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Integrated surface-subsurface water flow modelling of the Laxemar area

Application of the hydrological model ECOFLOW

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Abstract

Since 2002, the Swedish Nuclear Fuel and Waste Management Co (SKB) performs site investigations in the Simpevarp area, for the siting of a deep geological repository for spent nuclear fuel. The site descriptive modelling includes conceptual and quantitative modelling of surface-subsurface water interactions, which are key inputs to safety assessment and environmental impact assessment. Such modelling is important also for planning of continued site investigations. In this report, the distributed hydrological model ECOFLOW is applied to the Laxemar subarea to test the ability of the model to simulate surface water and near-surface groundwater flow, and to illustrate ECOFLOW's advantages and drawbacks. The ECOFLOW model area is generally characterised by large areas of exposed or shallow bedrock. The ECOFLOW modelling results are compared to previous results produced by MIKE SHE-MIKE 11 and PCRaster-POLFLOW, in order to check whether non-calibrated surface and subsurface water flows computed by ECOFLOW are consistent with these previous results. The analyses include quantification and comparison of inflow and outflow terms of the water balance, as well as analyses of groundwater recharge-discharge patterns.

ECOFLOW is used to simulate a one-year non calibrated period, considering seven catchments (including three areas with direct runoff to the sea) within the Laxemar subarea. The modelling results show the ability of the model to produce reasonable results for a model domain including both porous media (Quaternary deposits) and discontinuous media (bedrock). The results demonstrate notable differences in the specific discharge between the considered catchments, with specific discharge values in the range 157–212 mm year^{-1}; the lowest value (the Lake Frisksjön catchment) may however be erroneous due to numerical instability in the model. Overall, these results agree with specific discharge values computed by MIKE SHE-MIKE 11 and PCRaster-POLFLOW (190 and 128–186 mm year^{-1}, respectively), as well as the independently estimated long-term average (150–180 mm year^{-1}). Moreover, ECOFLOW computes groundwater recharge-discharge patterns that generally match the patterns identified using MIKE SHE; groundwater recharge occurs at topographic highs, whereas groundwater discharge occurs at streams, lakes and wetlands.

Compared to MIKE SHE-MIKE 11, major advantages of the ECOFLOW model are (much) shorter run-times and fewer model parameters. Main ECOFLOW drawbacks include limitations in the handling of surface water (channel) and overland flow. Moreover, ECOFLOW uses MODFLOW to simulate groundwater flow, which implies that the well known "dry cells" problem in MODLOW is a problem also in ECOFLOW. The study demonstrates that ECOFLOW has capability to produce more or less similar results as MIKE SHE-MIKE 11, and that ECOFLOW is a reliable tool for simulation of complex hydrologic systems. In particular, the relatively simple ECOFLOW model structure means that relatively fast simulations are possible even for long-term hydrologic runoff predictions, which usually require long run-times when more complex models are used for simulation of large and mid-scale catchments.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) bedriver sedan 2002 platsundersökningar i Simpevarpsområdet för lokalisering av ett djupförvar för använt kärnbränsle. Den platsbeskrivande modelleringen inkluderar konceptuell och kvantitativ modellering av interaktionen mellan yt- och grundvatten, vilken utgör nyckelunderlag för säkerhetsanalys och miljökonsekvensbeskrivning. Sådan modellering är också viktig för planering av fortsatta undersökningar. I denna rapport tillämpas den distribuerade hydrologiska modellen ECOFLOW på delområde Laxemar för att testa modellens förmåga att simulera flöde av ytvatten och ytnära grundvatten, och för att illustrera ECOFLOWs för- och nackdelar. Modellområdet karaktäriseras generellt av stora områden med berg i dagen eller ytnära berg. Modellresultaten från ECOFLOW jämförs med tidigare resultat som tagits fram med MIKE SHE-MIKE 11 och PCRaster-POLFLOW, i syfte att testa om okalibrerade yt- och grundvattenflöden som beräknats med ECOFLOW överensstämmer med dessa tidigare resultat. Analyserna inkluderar kvantifiering och jämförelse av vattenbalansens in- och utflödeskomponenter, samt analys av grundvattnets in- och utströmningsmönster.

ECOFLOW används för att simulera en ettårig okalibrerad period avseende sju avrinningsområden inklusive tre områden med avrinning direkt till havet) inom delområde Laxemar. Modelleringsresultaten visar modellens förmåga att ge rimliga resultat för en modelldomän som inkluderar både porösa (kvartära avlagringar) och diskontinuerliga medier (berg). Resultaten visar på tydliga skillnader i den specifika avrinningen mellan de modellerade avrinningsområdena, med en specifik avrinning i intervallet 157–212 mm år^{-1}; det lägsta värdet (Frisksjöns avrinningsområde) kan dock vara behäftat med fel på grund av numerisk instabilitet i modellen. I stort överensstämmer dessa resultat med de värden på specifik avrinning som beräknats med MIKE SHE-MIKE 11 och PCRaster-POLFLOW (190 respektive 128–186 mm år^{-1}), liksom det uppskattade långtidsmedelvärdet (150–180 mm år^{-1}). Dessutom beräknar ECOFLOW in- och utströmningsmönster för grundvatten som generellt överensstämmer med de mönster som identifierats med MIKE SHE; grundvatteninströmning sker i topografiska höjdområden, och grundvattenutströmning sker längs sluttningar och under vattendrag, sjöar och våtmarker i Laxemarområdet.

De viktigaste fördelarna med ECOFLOW jämfört med MIKE SHE-MIKE 11 är (mycket) kortare simuleringstider och färre modellparametrar. Viktiga nackdelar är begränsningar avseende hanteringen av ytvatten(kanal-)flöde och avrinning på markytan. ECOFLOW använder dessutom MODFLOW för att simulera grundvattenflöde, vilket innebär att det välkända problemet med "torra celler" i MODFLOW är ett problem även i ECOFLOW. Studien visar att ECOFLOW kan ge mer eller mindre motsvarande resultat som MIKE SHE-MIKE 11, och att ECOFLOW är ett pålitligt verktyg för simulering av komplexa hydrologiska system. Speciellt innebär ECOFLOWs relativt enkla modellstruktur att relativt snabba simuleringar är möjliga för avrinningsberäkningar även för längre tidsperioder, vilket normalt kräver långa beräkningstider då mer komplexa modeller används för simulering av stora och medelstora avrinningsområden.

Contents

1 Introduction

1.1 Background

Since 2002, the Swedish Nuclear Fuel and Waste Management Co (SKB) performs site investigations at two different locations, Forsmark and Simpevarp, with the objective of establishing a geological repository for spent nuclear fuel /SKB 2005/. These investigations should provide a basis for the Site Descriptive Model (SDM), which will be used for safety assessment, repository design, and environmental impact assessment. Conceptual and quantitative modelling of the hydrological and hydrogeological conditions constitute key inputs to the SDM, and also for the planning of the continued site investigations /Werner et al. 2005/.

A regional model area is defined in Simpevarp within the SDM development framework. The Simpevarp region occupies a part of the Swedish coastal shore northeast of the community of Oskarshamn, Småland. Figure 1-1 shows an overview of the Simpevarp regional area, indicating the boundaries of the Simpevarp and Laxemar subareas, which are outlined by blue and red lines, respectively.

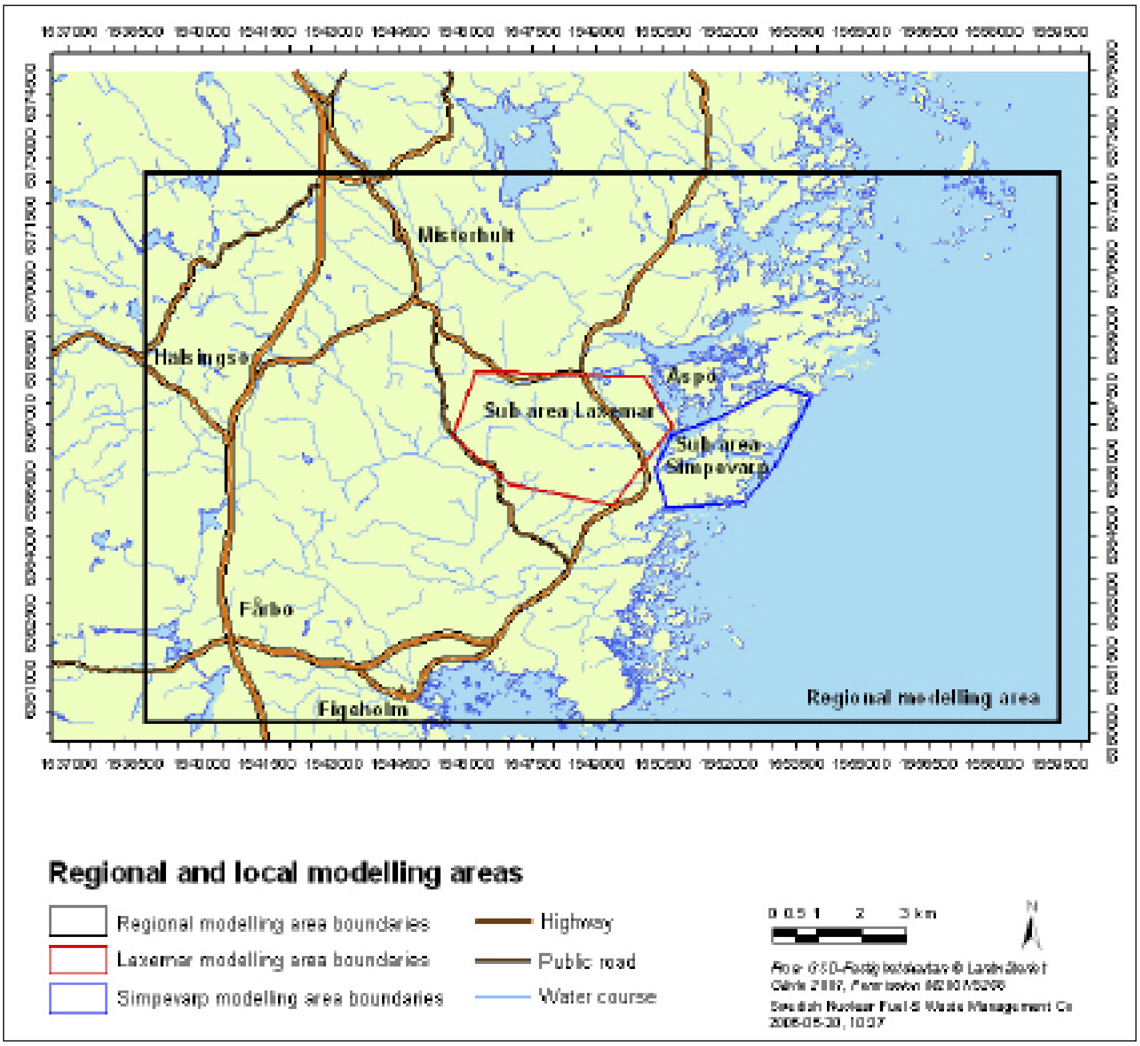

Figure 1-1. Overview of the Simpevarp regional model area and location of the Simpevarp and Laxemar subareas. The boundaries of the Simpevarp regional model area are outlined by black lines, the boundaries of the Simpevarp subarea by blue lines, and the boundaries of the Laxemar subarea by red lines.

During the last years, both subareas have been subject to detailed investigations and modelling. Regarding local surface-subsurface water interactions /Werner et al. 2005/ and /Jarsjö et al. 2006/ have reported MIKE SHE-MIKE 11 and PCRaster-POLFLOW modelling results, respectively, for the Laxemar subarea, focusing on groundwater basin behaviour and water budget issues.

1.2 Objectives and scope

The main purpose of this project is to apply the distributed hydrological model ECOFLOW to the Laxemar subarea to test the ability of the model to simulate surface water and "near-surface" groundwater systems in catchments with relatively large areas of exposed or very shallow bedrock, and reveal the advantages and limitations of the ECOFLOW model. To achieve this goal, it is tested whether the non-calibrated local surface and subsurface water flows computed by ECOFLOW are consistent with observed values as well as independent uncalibrated modelling results, produced for the same area by the MIKE SHE-MIKE 11 /Werner et al. 2005/ and PCRaster-POLFLOW /Jarsjö et al. 2006/ models. The objectives incorporate calculating and comparing the inflow and outflow terms of the water balance: (1) groundwater recharge, (2) overland flow, (3) evapotranspiration, and (4) stream flow. Another objective is to investigate whether groundwater recharge-discharge patterns agree with those identified by the MIKE SHE Laxemar model.

2 Brief description of the ECOFLOW model

The ECOFLOW model is an integrated surface and subsurface water flow model. The model consists of the hydrological model ECOMAG /Motovilov and Belokurov 1997/ and the well-known groundwater model MODFLOW /McDonald and Harbaugh 1988/. The model considers the hydrological processes that occur in a catchment area, such as infiltration, evapotranspiration, thermal and water regimes of the soil, surface and subsurface flow, snow accumulation and snowmelt /Sokrut 2005/.

ECOFLOW was developed especially for boreal (northern) conditions where processes of snow formation, distribution and accumulation, soil freezing and thawing control the runoff formation and water transport from upland and hill slope areas to streams and other water bodies. The model has previously been tested on different catchments of varying topography and land use across Scandinavia, e.g. the Gardemoen region near Oslo (Norway), Vemmenhög in Scania (Skåne), and Örsundaån in the Mälardalen region /Sokrut 2005/. The model was successfully calibrated and validated in the framework of the NOPEX project, conducted in the Uppsala region, yielding good results in computing stream flows for a series of years /Motovilov et al. 1999, Gottschalk et al. 2001/.

An essential feature of the model is the ability to simulate catchment processes using two distinct operational strategies, a grid approach and a Representative Elementary Area (REA) approach. The grid approach, which is applied in most traditional water flow models, implies working directly with a 3D grid, assigning all model parameters on a cell-by-cell basis /Abbott and Refsgaard 1996/. The grid approach is used in this particular study.

The concept of an REA was introduced by /Wood et al. 1988/ in order to handle spatial variability by dividing a catchment into smaller units, still providing fast and simple simulations on catchment scale. Areas of the catchment within these units are assumed to behave similarly in terms of their hydrological response to different climatic inputs.

An important feature of ECOFLOW is that the model uses the "water constant" approach /Baver and Gardner 1972/ instead of Richards' equation /Richards 1931/ to describe water flow in the unsaturated zone. This "water constant" method is based on estimating soil water movement using soil reference curves and water-retention parameters (cf. Table 3-4).

In the ECOFLOW model surface runoff is described by a simplified version of the kinematic wave equation, which is based on Rose's approximation /Rose et al. 1983/. This method describes overland flow as a single-valued function of water depth for routing the rainfall excess to the catchment outlet.

A cross-section of a grid cell of the ECOFLOW model is presented in Figure 2-1. The grid cell is divided into a number of layers: a snow cover layer (only present during the cold period), a surface layer and two subsurface layers: an unsaturated top layer (horizon A) and a saturated layer (groundwater horizon); the latter is computed by MODFLOW. If the rain intensity is lower than the infiltration capacity of the soil, the water infiltrates into the soil and percolates downward towards the groundwater table. After filling the depressions on the surface, the excess of water that has not infiltrated into the soil, forms surface runoff. The water from the surface depressions (surface water storage, cf. Figure 2-1) and the vadose zone (soil horizon A, cf. Figure 2-1) is evapotranspirated. The surface and subsurface (baseflow) flows form the lateral inflow into the stream network. The water moving from the saturated to the vadose zone is defined hereinafter as a return flow.

