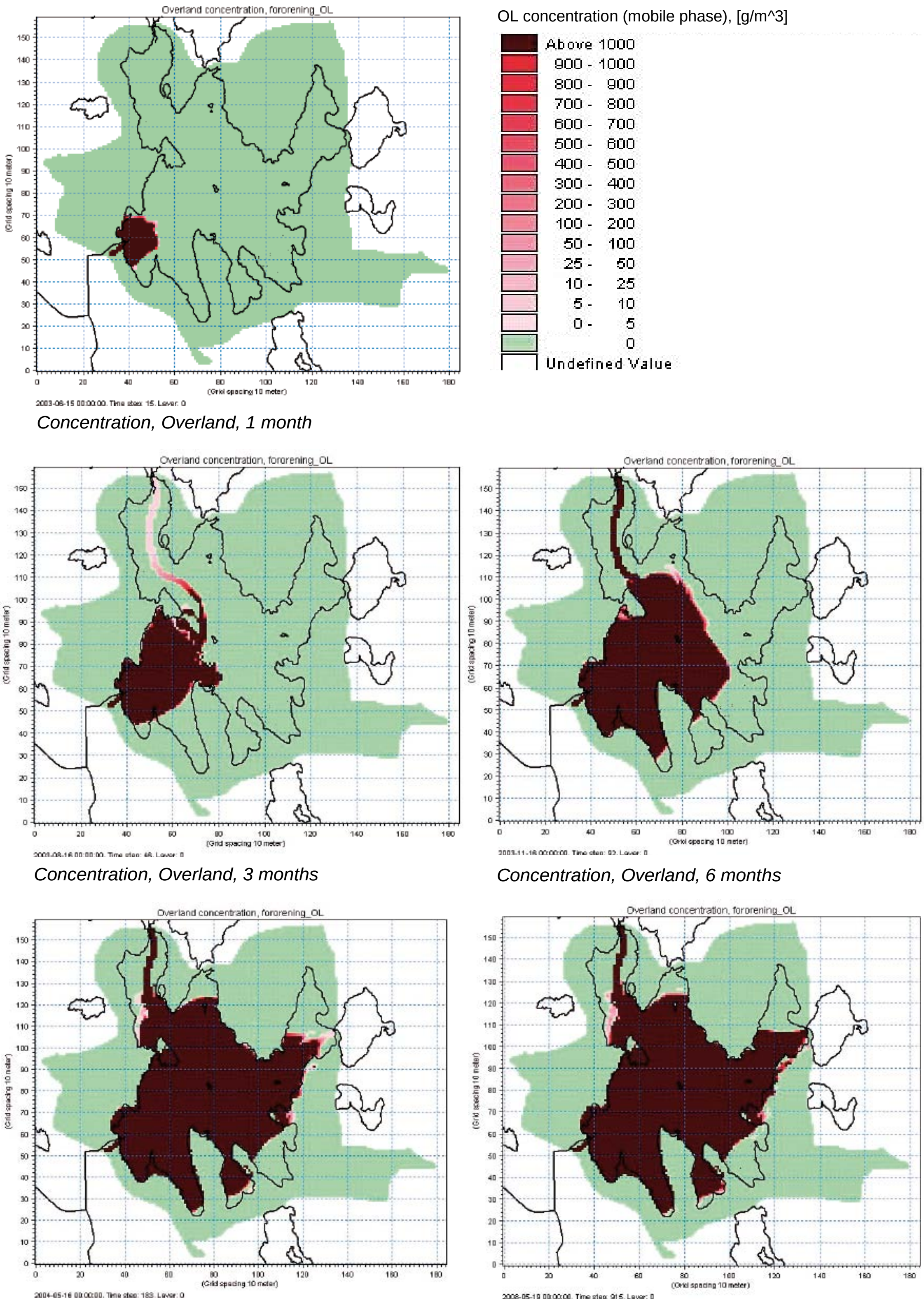
Figure 6-21 to 6-23 illustrate how the overland source pollution is transported from and over the peat surface, and how the pollution is infiltrated and transported vertically through the model. For the saturated zone, high dispersivities were used. For overland flow, the dispersivities were zero.