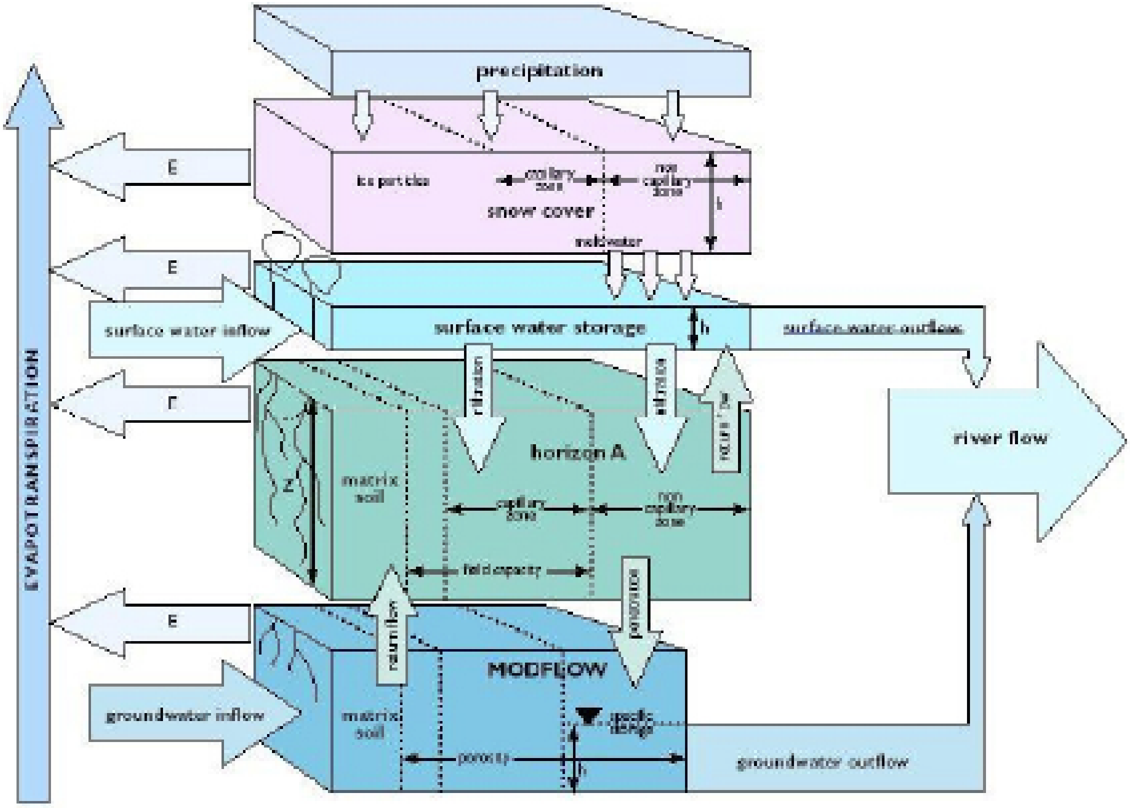

Figure 2-1. *Vertical structure of ECOFLOW for a grid cell /Sokrut 2005/. E is the evapotranspiration rate from every box forming the total evapotranspiration rate, h denotes the snow depth, a surface flow depth, and a groundwater level in the relevant boxes. Z is the depth of the unsaturated zone.*

Simulation of the hydrological processes for each landscape element is made consistently for each layer. The percolation from horizon A is calculated at every time step, and forms the groundwater recharge in all active cells of MODFLOW. The catchment runoff values calculated by the ECOFLOW model are the sum of the surface water outflow (surface runoff) and the groundwater outflow (subsurface flow).

The ECOFLOW approach to simulate the effects of plant transpiration and direct evaporation from the groundwater zone is based on the following assumptions: (1) when the water table is at or above a specified elevation, termed the "transpiration surface" (20 cm), transpiration loss from the water table occurs at a maximum rate; (2) when the depth of the water table below the "transpiration surface" elevation exceeds a specified interval, termed the "extinction depth", transpiration from the water table ceases; and (3) between these limits, evapotranspiration from the water table varies linearly with water table elevation. Depths to groundwater of 40 cm and 330 cm are chosen as the "extinction depths" on rock outcrops and Quaternary deposits, respectively, based on the fact that pine typically has rooting depths of about 40 cm on rocky soils and 330 cm on till soils /Canadell 1996/. Particularly, the map of Quaternary deposits and land use map are in this study used to estimate areas with specific extinction depths.

In ECOFLOW, the unsaturated zone is characterised by the following parameters: horizontal and vertical hydraulic conductivity, porosity, wilting point, field capacity, organic matter content, and soil bulk density. Moreover, the surface water flow is described by the parameters Manning's roughness coefficient, potential evaporation rate, and infiltration rate.

As outlined in Section 1.2, this report contains comparisons of local surface and subsurface water flows computed by ECOFLOW and modelling results for the same area by the MIKE SHE-MIKE 11 and PCRaster-POLFLOW models. A brief description of the MIKE SHE-MIKE 11 software packages is provided in /Werner et al. 2005/. Flow in the unsaturated zone is in both MIKE SHE and ECOFLOW assumed to be 1D (up- and downwards). Similar to ECOFLOW, MIKE SHE incorporates a conventional 2D/3D finite-difference groundwater model, which is very similar to the MODFLOW structure. However, the use of the Richards' equation and the St. Venant's equation principally differentiates MIKE SHE-MIKE 11 from the ECOFLOW model, which utilises the "water-constant" algorithm for unsaturated flow and the kinematic wave equation for overland flow.

Another distinction between the ECOFLOW and MIKE SHE models is that there is a formulation of the soil moisture freezing-thawing processes in the ECOFLOW routines. The MIKE SHE snow routine simulates snow accumulation and snow melt, whereas the freezing-thawing processes are not included. The ECOFLOW model assumes a linear vertical temperature profile in snow, frozen and unfrozen soil, and neglects, therefore, the transport of moisture to the freezing-front. Frozen soil has reduced hydraulic conductivity due to the ice present in the pores. Description of the meltwater infiltration into frozen soil is provided in /Vehvilainen and Motovilov 1989/.

3 Study area and model development

3.1 Meteorological data

3.1.1 Precipitation

Precipitation in the model area is generally in the range 600–700 mm per year /Larsson McCann et al. 2002/. The current project uses meteorological data covering one year of observations from the Äspö meteorological station, which is operated by SKB and located on the Äspö Island, 2 km northeast from the modelled area. Corrected precipitation records are used in simulations to assure that precipitation input data are compatible with those used by MIKE SHE and provided in /Werner et al. 2005/. This correction is motivated by the fact that the measured precipitation is always less than the actual, mainly due to wind and in particular when precipitation falls in the form of snow. The correction is made by the Swedish Meteorological and Hydrological Institute (SMHI) /Alexandersson and Eggertsson Karlström 2001/. The half-hour data of corrected precipitation data are transformed into daily values and used in the ECOFLOW simulation for the year 2004.

3.1.2 Air temperature

The Baltic Sea creates a moderate, cool, and moist maritime climate in the entire region. The area experiences long, mild winters (averaging about –2°C in January) and cool summers (the mean daily July temperature is 17°C). The average annual growing season is 200 growing degree days above 5°C /Larsson-McCann et al. 2002/. Half-hour readings of air temperature from the Äspö station are transformed into diurnal values and used in the ECOFLOW simulation for the year 2004.

3.1.3 Vapour-pressure deficit

Recorded time series of relative humidity, obtained from the Äspö station, are recalculated into vapour-pressure deficit (VPD) diurnal series, which are used in the modelling. VPD is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated.

In accordance with the Magnus approach /Murray 1967/, where the VPD is defined as the difference between the saturated vapour pressure ($e_{w,i}$) and the vapour pressure (e_i), the following equations are used:

$$VPD = e_{w,i} - e_i \tag{1}$$

where $e_{w,i}$ and e_i are in kPa.

The saturated and non-saturated vapour pressures are computed as follows:

$$e_{w,i} = A\exp\left(\frac{m \cdot t_i}{T_n + t_i}\right) \tag{2}$$

and

$$e_i = \left(\frac{e_{w,i} \cdot U_{w,i}}{100\%}\right) \tag{3}$$

where $U_{w,i}$ is the relative humidity (%) and t_i is the air temperature (°C). In (2), A and m are constants, with the values $A = 6.112$ and $m = 17.27$. Moreover, in (2), T_n is the air temperature in °*K*; *T* (°*K*) = *T* (°*C*) + 273.15.

3.2 Hydrological data

3.2.1 Regional area description

The regional Simpevarp area is located between two major river catchments draining into the Baltic Sea, namely Marströmmen in the north (SMHI catchment No. 72) and Virån in the south (SMHI catchment No. 73). The area between these two catchments, including the Simpevarp area, is named No. 72/73 according to the SMHI abbreviation system. The 72/73 catchment is divided into five minor catchments; three of those, namely Kärrviksån, Laxemarån and Släthultebäcken, are situated within the modelling area.

The regional Simpevarp area consists of 26 main catchments as depicted in Figure 3-1. Eighteen catchments are located inland (Nos. 1–18), whereas 8 catchments are situated on islands, namely Nos. 19–20 (island of Upplångö), No. 21 (island of Äspö), No. 22 (island of Utlångö), and Nos. 23–26 (island of Ävrö). These 26 catchments are further subdivided into 96 sub catchment areas; note that only the main catchments are displayed in Figure 3-1.

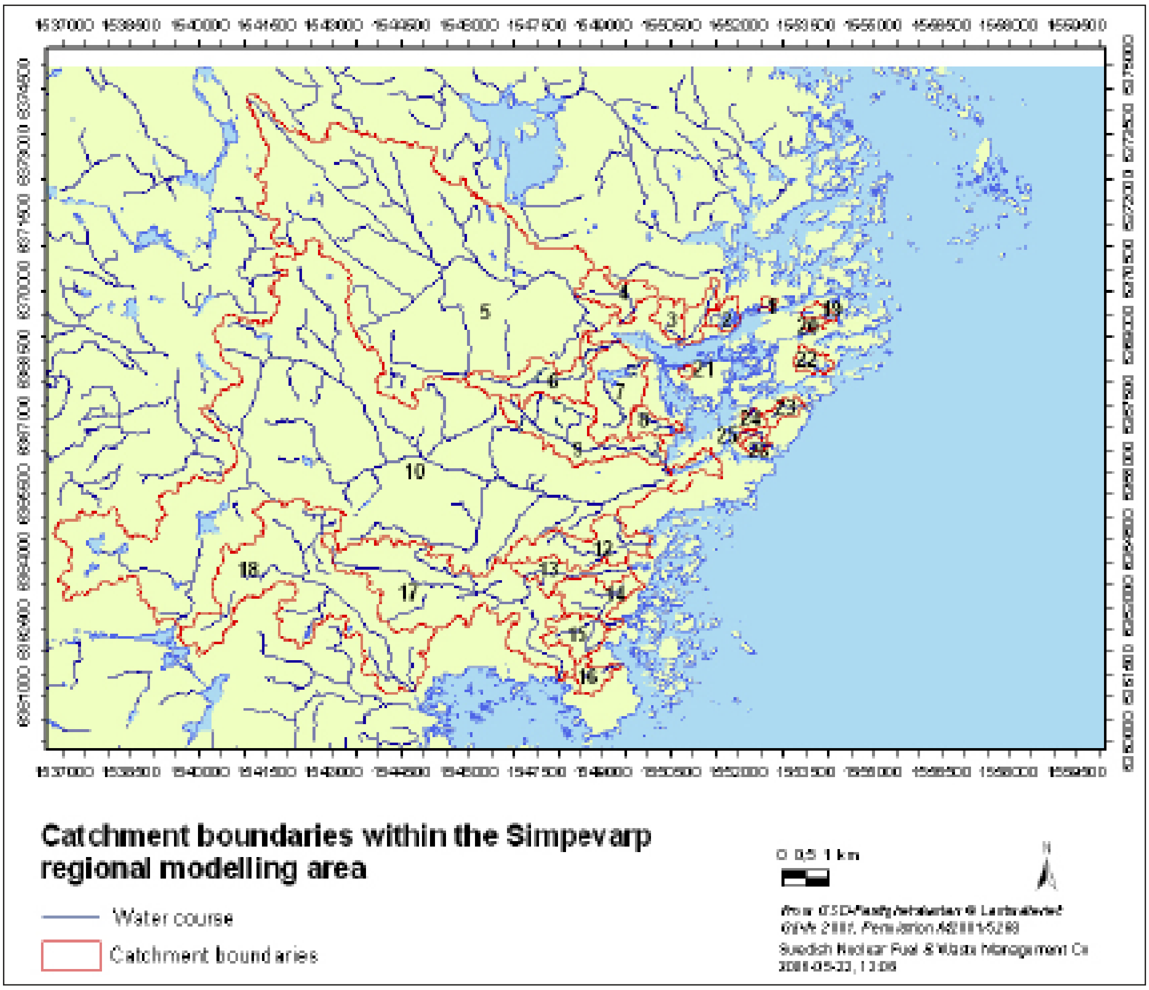

Figure 3-1. Location of catchment boundaries within the Simpevarp regional model area. The name of the main watercourse in each catchment is listed in Table 3-1.

Table 3-1. Names of the main watercourses in the 26 catchments within the Simpevarp regional model area /Brunberg et al. 2004/.

No	Name
1	Långbonäsbäcken
2	Bodvikebäcken
3	Sörviksån
4	Bjurhidebäcken
5	Kärrviksån
6	Mederhultsån
7	Kåreviksån
8	Pistlanbäcken
9	Ekerumsån
10	Laxemarån
11	No water course
12	Glostadsbäcken
13	Stålglobäcken
14	Stekebäcken
15	Södra Uvöbäcken
16	Svartebäck
17	Uthammarsån
18	Släthultebäcken
19	Flakvarpebäcken
20	Jössesbäcken
21	Äspöbäcken
22	Stekflagebäcken
23	Vadvikebäcken
24	Lindströmmebäcken
25	Gloebäcken
26	Skölkebäcken

The Laxemar model area considered in the present study includes catchments Nos. 6–9 and three catchments at the coast, referred hereinafter as "direct runoff areas" I–III (see Figure 3-3).

Morphometry data from /Brunberg et al. 2004/ for the catchment areas Nos. 6–9 are provided in Table 3-2. The table contains sizes, maximum and minimum elevations, and mean discharge values for each catchment except for the direct runoff areas I–III. The mean discharge is computed here as a product of a specific discharge value for each catchment (defined as discharge per unit area) times the upstream watershed area (cf. Table 4-2).

Table 3-2. Morphometry data for catchment areas1 No. 6–9 within the Laxemar model area /Brunberg et al. 2004/. M.a.s.l. denotes metres above sea level.

No	Name	Area (km²)	Max level (m.a.s.l.)	Min level (m.a.s.l.)	Average discharge (m³/s)
6	Mederhultsån	2.003	32	1	0.0106
7	Kåreviksån	2.062	25	1	0.0109
8	Pistlanbäcken	0.499	22	0	0.0026
9	Ekerumsån	2.834	31	1	0.0150

[1] Direct runoff areas I, II, III are not presented in the table.

The ECOFLOW model uses a Shreve stream algorithm to measure the position of each watercourse in the hierarchy of tributaries when constructing a watercourses/tributaries network (hereinafter referred to as a stream network) for every catchment (Figure 3-2). The stream magnitude is enumerated according to the Shreve classification scheme by creating a hierarchic structure of a stream network from the parts to build the whole network /Shreve 1974/.

A series of shape files representing a stream network provided by SKB are utilised to compute stream lines within catchments 6–9 using the Shreve stream algorithm (Figure 3-3). The same algorithm is used to identify stream networks within the direct discharge areas, though they have no documented watercourses /Brunberg et al. 2004/.

Figure 3-3 illustrates that the stream network delineated from the Digital Elevation Model (DEM) differs significantly from that provided in the shape files. Similarly to /Brunberg et al. 2004/ the DEM is corrected by filling all localised depressions with the ECOFLOW subroutine to ensure all cells in the map drain cleanly off the DEM using, an algorithm by /Jenson and Domingue 1988/.

Two criteria for stream order enumeration, order and magnitude, are considered in the current modelling. Since Shreve stream order cannot handle braiding networks, the algorithm simply chooses a path through a braiding section based on the order in which the lines are stored in a given shape file. All other lines in a braid are defined as zeros /Jenson and Domingue 1988/.

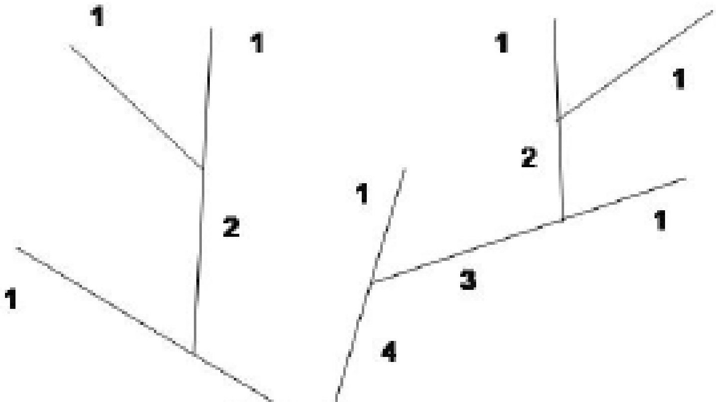

Figure 3-2. Shreve stream order for a river network.

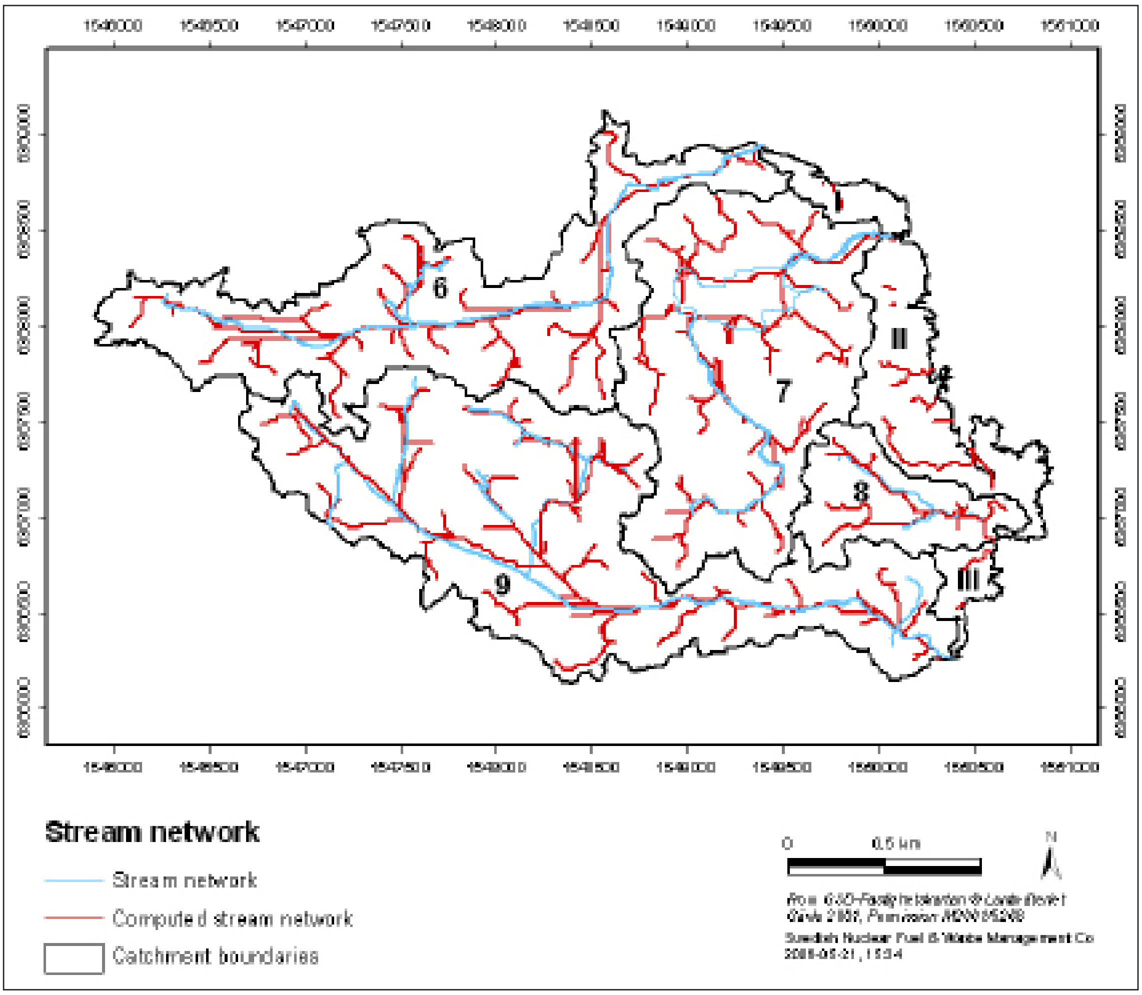

***Figure 3-3.** Observed and computed watercourses within the Laxemar model area, including catchments Nos. 6–9 and direct discharge areas I–III.*

Most discrepancies related to the observed (cf. Figure 3-3) and computed stream network occur around the tributaries of 1st and 2nd orders of magnitude according to the Shreve order for inland sub catchments. The major reason seems to be the high drainage density of the area, where several water courses exist in a form of conduits and/or culverts /Carlsson et al. 2005/ and are not featured in the shape files. These water courses, which are not registered in the SKB GIS database and hence can be referred to as "missing", are not considered in the MIKE SHE-MIKE 11 modelling either /Werner et al. 2005/.

The discrepancies are likely also due to that the current computed hierarchic structure of a stream network did not include sub catchment recognition. For example, catchment No. 7 (where Lake Frisksjön is located) is divided into two sub catchments, 7:1 and 7:2 /Brunberg et al. 2002/. This sub division is not implemented in the ECOFLOW simulation. Another reason for the discrepancies is thought to be errors in the DEM interpolation, causing erroneous estimations of the topographical features in the model input data.

3.3 Local physiography

3.3.1 Topography

The local topography undulates gently, differing between catchments Nos. 6–8 (including the direct runoff areas) and catchment No. 9, where the average elevation ranges from 20 to 24 m above sea level and from 30 to 34 m above sea level, respectively (cf. Figure 3-4 and Table 3-2).

3.3.2 Modelling settings

SKB's methodology framework for the descriptive modelling of surface and subsurface water flow is outlined in the modelling strategy report /Rhén et al. 2003/. The report highlights the need to develop site-specific hydrological modelling tools that enable proper modelling of the interaction between surface- and subsurface water in the Quaternary deposits (in the following referred to as QD) and groundwater in the bedrock.

Figure 3-5 illustrates SKB's principal approach to hydrogeological modelling of subsurface water flow, dividing the entire hydraulic domain into a set of sub domains. These are overburden (Hydraulic Soil Domain, HSD), rock mass (Hydraulic Rock Domain, HRD) and conductors in the bedrock, i.e. larger deformation zones that are treated deterministically in the modelling (Hydraulic Conductor Domain, HCD). In terms of hydrogeology, this partition provides the

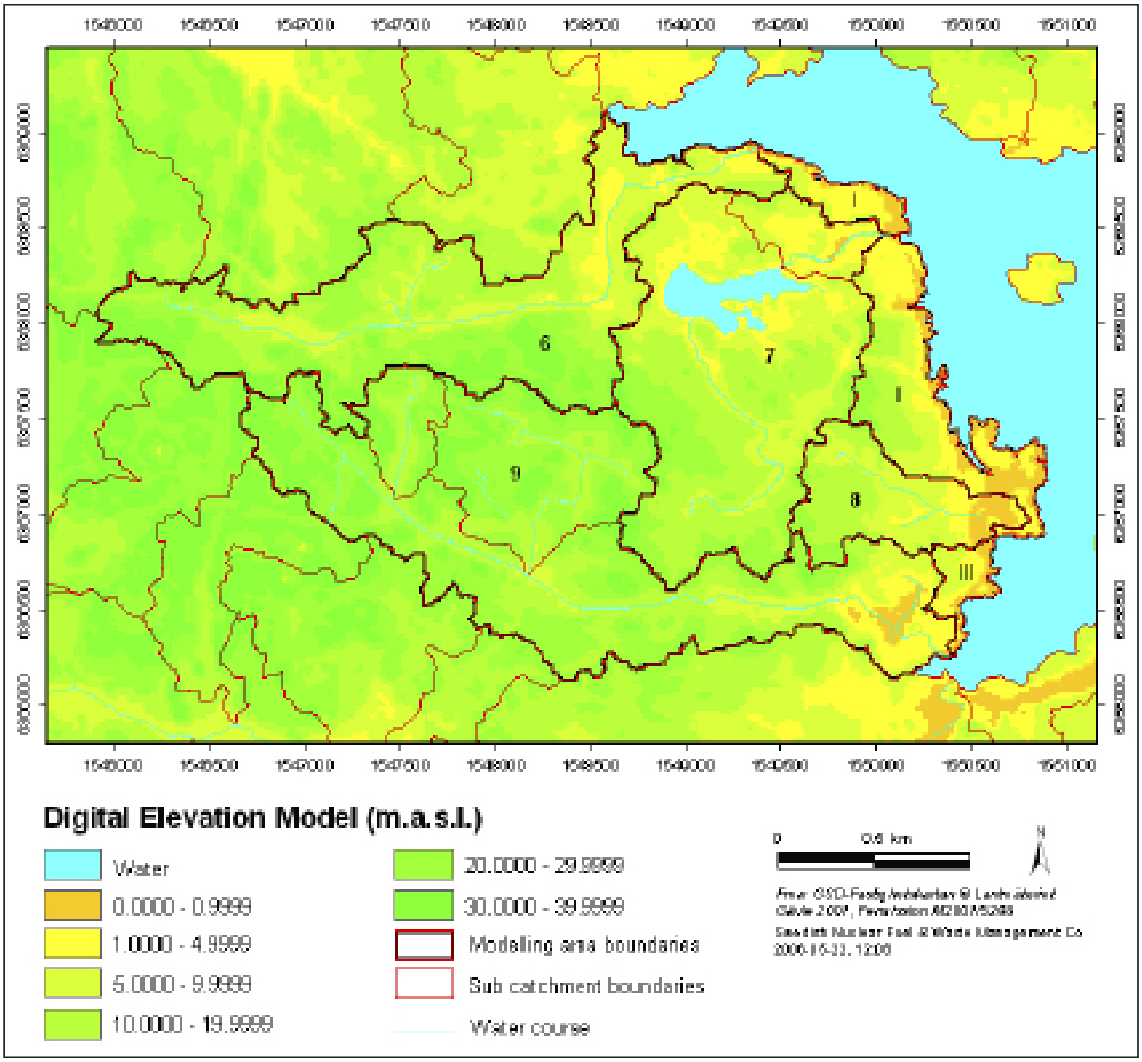

Figure 3-4. Digital Elevation Map (metres above sea level) over the Laxemar model area, including catchments Nos. 6–9, and direct runoff areas I–III.

basis for the quantitative modelling, whereas collected geological data and associated interpretations provide the basis for the ECOFLOW modelling of each individual domain.

This project combines modelling of the QD and the upper part of the bedrock as displayed in Figure 3-6. The interface between "shallow" and "deep" bedrock is supposed to be located at –150 m above sea level, in order to make the ECOFLOW model compatible with the MIKE SHE Laxemar model /Werner et al. 2005/. This hypothesis is implied in the current modelling by describing both the unsaturated (horizon A) and saturated (groundwater) (cf. Figure 2-1) zones according to the definition the surface system description provided by /Lindborg 2005/.

Therefore, the hydraulic properties of the shallow bedrock are described by assigning equivalent parameter sets for the horizontal and vertical hydraulic conductivity, porosity, specific yield and storage coefficient provided by /Werner et al. 2005/. The exposed bedrock areas in the ECOFLOW model are also treated by assigning a set of model parameters for the unsaturated zone as well as surface water storage.

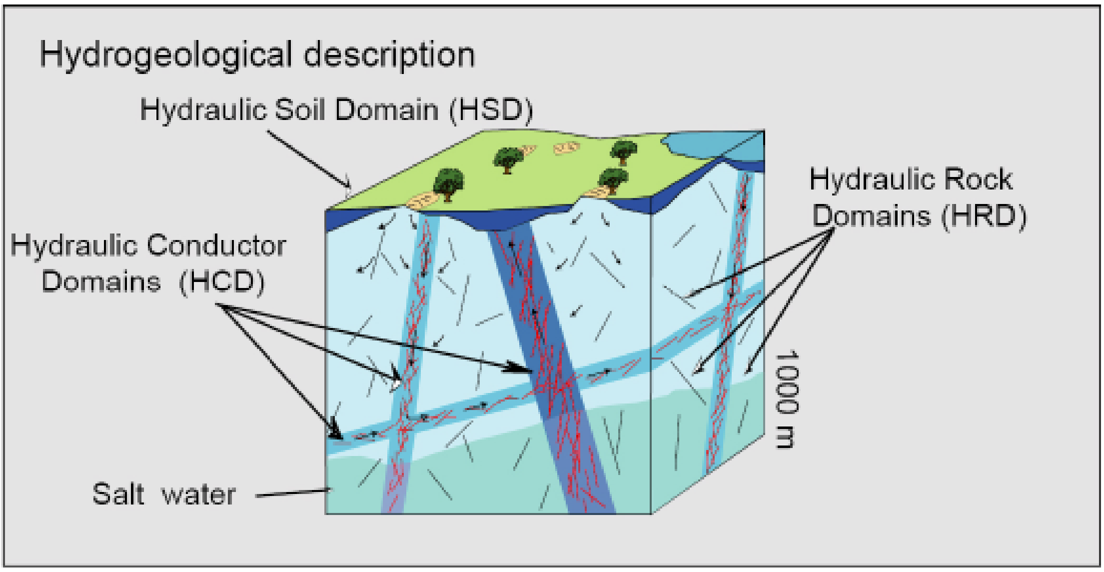

Figure 3-5. *Sub division of the entire domain, embodying both Quaternary deposits and bedrock, into domains representing the overburden or Hydraulic Soil Domain (HSD) and the rock domains (HRD) surrounded by fracture zones, which are denoted as hydraulic conductor domains (HCD). From /Rhén et al. 2003/.*

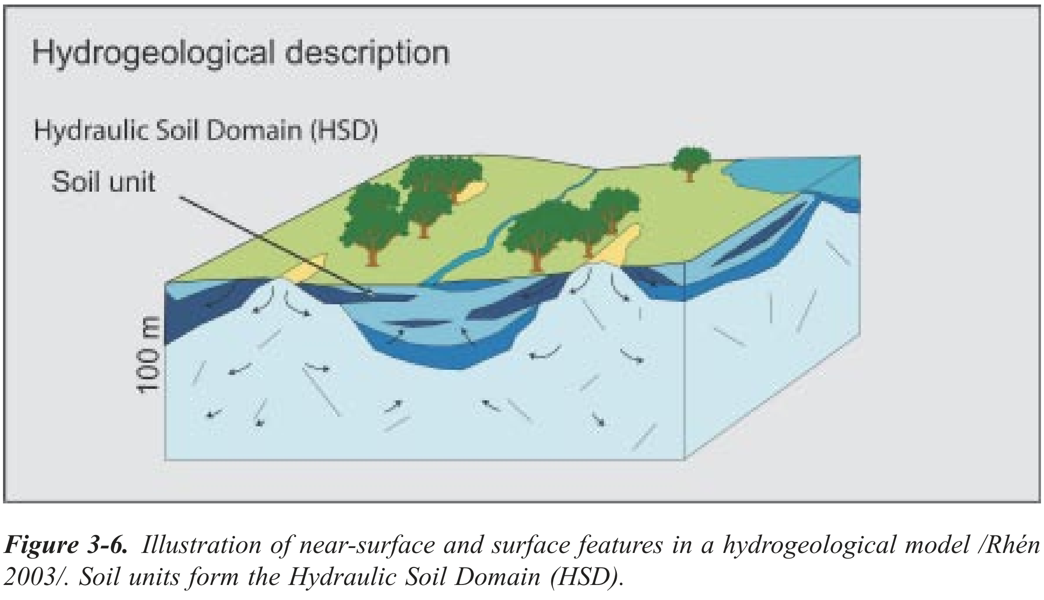

Figure 3-6. *Illustration of near-surface and surface features in a hydrogeological model /Rhén et al. 2003/. Soil units form the Hydraulic Soil Domain (HSD).*

3.3.3 Land use

There are nine land use (vegetation) classes identified in the Laxemar model area. These are (in order of area coverage): (1) coniferous forest, (2) cultivated ground (agricultural area), (3) open land, (4) water (lake), (5) logged area, (6) wetland, (7) swamp, (8) wetland/coniferous forest, (9) deciduous forest. Hence, the prevailing vegetation cover in the Laxemar model area is coniferous forest, which is denoted in Figure 3-7 in jade. Cultivated ground is the second most common land use category followed by open land, open water (lake) and logged areas /Rudmark et al. 2005/. Other classes have minor importance for the land use in the Laxemar model area in the ECOFLOW simulations, but occasionally appear at the local scale.