As Figure 6-21 show, the solute starts to spread horizontally on the surface before it is transported through the whole water course. This is a result of the surface roughness in the water course. The Manning number is set to 10, which represent a high degree of meandering and vegetation. This contributes to the low flow velocities in the water course (around 0.002 m/s) and the development of a water pressure gradient close to the narrowing of the water course.

Due to the recharge area that has formed in the mire, the solute is transported to underlying layers as shown in Figure 6-22 for calculation layer three. The transport follows the discharge and recharge areas described in chapter 5.5.3, which is clearly seen after one year.

Figure 6-23 show the transport of solute from the surface to calculation layer 5. The transport follows the discharge and recharge areas described in chapter 5.5.3. After five years, nearly the whole discharge area has reached source strength, while low concentrations are found by the recharge area near the outlet.

The results show that a solute reaching the wetland through surface runoff is transported relatively slowly through the mire. After 3 months, the solute concentration is starting to reach the outlet. Due to the downwards groundwater flow, the solute is spread to the underlying groundwater aquifer. The vertical solute transport follows the discharge and recharge areas, where high concentrations, up to the source strength, are reached in the major parts of the formation, while lower concentrations are reached in the discharge areas and underneath clay sediment.



Concentration, Overland, 1 month

Concentration, Overland, 3 months

Concentration, Overland, 6 months

Concentration, Overland, 1 year

Concentration, Overland, 5 years

Figure 6-21. *Concentrations of overland source (arbitrary units, in the figure expressed as g·m^{-3}) in the overland water on peat surface, case 2, Bolundsfjärden.*