3.3.4 Properties of Quaternary deposits

About half of the regional Simpevarp model area consists of exposed or very shallow bedrock /Rudmark et al. 2005/. Figure 3-8 shows a detailed map of QD in the Laxemar model area. One should note that since the "mapping depth" is 0.5 m, areas marked as exposed bedrock on the map of QD may be covered by thin deposits and/or a thin layer of vegetation. Exposed

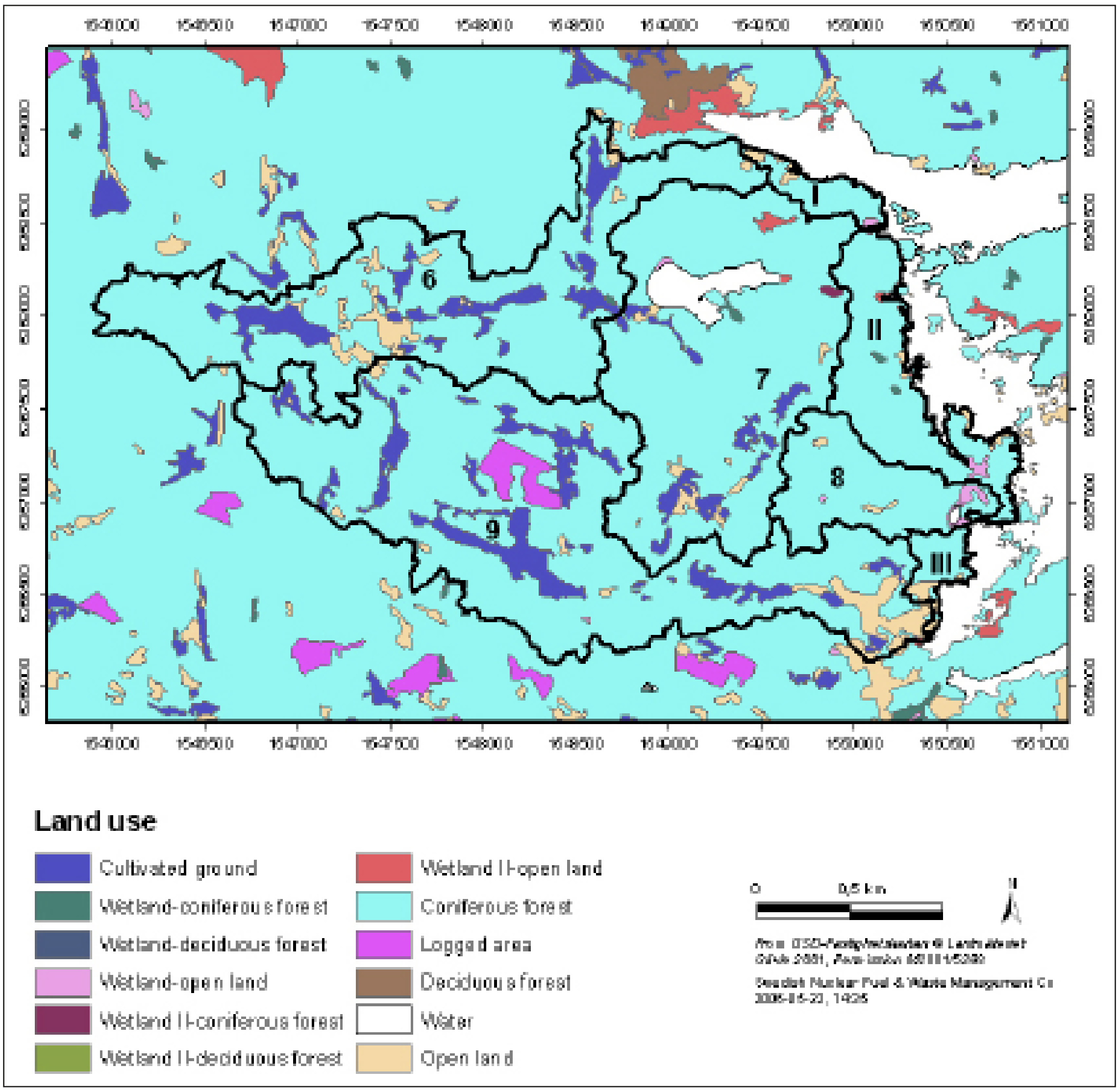

Figure 3-7. Land use map over the Laxemar model area, including catchments Nos. 6–9, and direct discharge areas I–III.

bedrock is primarily found in local topographic highs /Werner et al. 2005/. On the contrary, local topographic lows have thicker QD in a form of till and/or peat layers. There are four main water bearing glaciofluvial lows deposits (or eskers) located within the regional model area. The Gässhult esker (Gässhultsåsen, catchment No. 6) is partly located within the present model area.

The till is often covered by postglacial sediments (gyttja clay, peat and/or wave-washed material) /Werner et al. 2005/ within the valleys, where the thickest QD are found. The average thickness of the till is about 2 m. In the southern parts of the Laxemar model area (e.g. catchment No. 9) the till depth can extend down to 10 metres /Nyman 2005/. At some locations, the till is overlain by glacial sediments (mostly glacial clay). A layer of silt or sand is sometimes found between the postglacial and glacial sediments /Werner et al. 2005/. Data gathered by means of Vertical Electrical Soundings (VES) /Thunehed and Pitkänen 2003/ revealed that the maximum depth of QD over the Laxemar subarea is about 50 m.

The central part of the Laxemar model area is composed of hummocky moraine formations formed by the water courses to the Baltic Sea coast, which drain all catchments in the area /Rudmark et al. 2005/. Till is the major QD in this formation, commonly extending deeper than in topographically higher areas.

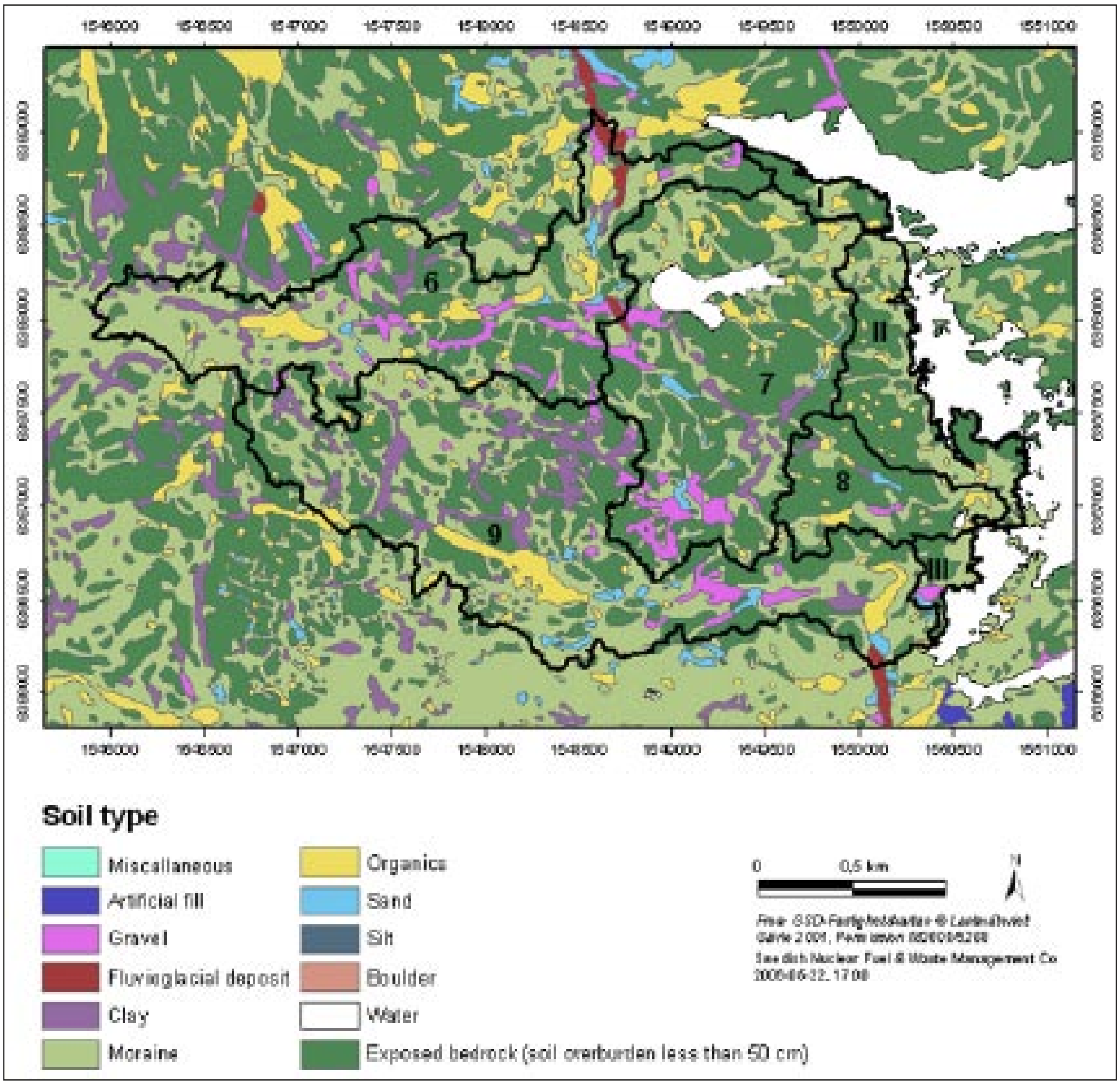

Figure 3-8. *Detailed map of Quaternary deposits in the Laxemar model area, including catchments Nos. 6–9, and the direct discharge areas I–III (cf. /Rudmark et al. 2005/).*

The conceptual model approach is used to construct the ECOFLOW model of catchments Nos. 6–9 and direct runoff areas I, II, III in the Laxemar model area. This approach involves using the GIS tools (embedded in the ECOFLOW model) to develop a conceptual model for each catchment. The term "conceptual model", as used hereinafter, includes geological settings, hydrostratigraphy, three-dimensional flow system, and boundaries of the system, cf. /Anderson and Woessner 1992/. The locations of sources/sinks, layer parameters such as hydraulic conductivity, and all other data necessary for the simulations are also defined in the conceptual model. Once this model is complete, the 3D grid is generated, the conceptual model is converted to the grid model and all of the cell-by-cell assignments are performed automatically.

The conceptual models of the Hydraulic Soil Domains and hydraulic properties of the shallow bedrock, utilised in the ECOFLOW simulations for each catchment, are based upon a geometrical model "g-HSD" reported in /Nyman 2005/, borehole data, geophysical and mapping of Quaternary deposits, and the digital elevation model.

Similarly to the g-HSD model, the ECOFLOW conceptual model consists of three QD layers, denoted herein as Z1–Z3, and two supplementary layers, denoted herein as M1 and M2. A typical cross-section through the area is depicted in Figure 3-9 including layers as follows: Z1 (uppermost), Z2 (clay/gyttja), Z3 (till), M1 (peat), M2 (glaciofluvial sediment), and M3 (artificial fill). As can be seen from Figure 3-9, layer M1 replaces layer Z1 if peat occurs, whereas layer M2 replaces layers Z2 and Z3 if glaciofluvial sediments occur. The glaciofluvial sediments (M2) form water bearing formations (eskers) within catchments Nos. 6, 7 and 9 (cf. Figure 3-8).

Note that the M3 layer (lens) defined in /Nyman 2005/, is not displayed in Table 3-3. This layer is excluded from the ECOFLOW computations, as artificial fill does not appear on the Quaternary deposit map of the Laxemar model area (cf. Figure 3-8). The thickness of each layer included in the ECOFLOW model corresponds to the layer depths used in the g-HSD model. The QD in the upper zone layer Z1 is based upon mapping visualised in Figure 3-8. In the modelling, all exposed bedrock areas are assigned a 0.2 m soil overburden (cf. Figure 3-8). Layers Z2 and Z3 are formed by clay and till, respectively (cf. Table 3-3).

Table 3-3. Notation of Quaternary deposits; modified after /Nyman 2005/.

Deposit	Notion	Occurrence
Layer 1 (soil upper zone)	Z1	Occurs in the entire model area, except for peat areas
Layer 2 (clay)	Z2	Occurs if the map of QD reveals peat, glacial/postglacial clay or postglacial sand-gravel at the surface
Layer 3 (till)	Z3	Occurs over the entire region, except if the QD map reveals bedrock or glaciofluvial sediments at the surface
Layer 4 (peat)	M1	Occurs if the QD map reveals peat at the surface
Layer 5 (glaciofluvial sediments)	M2	Occurs if the QD map reveals glaciofluvial sediment at the surface

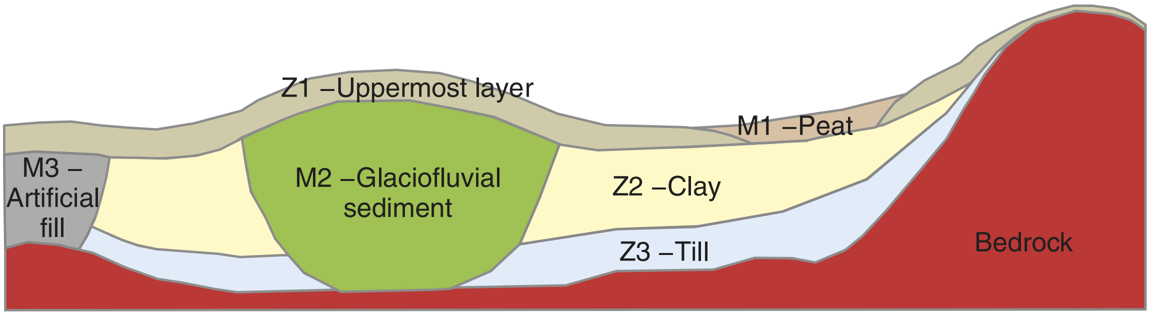

Figure 3-9. A typical cross-section through the Laxemar model area /modified after Nyman 2005/. Deposit notations are shown in Table 3-3.

The ECOFLOW model uses water retention parameters, field capacity and residual water content stored in its database, and other hydrogeological data as reported by /Werner et al. 2005/ (cf. Tables 3-4 and 3-5). The field capacity is defined here as a point where the remaining water held by surface tension on the soil particles is in equilibrium with the gravitational forces causing drainage /Maidment 1993/. The residual water content as used in ECOFLOW is defined as the water content at a soil suction of 1,500 kPa /van Genuchten 1980/.

3.3.5 Bedrock properties

The Laxemar model area encompasses the valley sediments bounded by the hills and underlain by crystalline bedrock, which very often outcrops to the surface in parts of the area (Figures 3-8 and 3-10). Since both the surface and subsurface water flow modules (ECOMAG and MODFLOW) are designed to be implemented for continuous water flow in porous media, the current modelling approach is to represent the fractured crystalline bedrock mass including discrete faults, fractures and fracture zones by equivalent properties and to treat them as a porous medium. In the current modelling, a set of hydraulic properties for shallow and deep bedrock domains is obtained from the DarcyTools model, which employs the Discrete Fracture Network (DFN) modelling principle as a basis for developing a continuum description of the rock /Follin et al. 2005, Svensson et al. 2004/. The resulting parameter fields are assigned to the grid cells in the ECOFLOW model.

Table 3-4. Water retention properties for Laxemar soils applied in the surface module ECOMAG. After /Werner et al. 2005/.

Texture class	Field capacity (–)	Residual water content (–)
Sand	0.04	0.02
Gravel	0.09	0.02
Till	0.30	0.03
Clay/gyttja	0.31	0.10
Peat	0.60	0.10

Table 3-5. Hydraulic properties of QD in the Laxemar model area applied in the subsurface module MODFLOW. After /Werner et al. 2005/.

QD type	Horizontal hydraulic conductivity K_H (m/s)	Specific yield S_Y (–)	Storage coefficient S_S (1/m)
Clay/gyttja	$1\cdot10^{-7}$	0.03	$6\cdot10^{-3}$
Clay (postglacial/ glacial)			
Z1	$1\cdot10^{-6}$	0.03	$6\cdot10^{-3}$
Z2	$1\cdot10^{-8}$	0.03	$6\cdot10^{-3}$
Till			$1\cdot10^{-3}$
Z1	$4\cdot10^{-5}$	0.15	
Z2–Z3	$4\cdot10^{-5}$	0.05	
Gravel	$1\cdot10^{-2}$	0.25	0.025
Sand	$1\cdot10^{-3}$	0.25	0.025
Peat	$1.5\cdot10^{-6}$	0.24	$5\cdot10^{-2}$
Glaciofluvial deposits (coarse sand, gravel)	$1\cdot10^{-4}$	0.25	0.025

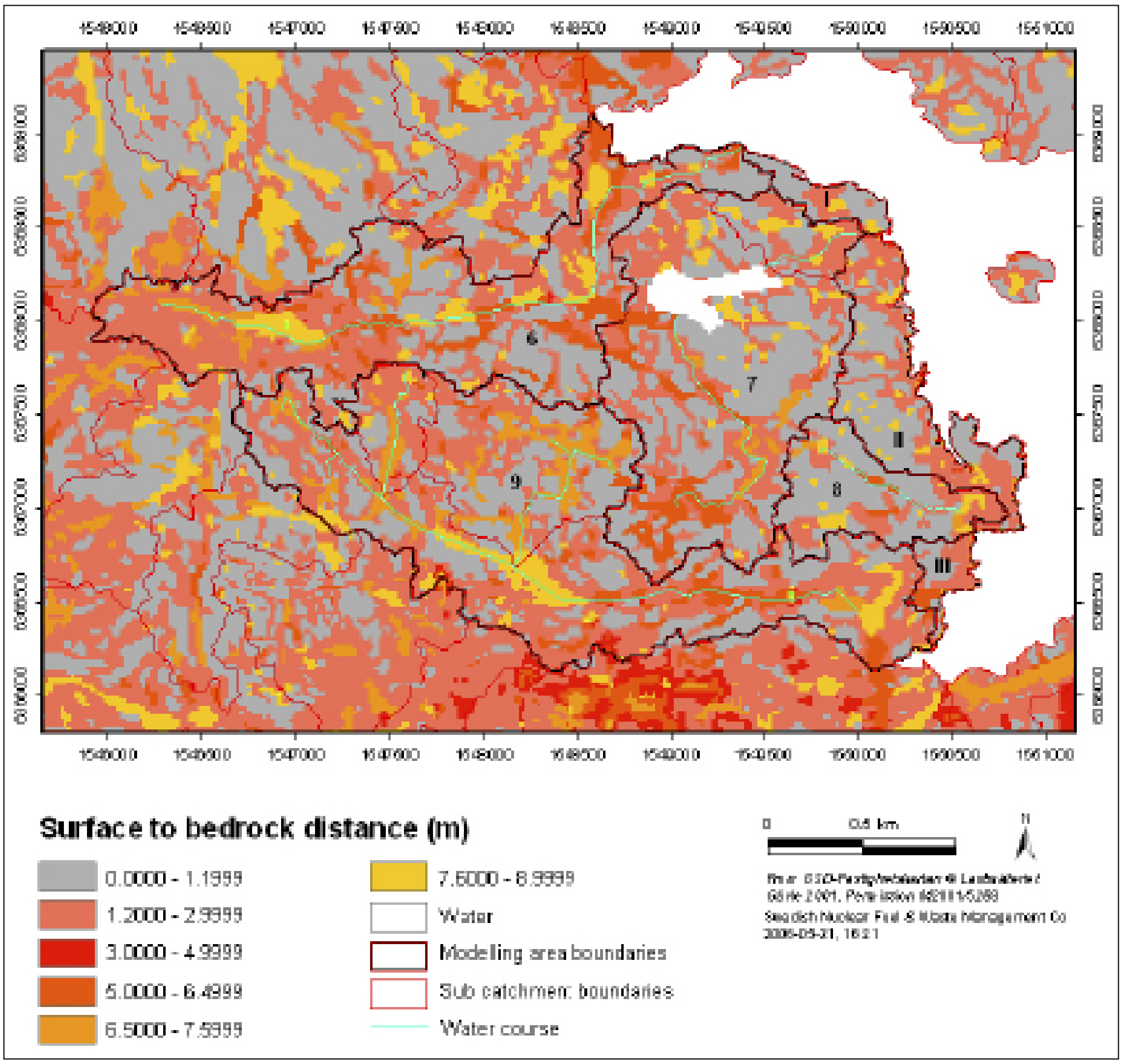

Figure 3-10. Mapping of depth to bedrock in the Laxemar subarea, including catchments Nos. 6–9, and direct runoff areas I–III (cf. /Nyman 2005/).

The equivalent hydraulic properties for the exposed bedrock are assigned to the ECOFLOW grid cells in the Laxemar model area according to the data provided in /Werner et al. 2005/. Thus, horizontal hydraulic conductivity, K_H (ms^{-1}), is set equal to $1.05 \cdot 10^{-7}$, specific yield, S_Y (–), is set equal to 0.005, and storage coefficient, S_S (m^{-1}), is set equal to $1.5 \cdot 10^{-6}$.

The equivalent hydraulic properties of the deep crystalline bedrock domains, including horizontal and vertical hydraulic conductivities and effective porosities, are documented in the following files, provided by SKB: (a) effective porosity; (b) horizontal hydraulic conductivity; (c) vertical hydraulic conductivity.

It is assumed in /Werner et al. 2005/ that the specific yield (S_Y) is equal to the effective porosity value. The specific storage coefficients in the fractured bedrock are computed according to an empirical relationship between S_S and the horizontal hydraulic conductivity K_H /Werner et al. 2005/:

$$S_S = a \cdot K_H^{\,b} \qquad (4)$$

where $a = 6.037 \cdot 10^{-5}$ and $b = 0.2312$. The values of the empirical coefficients a and b are obtained from investigations at the Äspö Hard Rock Laboratory.

3.4 Domain setup

3.4.1 Grid size

Unlike the MIKE SHE model set-up for the Laxemar model area, the present version of ECOFLOW does not allow simulation of more than one single catchment at a time. Each catchment is therefore simulated individually, using 9 layers (5 in QD and 4 in bedrock) in the computational grid, each cell measuring 20 by 20 m in plan view. Table 3-7 shows the computational domains, and the number of rows and columns for each individual grid.

The horizontal computational grid cell size in the ECOFLOW model is the same as in the MIKE SHE model /Werner et al. 2005/ in order to ensure proper comparison with the MIKE SHE computations.

The thickness of the cells in the vertical (z) direction in the ECOFLOW computations for each catchment follows the top and bottom elevations for each layer (Z1, Z2, Z3, M1, M2, Layer 4, 5, 6, and 7) of the grid (cf. Table 3-7 below).

3.4.2 Boundary conditions

The Baltic Sea forms the eastern margin along the sea interface for the direct-runoff areas I, II, III (adjacent to the sea-shore) and constitutes a constant-head boundary at the outlets of the catchments Nos. 6–9 (see e.g. Figure 3-8). The outer boundaries of the ECOFLOW model domain coincide with those of the Laxemar MIKE SHE model, except for the coastal sea areas (cf. Figure 4-5 in /Werner et al. 2005/), where the boundaries extend into the adjacent sea bay. The domain boundaries setup in ECOFLOW is different from that in MIKE SHE. To avoid interpolation errors caused by inconsistencies in the DEM and DarcyTools' spatial resolution, the constant head boundaries for rock domains Nos. 5–7 in MIKE SHE are replaced by variable head boundaries in ECOFLOW, cf. Table 3-7 and Table 4-4 in /Werner et al. 2005/.

Since the interior catchment areas boundaries (water divides) all over the Laxemar model area are likely to match the boundaries of the shallow groundwater domains /Werner et al. 2006/, it is assumed that no-flow boundaries represent the water divides between catchment areas Nos. 6–9, and the direct runoff areas I, II, III. However, this assumption is not valid for the deep bedrock flow domains, which may have continuous groundwater interactions through the network of fractures and faults.

Table 3-6. Computational domains and number of grid cells for each individual domain.

Domain	Number of grid cells (rows·columns)
Catchment area 6	16,912 (88·184)
Catchment area 7	76,248 (108·76)
Catchment area 8	2,706 (41·66)
Catchment area 9	16,340 (86·190)
Direct runoff area I	1,025 (25·41)
Direct runoff area II	4,510 (82·55)
Direct runoff area III	693 (33·21)

Table 3-7. Boundary conditions in the ECOFLOW model (modified from /Werner et al. 2005/.

Layer	Domain	Bottom level (m.a.s.l.)	Source file	Boundary conditions
Layer_Z1, M1	QD	g-HSD	z1_modeller.asc m1_modeller.asc	Constant head along the sea interface (if any); no flow along water divides (catchment boundaries). Upper (phreatic) boundary from DEM, ile höjdmodell_.asc[2]
Layer_Z2, M2[3] (if any)	QD	g-HSD	z2_modeller.asc m2_modeller.asc	Constant head along the sea interface (if any); no-flow water divides (catchment boundaries)
Layer Z3	QD	g-HSD	Z3_modeller.asc	Constant head long the sea interface; no-flow along water divides (catchment boundaries)
Layer 7	Bedrock	~ 10	Z_L7. grd/dat	Variable heads
Layer 6	Bedrock	~ –10	Z_L6. grd/dat	Variable heads
Layer 5	Bedrock	~ –60	Z_L5. grd/dat	Variable heads
Layer 4	Bedrock	–150	Z_L4. grd/dat	No flow

[1] According to the g-HSD /Nyman 2005/.

[2] According to the DEM /Brydsten and Strömgren 2005/.

[3] Substitutes both Layer_Z2 and Layer_Z3 /Nyman 2005/.

The upper time-variable head boundary for each model domain (Nos. 6–9, I–III) conforms to the DEM /Brydsten and Strömgren 2005/ and the bottom boundaries of the domains are uniformly extended to a depth of –150 m above sea level. In the ECOFLOW modelling, no flow is assumed to take place across the bottom boundary, which is also the case in the MIKE SHE model. Table 3-7 gives a summary of boundary conditions applied in the ECOFLOW conceptual model for the Laxemar catchments, including QD and bedrock computation layers.

3.4.3 Initial conditions

Hydraulic head data are used as initial conditions for the ECOFLOW simulations. An initial simulation period of ten years was performed to reach stable transient conditions, where the inflow to the system is equal to the outflow during each year. Each year during this initial simulation period uses meteorological data from the year 2004. The resulting stable transient condition is then used to calculate the water budget (cf. Section 4.1).

4 Results

4.1 Computed water balance

This section outlines the surface and subsurface water balance, as computed for each of the considered catchment areas within the Laxemar model area. The water balance is the hydrologic balance of a catchment area, quantified by the terms inflow, outflow, and change in water storage. The water balance includes both QD and bedrock, thereby making the present modelling results comparable with the MIKE SHE-MIKE 11 Laxemar modelling /Werner et al. 2005/.

Assuming that precipitation is the only inflow term for a catchment area, the annual water balance becomes

$$P = GW + OL_{stream} + OL_{boundary} + ET \pm \Delta W \qquad (5)$$

where P is precipitation, GW is groundwater recharge (equal to groundwater discharge minus evapotranspiration from the saturated zone), OL_{stream} is overland flow directly to streams, $OL_{boundary}$ is overland outflow across the catchment boundary, ET is total evapotranspiration, and ΔW denotes water storage change.

In each grid cell, groundwater recharge (GW) is computed as precipitation minus overland flow minus evapotranspiration from surface and unsaturated water storages (cf. Figure 2-1). Water outflow from the saturated zone is the sum of evapotranspiration from the saturated zone and groundwater discharge to streams.

The component $OL_{boundary}$ denotes surface water that does not enter streams, hence, this component only applies to direct runoff areas. Moreover, the sum of the components OL_{stream} and GW in (5) is equal to stream discharge, hence constituting total catchment runoff by stream flow (cf. Figure 2-1).

If the inflow and outflow sides of the water balance are not equal, there is obviously a change in water storage, either negative or positive. For instance, if the outflow is larger than the inflow, there is a negative change in water storage. For convenience, in this study the considered time period is long, implying that the storage term W is zero or close to zero.

Table 4-1 summarizes the water balance terms for each of the considered catchments. For the output, surface water leaves by evapotranspiration, groundwater infiltration, stream and overland runoff (see (5)). The evapotranspiration term in (5) includes precipitation retained on vegetation (interception), and evaporation and transpiration losses from the surface, unsaturated and saturated water reservoirs (cf. Figure 2-1). The amount of water that is not consumed through evaporation and transpiration either returns to streams or form groundwater recharge.

In the Laxemar area, groundwater recharge takes place in the form of percolation of precipitation at topographical highs. The actual precipitation value computed for year 2004 (cf. Section 3.1.2) equals to 659 mm. As computed by ECOFLOW, the streams receive water either from the surface or the seepage from a subsurface zone, which are overland flow and base flow, respectively (cf. Figure 2-1). The output of the streams is the runoff, which is tabulated in Table 4-1 and will be presented in Section 4.2 in more detail.

In areas where the groundwater level is below the stream water level, the stream may act as a source for groundwater recharge. Actual groundwater recharge in such areas depends on the hydraulic head difference across the stream-groundwater interface, as well as the thickness and hydraulic conductivity of the bottom sediments of the stream. Considering that most streams in Laxemar are small, it can be assumed that the contribution from streams to groundwater recharge is small.

Table 4-1. Summary of computed annual water balance terms (mm year^{-1}). The areas denote the areas of the catchments. The corresponding total runoff values calculated by MIKE SHE-MIKE 11 /Werner et al. 2005/ are shown in parentheses.