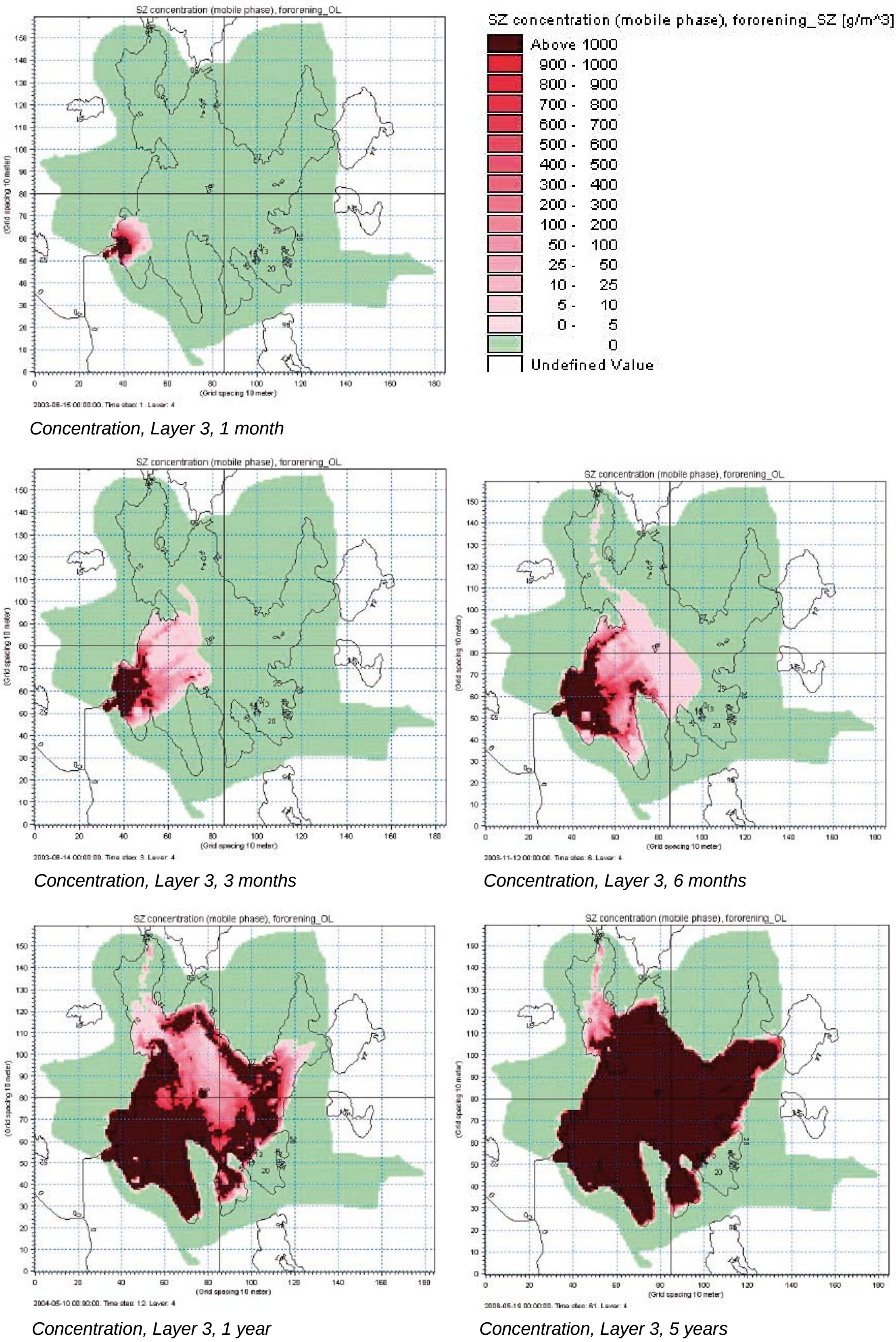


Figure 6-22. *Concentrations in calculation layer 3(groundwater layer below sediments) of overland source (arbitrary units, in the figure expressed as g·m^{-3}) in the overland water, case 2, Bolundsfjärden.*