Catchment	6 (2.003 km^2)	7 (2.062 km^2)	8 (0.499 km^2)	9 (2.834 km^2)	DRA I (0.132 km^2)	DRA II (0.604 km^2)	DRA III (0.108 km^2)
P[1]	659	660	659	659	659	660	659
GW	99	70	93	96	75	78	73
OL_{stream}	94	88	107	99	37	76	38
$OL_{boundary}$[2]	[1]	[1]	[1]	[1]	90	55	101
Total runoff	193 (188)	157 (181)	200 (203)	195 (189)	202 (203[3])	209 (203[3])	212 (203[3])
ET	466	502	459	464	457	451	447

[1] Differences are due to quasi steady state character of simulations.

[2] Overland flow across catchment boundaries applies only to direct runoff areas (DRA).

[3] Total runoff for all direct runoff areas I–III.

Table 4-1 shows that the model-calculated groundwater recharge, *GW*, is on the order of 90–100 mm year^{-1} for catchments Nos. 6, 8, and 9, and smaller (c. 70–80 mm year^{-1}) for catchment No. 7 and the direct runoff areas. An additional outflow term for the latter areas is overland flow to the sea ($OL_{boundary}$). This outflow term constitutes 25–50% of the total runoff from these areas, and is probably characterised by short surface water routing (travel) time, i.e. most of this overland water discharges into the sea before it forms groundwater and/or reaches a stream. In these areas, there is therefore little groundwater contribution to stream flow, and groundwater discharge mostly discharges into the sea. This is particularly the case during prolonged dry periods, when most intermittent streams in the Laxemar subarea cease to flow /Werner et al. 2005/.

It should be noted that cross-catchment boundary groundwater flow is a potentially large in- or outflow component, which is not considered in the ECOFLOW model. As mentioned in section 3.4.1, this limitation is due to that the present version of ECOFLOW does not allow simulation of more than a one catchment at a time. It should also be observed that submarine groundwater discharge from the direct runoff areas I–III is not taken into consideration. For these areas, groundwater outflow to the sea is computed as return flow in QD (cf. Figure 2-1), and is hence included in the computed base flow, i.e. the groundwater component of the stream flow.

Evapotranspiration (*ET*) constitutes the largest outflow for all catchments, in particular for catchment No. 7. Lake Frisksjön constitutes 11% of the catchment /Brunberg et al. 2004/, which partially can explain the large *ET* in this catchment. It should be observed that evapotranspiration from streams is not considered in ECOFLOW.

The model-calculated total annual discharge from the whole ECOFLOW model area is 1,537,935 m^3 year^{-1}, which corresponds to a specific discharge of c. 186 mm year^{-1} (obtained by dividing the total discharge by the total model area). This discharge deviates only slightly from the discharge computed for the corresponding model area by MIKE SHE-MIKE 11 (1,583,700 m^3 year^{-1}; 189 mm year^{-1}).

Specific discharge values computed by ECOFLOW agree both with values computed by MIKE SHE-MIKE 11 for the Laxemar model area (in the range 188 to 203 mm year^{-1} for the same catchments; /Werner et al. 2005/) and PCRaster-POLFLOW (in the range 128–186 mm year^{-1} for the entire Simpevarp regional model area; /Jarsjö et al. 2006/). The largest difference between the ECOFLOW and MIKE SHE-MIKE 11 results is the model-calculated discharge from catchment No. 7. As also discussed in Section 4.2, the low discharge value may be erroneous due to numerical instability in the model. Moreover, it is noted that the total discharge from the direct runoff areas I, II, and III (175,192 m^3 year^{-1}) computed by ECOFLOW is less than the value computed by MIKE SHE-MIKE 11 (200,500 m^3 year^{-1}).

4.2 Computed stream flows

This section summarises modelling results in terms of model-calculated stream flows. Figures of computed stream flows and measured precipitation time series can be found in Appendix 1. Since measured stream flow time series are not available at time of writing, no comparisons with observed hydrographs are made in this study.

Typical for Sweden, major contribution to stream flows is the accumulation of snow during winter, which melts during a relatively short period during spring /Gottschalk et al. 2001/. This accumulation-melting pattern produces a characteristic hydrograph of high stream flows during mid spring, and decreasing stream flows during late summer. In the Laxemar model area, mild winter temperatures during the simulated period, combined with the high mid summer precipitation, produced multi-peaked hydrographs, where all inland catchment areas 6–9 demonstrate quick responses to precipitation events (see Appendix 1).

An example of such patterns is illustrated in Figure 4-1, showing model-calculated stream flows versus observed precipitation time series for catchment No. 6 (Mederhultsån). The general hydrological response pattern indicates a hydrologic system for which groundwater discharge (base flow) dominates stream flow during low-flow periods, and surface water (overland) flows and more shallow subsurface water have the largest contributions to stream flow during high-flow periods (events).

A somewhat deviating computed stream flow pattern is observed for catchment No. 7 (Appendix 1), where Lake Frisksjön is located. The lake may reduce and delay peak flow events due to its storage capacity and also high evaporation. The lakebed sediments are in the groundwater module MODFLOW simulated by a lakebed leakage term, which is a function of the thickness and the hydraulic conductivity of the sediments. Groundwater discharge into the lake is a function of both this lakebed leakage term, and the hydraulic conductivity below the sediments. Site investigation data indicate that the lakebed sediments consist of low-permeable layers of gyttja and clay /Werner et al. 2005/, Lake Frisksjön is hence likely rather isolated from the groundwater zone. It should be noted that for catchment No. 7, large hydraulic head changes over short distances in near-lake areas caused numerical instability problems in ECOFLOW, making it difficult to obtain a reliable estimate of the groundwater discharge to the lake.

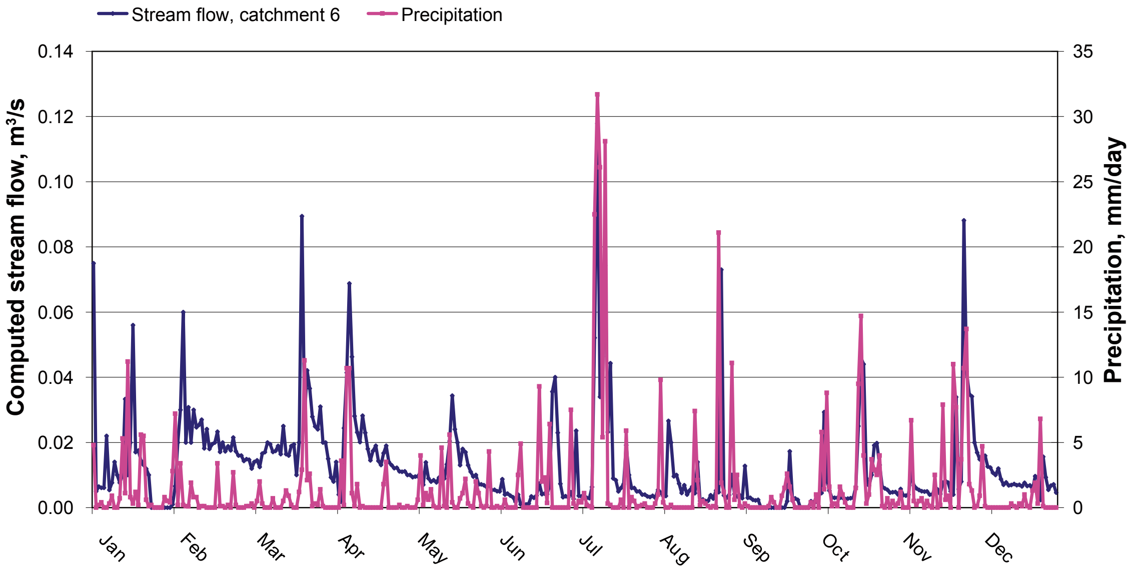

Figure 4-1. *Model-calculated stream flow versus observed precipitation time series for catchment No. 6 (Mederhultsån).*

The hydrological response in catchment No. 8 reflects the influence of shallow subsurface water flows. Moreover, the more abundant stream networks in catchments Nos. 6 and 9 are reflected in more rapid hydrograph recessions in these catchments. For the direct runoff areas I–III, the model results show that rainfall rates greater than 5 mm day^{-1} produce noticeable runoff.

Throughout the model area, the upper zone of the soil (horizon A, cf. Figure 2-1) experiences freeze-thaw cycles, since the snow melt season is characterised by multiple accumulation periods, which increase the slope of the recession limbs of the hydrographs (cf. Figures 4-1 and 4-3). This is especially the case when there is an impenetrable ice layer over herbaceous vegetation. This effect can be noted throughout the model area, except for the direct runoff areas I, II, III.

4.3 Identification of recharge and discharge areas

This section summarises ECOFLOW results in terms of model-calculated hydraulic heads, aiming to identify groundwater recharge and discharge areas. The ECOFLOW modelling results show that the groundwater recharge areas are located at topographic highs, characterised by a relatively large depth to the groundwater table (in the range 5–10 m). In locations where the computed groundwater table reaches the ground surface (given by the DEM), groundwater discharges to form overland flow towards streams. In this study, these areas are identified as groundwater discharge areas.

As discussed in Section 4.2, during spring stream flow is dominated by snow melt, exceeding groundwater recharge and evapotranspiration. Stream flows reduce rapidly during late spring when snow melt ceases, which reflects a shift from surface flow-dominated to groundwater discharge-dominated runoff. The relative proportions of these flow regimes vary between catchments due to differences in available surface and subsurface water storage volumes.

Shallow QD may imply that low stream flows during summer (cf. Section 4.2) primarily are supplied by groundwater discharge, in turn dominated by groundwater recharge in upstream forest areas where QD overlie relatively impermeable crystalline bedrock. A small available water storage volume in these forest areas implies that the QD are saturated close to the ground surface during long periods of the year. Further, one can expect that groundwater flow recessions are largely controlled by the timing of snowmelt. During dry years, groundwater flow probably have earlier peaks and quicker flow recession.

The ECOFLOW modelling results show that in most of the modelled catchments, the evapotranspiration rates are larger than precipitation during the latter part of the summer during the simulated year. This causes a rapid drop of groundwater levels, and also that stream flow drops to zero (cf. Figure 4-1 and Appendix 1). On the other hand, the results show that groundwater levels in large parts of catchments Nos. 6, 7 and 9 remain at or close to the ground surface during the entire summer, despite the high evapotranspiration rates. In late summer, evapotranspiration rates decrease and groundwater levels rise slowly; groundwater levels reach seasonal maxima when substantial rainfall periods (and/or snowmelt) occur during late fall.

As exemplified in Figures 4-2 and 4-3 (see similar figures for the other catchments in Appendix 1), groundwater discharge is primarily associated with streams (and Lake Frisksjön in catchment No. 7, see Figure 4-2). Generally, it seems that ECOFLOW overestimates the extents of areas with surface water. In catchment No. 8 (Figure 4-3) and No. 9 (Appendix 1), the model-calculated groundwater table reaches the ground surface and causes flooding of areas surrounding the streams Pistlanbäcken and Ekerumsån. In the direct runoff areas I–III, groundwater discharge areas are mainly found along the coastline (areas I and III), and at a wetland in the southern part of direct runoff area II.

It should be noted that in many areas in Laxemar, groundwater may be drained by culverts /Werner et al. 2005/, which are not taken into consideration in the present model. Hence, it is likely that model-calculated groundwater levels are overestimated, which means that existing drainage levels may need to be assigned in the model to produce realistic results; this was also a conclusion in the MIKE SHE-MIKE 11 modelling /Werner et al. 2005/.

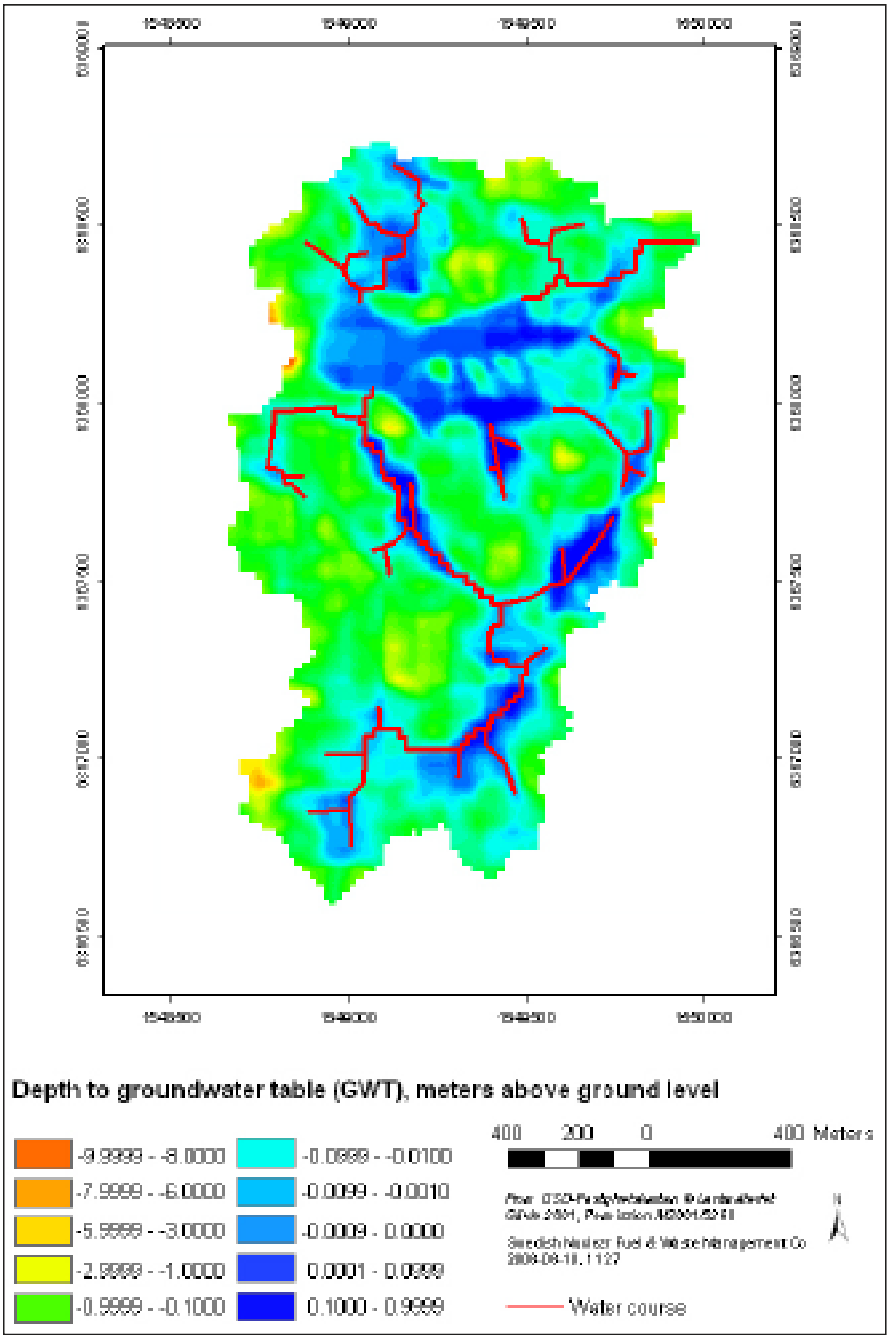

Figure 4-2. Model-calculated depth to the groundwater table (GWT) in the catchment No. 7. The solid red line represents the stream network computed by ECOFLOW for Kåreviksån.

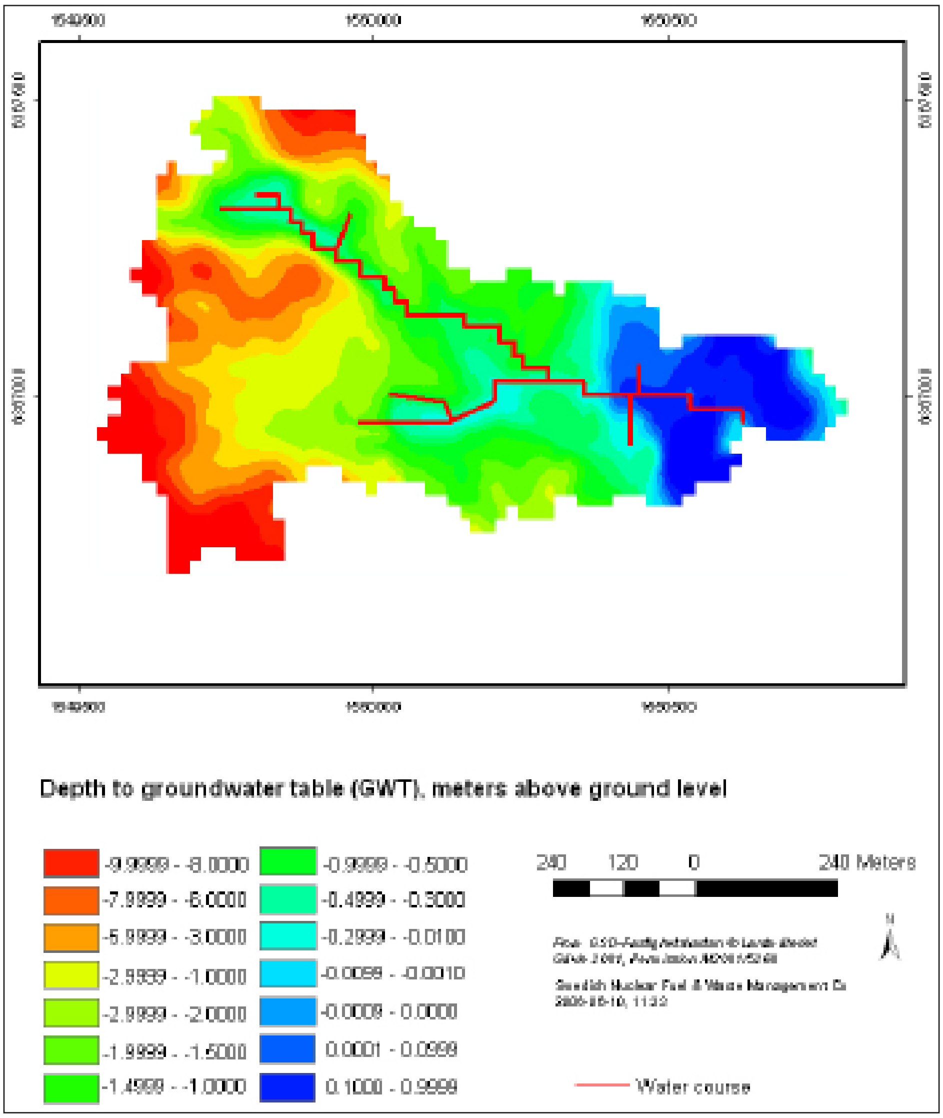

Figure 4-3. *Model-calculated depth to the groundwater table (GWT) in the catchment No. 8. The solid red line represents the stream network computed by ECOFLOW for Pistlanbäcken.*

5 Conclusions

The distributed hydrologic model ECOFLOW was applied to a model area in Laxemar, south-eastern Sweden. The primary objectives of the study were to assess the ability of the model to simulate surface water and near-surface groundwater systems in catchments with relatively large areas of exposed or very shallow bedrock, and reveal the advantages and limitations of the ECOFLOW model. ECOFLOW modelling results include transient surface and subsurface water flow simulations, which may further increase the understanding of the water balance and water flow patterns of the considered catchments. ECOFLOW modelling results were compared with corresponding results obtained by the MIKE SHE-MIKE 11 /Werner et al. 2005/ and PCRaster-POLFLOW models /Jarsjö et al. 2006/, focusing on the water balance and identification of groundwater recharge-discharge patterns.

ECOFLOW was used to obtain modelling results for a one-year non calibrated simulation period, considering seven catchments within the Laxemar subarea (including three areas with direct runoff to the sea). Similarly to the MIKE SHE-MIKE 11 modelling, ECOFLOW is vertically divided into nine layers (5 in Quaternary deposits (QD) and 4 in bedrock). The vertical discretisation of the QD follows the geometrical QD description /Nyman 2005/. Furthermore, the same site-specific data are used as in the MIKE SHE-MIKE 11 model set up, including meteorological data (precipitation, temperature and relative humidity time series), topographical data (the digital elevation model, or DEM), and other spatially distributed GIS data (e.g. land use, vegetation, and hydrological objects).

The ECOFLOW modelling results show that there are relatively large differences in the specific discharge between the considered catchments (157–212 mm year^{-1} for the simulated year, 2004); the lowest value (the Lake Frisksjön catchment) may be erroneous due to numerical instability in the model. Overall, the model-calculated values agree with the corresponding MIKE SHE-MIKE 11 (188–203 mm year^{-1}; /Werner et al. 2005/) and PCRaster-POLFLOW results (128–186 mm year^{-1} for the entire Simpevarp regional model area; /Jarsjö et al. 2006/). It should be noted that /Jarsjö et al. 2006/ used long-term averages of meteorological parameters from surrounding SMHI meteorological stations (Målilla, Oskarshamn and Ölands Norra Udde), whereas the ECOFLOW and MIKE SHE-MIKE 11 models use data from the on-site meteorological station on the Äspö island. Moreover, the PCRaster-POLFLOW modelling uses evapotranspiration data from Germany, which were recalculated to obtain a better fit to local discharge observations.

A potential source of uncertainty in the ECOFLOW water balance computation is the estimation of the evapotranspiration rate. This rate is based on site-specific potential evapotranspiration time series, water-retention parameters, and so called moisture extraction functions; the latter data types are taken from a generic data base in ECOFLOW. Calibration and correction of these parameters may provide better estimates of site-specific evapotranspiration rates. Recharge-discharge patterns computed by ECOFLOW agree with those identified using MIKE SHE-MIKE 11. Generally, the model-calculated groundwater table follows the topography, which implies that the DEM has large influence on the model-calculated recharge-discharge patterns. The results show that groundwater recharge is associated to topographic highs, characterised by a relatively large depth to the groundwater table (on the order of 5–10 m below ground surface). Model-calculated groundwater discharge areas are either located at streams, lakes (Lake Frisksjön in catchment No. 7) and wetlands. In the direct runoff areas, groundwater discharge mainly occurs along the coast. An additional uncertainty is that man-made drains are not considered in the ECOFLOW model, which at least partly explains that the model overestimates the extents of flooded areas.

Site investigation data indicate that the permeability of the bedrock decreases with depth. Hence, it is likely that groundwater flow at depth is small compared to near-surface groundwater flow. Even though this has not been analysed in this study, the use of no-flow boundaries (both laterally and vertically) at the depth –150 m above sea level has likely only minor influence on the modelling results. Continued data collection in Laxemar, in particular stream flow and hydraulic head time series, would be helpful for model calibration and further refinement of the ECOFLOW model of the site, and to test model abilities for mixed porous-fractured bedrock systems.

The main advantages of the ECOFLOW model compared to MIKE SHE-MIKE 11 are less time-consuming simulations and few model parameters. The model execution time is generally an important issue for long-term simulations of complex hydrological systems. As an example, simulation of a one-year period took 6–14 minutes for ECOFLOW, whereas the corresponding execution time for MIKE SHE-MIKE 11 is on the order of 8 hours or more /Bosson 2006/, using a time step of 1 day in both models. Short execution time facilitates automatic calibration procedures, as those embedded in the ECOFLOW core modules (ECOMAG and MODFLOW). An additional feature in ECOFLOW, not available in MIKE SHE, is that ECOFLOW simulates freeze-thaw cycles that may be important e.g. during periods when snowmelt is a dominant part of stream flow. This is particularly the case when snow melt occurs on frozen soil, thereby limiting groundwater recharge.

Main ECOFLOW limitations include the handling of surface water (channel) and overland flow. Moreover, the current version of ECOFLOW only supports particle tracking in the groundwater zone. This means that particles cannot be tracked in overland flow and channel flow. Moreover, ECOFLOW uses MODFLOW to simulate groundwater flow, which implies that the well known "dry cells" problem in MODLOW is a problem also in ECOFLOW. Manipulating the computation layers is commonly used to prevent dry cells and thereby overcoming this problem. Further, the current ECOFLOW version only allows computation of one catchment at the time, which increases pre- and post processing times. This constraint reduces the possibilities for direct comparisons between ECOFLOW and MIKE SHE-MIKE 11, since ECOFLOW cannot simulate (deep) groundwater flows across catchment boundaries.

The study demonstrates that ECOFLOW is able to produce almost the same results as MIKE SHE-MIKE 11, in terms of water balances and recharge-discharge patterns. The ECOFLOW model is a reliable tool for simulation of complex hydrologic systems, in particular in situations where multiple and/or long-term simulations are to be performed. The relatively simple ECOFLOW model structure means that relatively fast simulations are possible even for long-term hydrologic runoff predictions, which usually require long run-times when more complex models are used for simulation of large and mid-scale catchments.

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Appendix 1

Figures

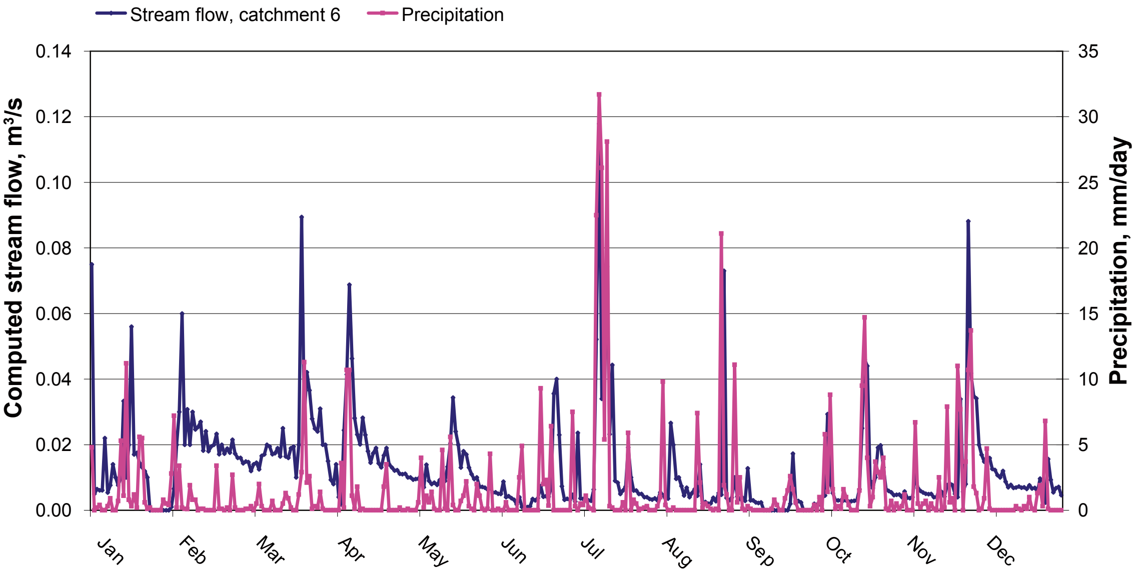

Figure A1-1. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for catchment No. 6 (Mederhultsån).*

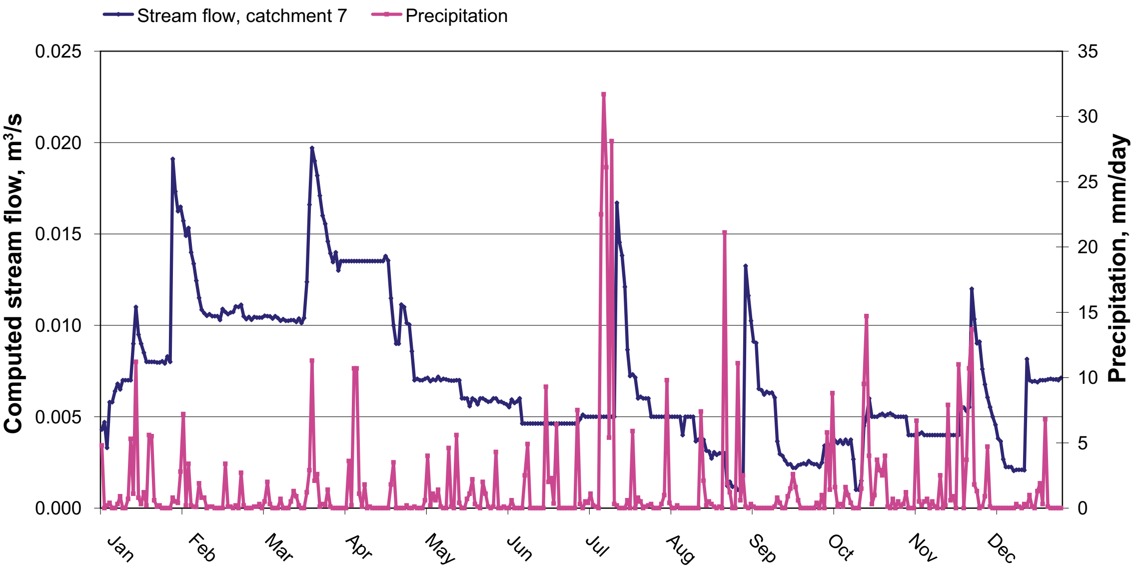

Figure A1-2. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for catchment No. 7 (Kåreviksån).*

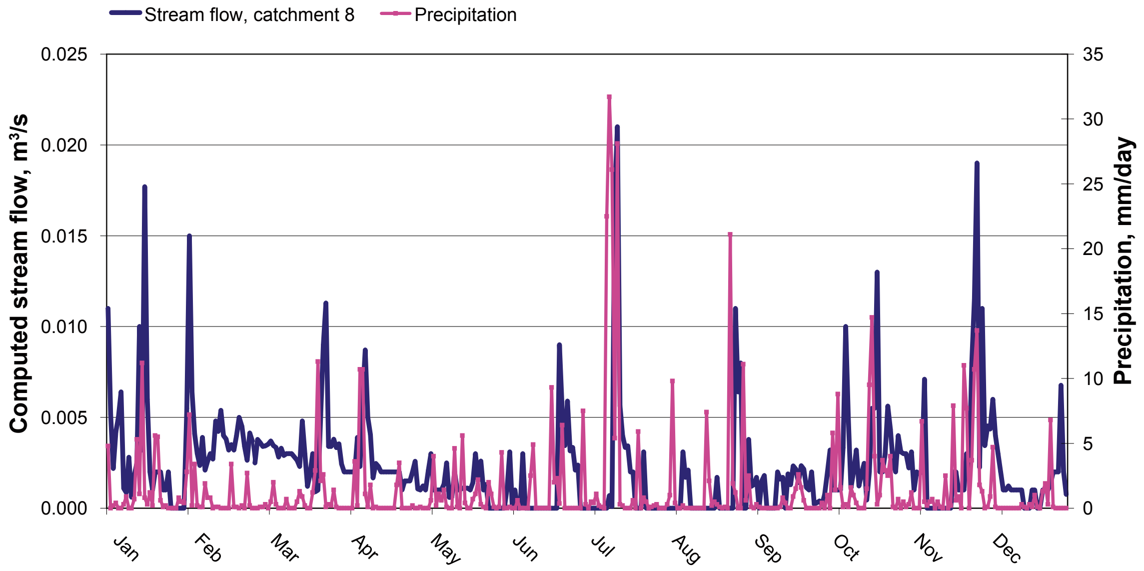

Figure A1-3. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for catchment No. 8 (Pistlanbäcken).*