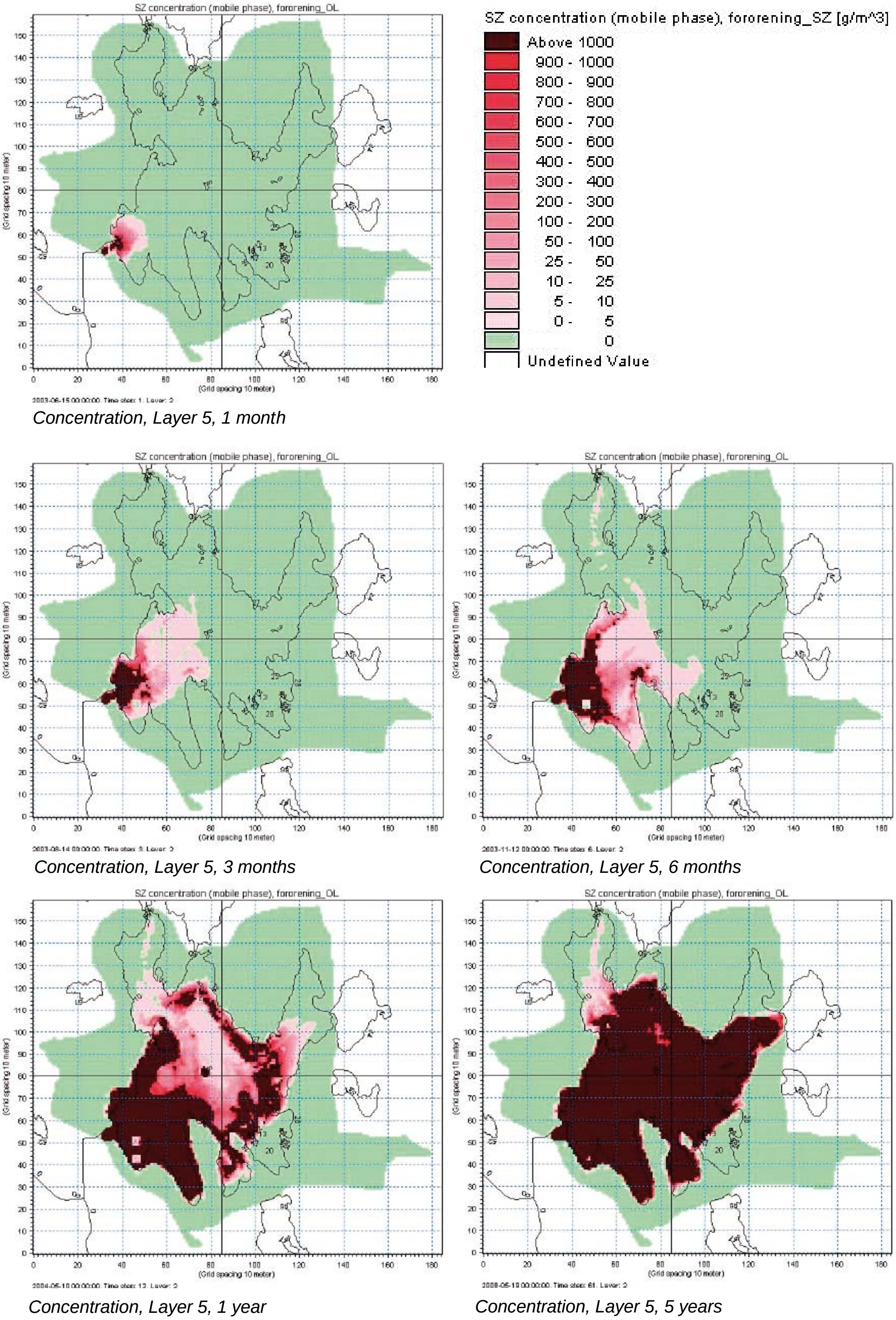


Figure 6-23. *Concentrations in calculation layer 5 (top layer of bedrock) of overland source (arbitrary units, in the figure expressed as g·m^{-3}) in the overland water, case 2, Bolundsfjärden.*

7 Discussion

The model results show that the total water balances are sensitive to all of the parameters studied, i.e. the type of vegetation, the type of peat that is developed and the hydraulic conductivities.

The effect of these parameters on the depth of overland water over the peat is however insignificant. It is mainly the boundary conditions that control the overland water depth.

The distribution of discharge and recharge is mainly affected by the boundary conditions.

The results show that the hydraulic conditions that exists today will somewhat alter as the peat is formed. For today's Lake Bolundsfjärden, the discharge area is weak with a few centimetres head difference between the upper calculation layer and the upper bedrock layer. This means that an increase in overland water pressure can be enough to turn the discharge area into a recharge area, which occurs as the future mires are flooded with surface runoff from upstream catchments. For Bolundsfjärden, where there during present conditions are weak discharge areas, a recharge area forms during the summer when the mires have developed. The same holds for Eckarfjärden, while Puttan after the peat has developed still is a discharge area due to its naturally strong discharge position close to the sea.

The results from the sensitivity analyses of dispersion and sorption coefficients in recharge areas with underlying sediment barriers show that the highest concentrations are reached when high dispersivities are used. This is due to the low vertical flow velocities, where the highest concentrations are reached with high dispersivities that transport the solute by dispersion.

For discharge areas, the vertical velocities are considerably higher, and the low dispersivities results in the highest concentrations as the solute transport is mainly velocity driven. At higher dispersivities, there is a horizontal loss of solute concentration in lower layers. When sorption is taken into account, the transport to upper layers is slower, however reaching the same concentrations as without sorption, but after a longer break through time.

The probability of a wetland forming in Bolundsfjärden may be limited due to the large amount of surface runoff that enters the present lake. For the simulations in this study, it was assumed that the surface runoff would not decrease as the landscape is changed. A decreased runoff entering the wetland might keep today's discharge area, not turning the wetland into a recharge area. This would result in a faster solute transport from a contamination from lower layers, but also in a slower transport to the groundwater aquifer from an overland contamination.

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