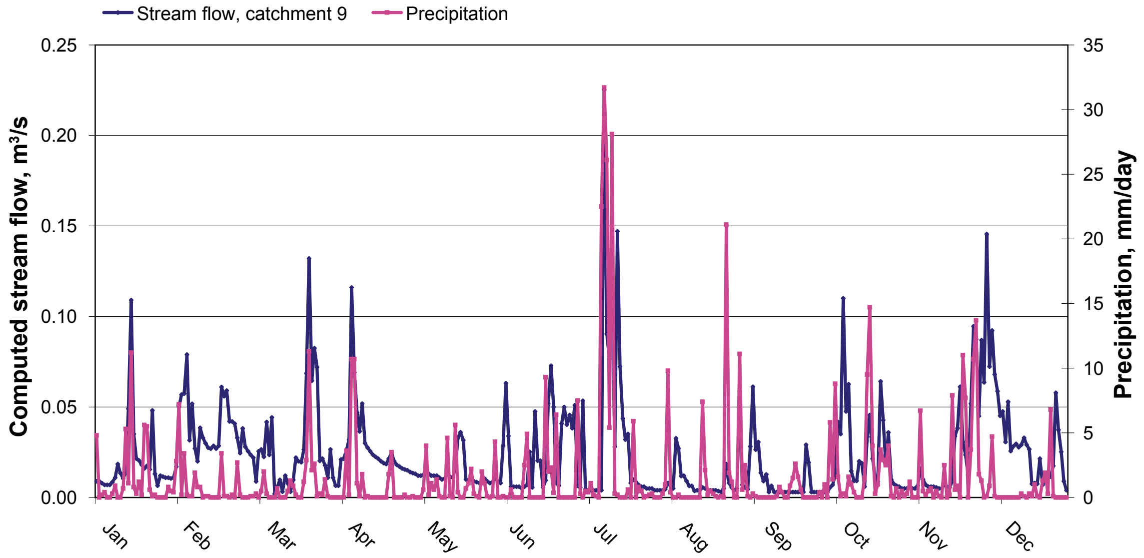

Figure A1-4. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for catchment No. 9 (Ekerumsån).*

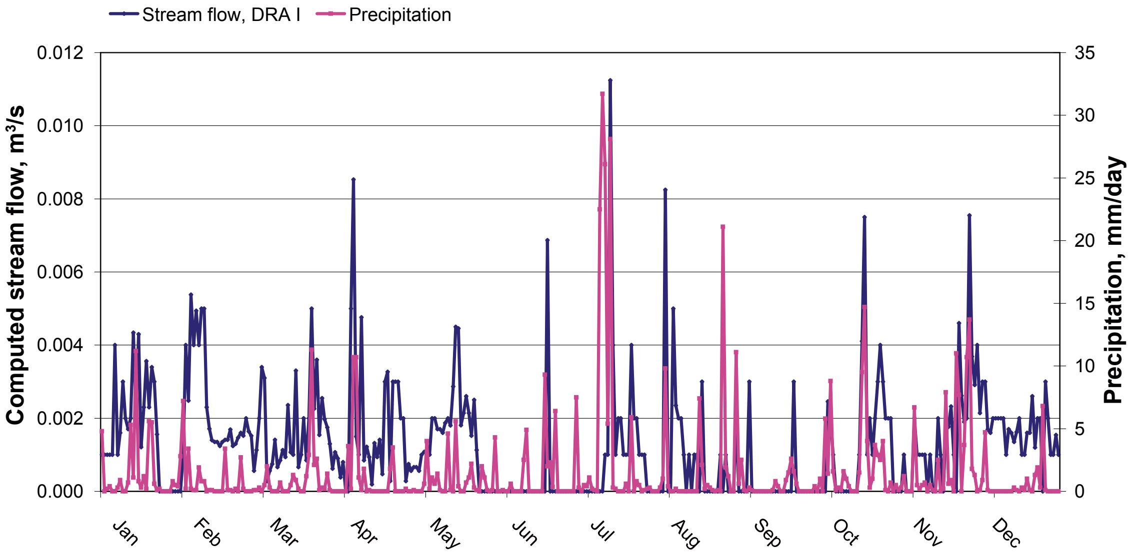

Figure A1-5. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for the direct runoff area I.*

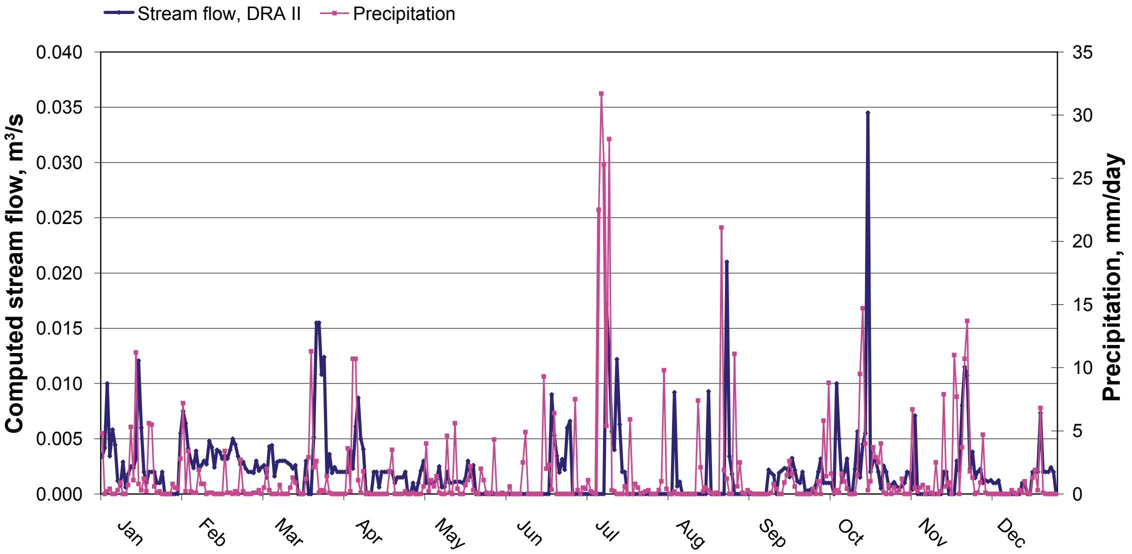

Figure A1-6. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for the direct runoff area II.*

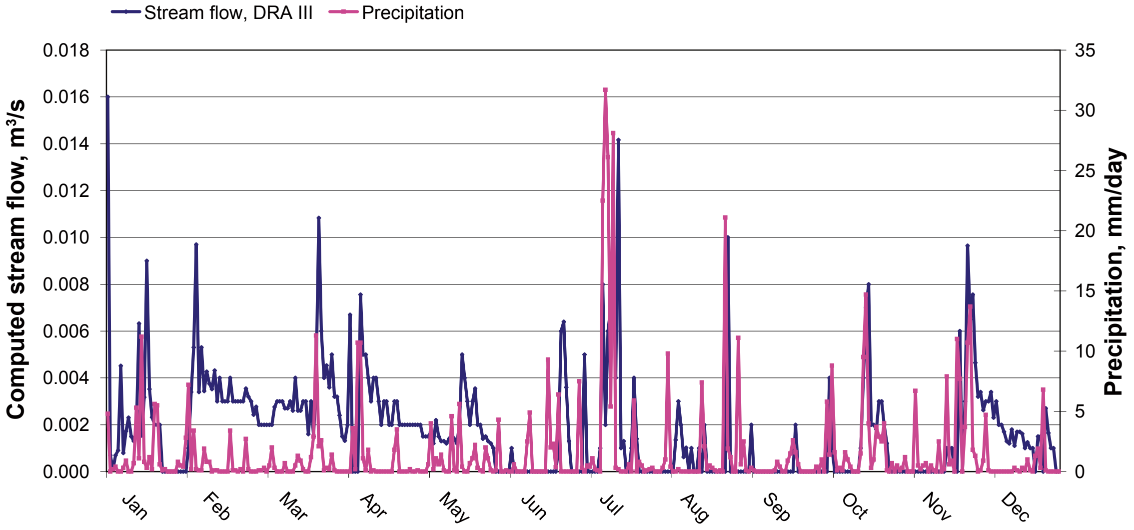

Figure A1-7. *Model-calculated stream flow (blue) and observed precipitation time series (lilac) for the direct runoff area III.*

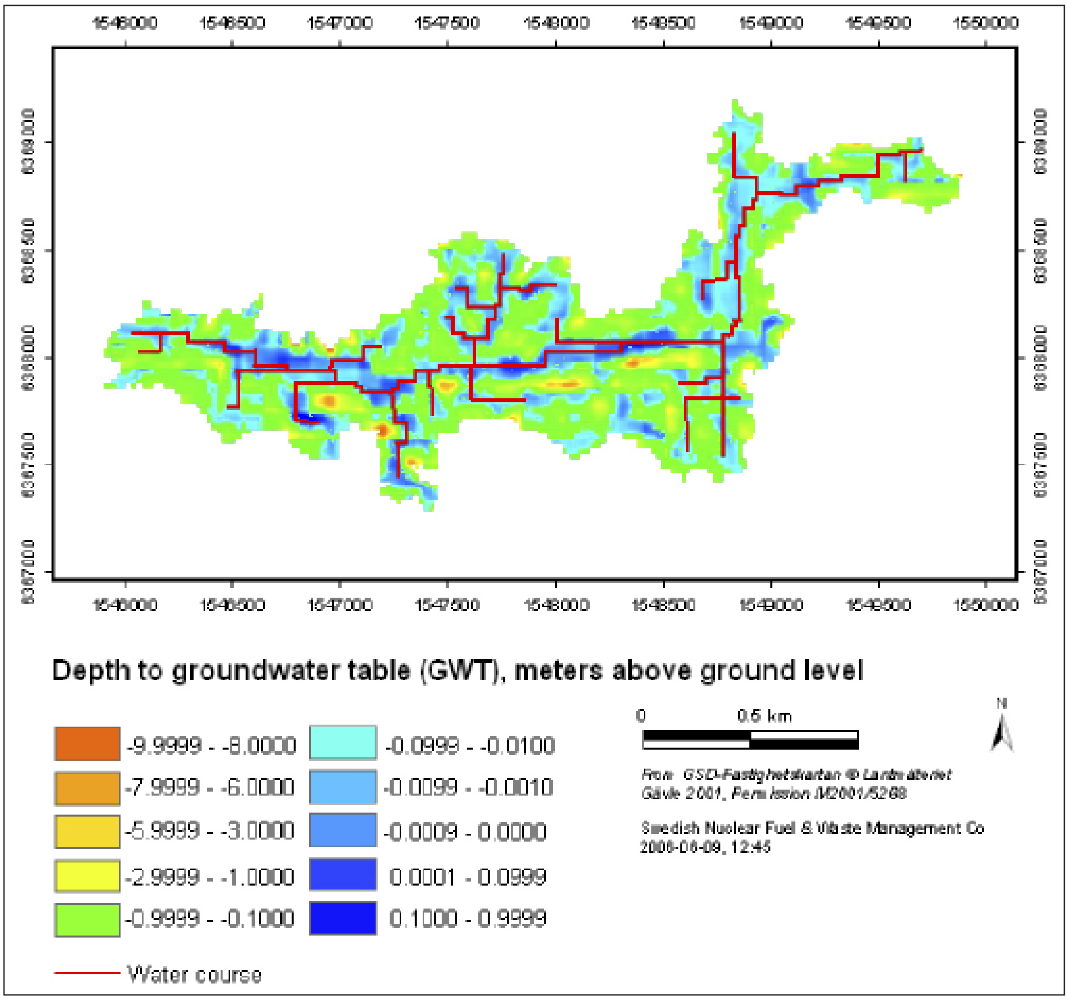

Figure A1-8. *Model-calculated depth to the groundwater table (GWT) in catchment No. 6. The solid red line represents the stream network computed by ECOFLOW for Mederhultsån.*

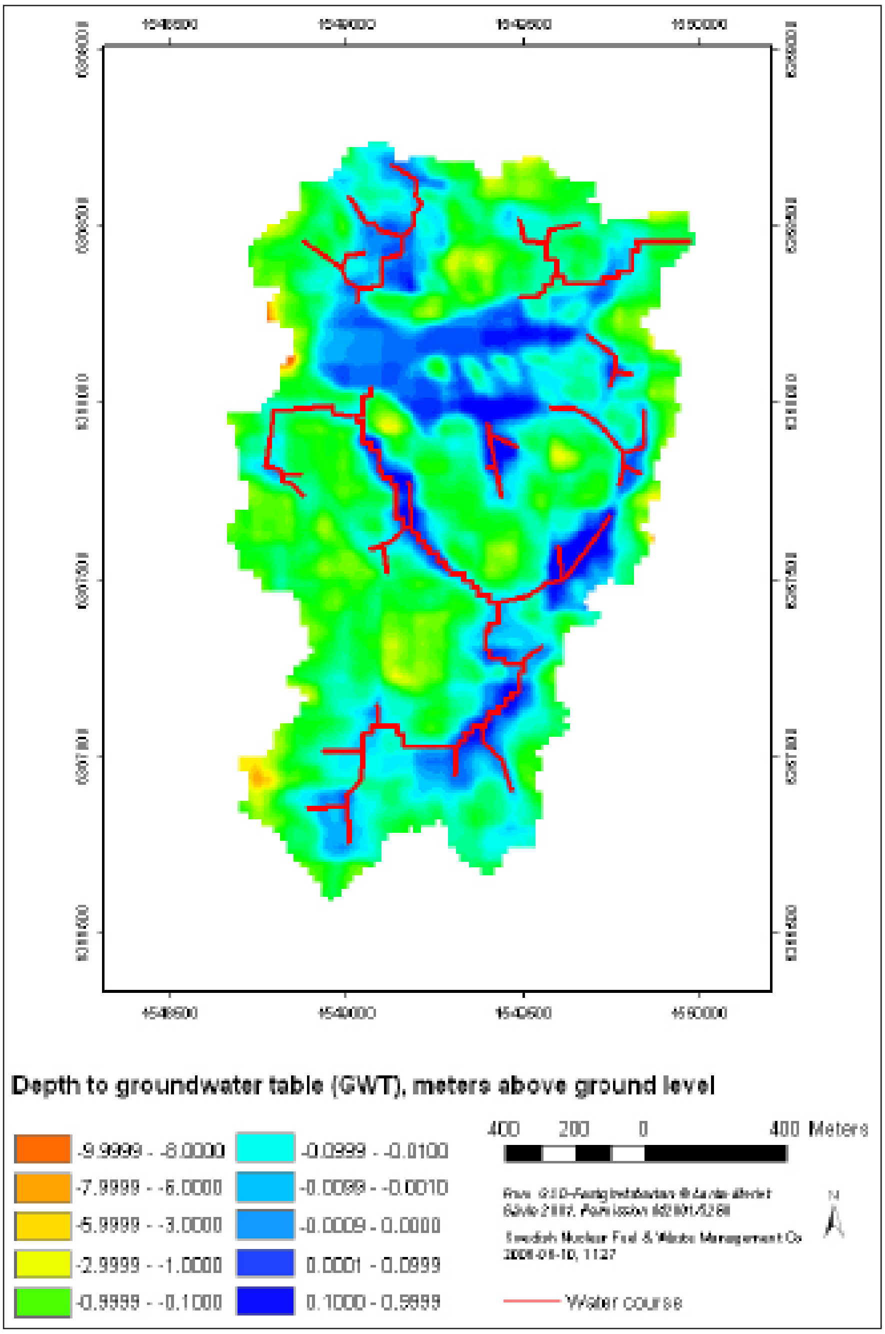

Figure A1-9. *Model-calculated depth to the groundwater table (GWT) in the catchment No. 7. The solid red line represents the stream network computed by ECOFLOW for Kåreviksån.*

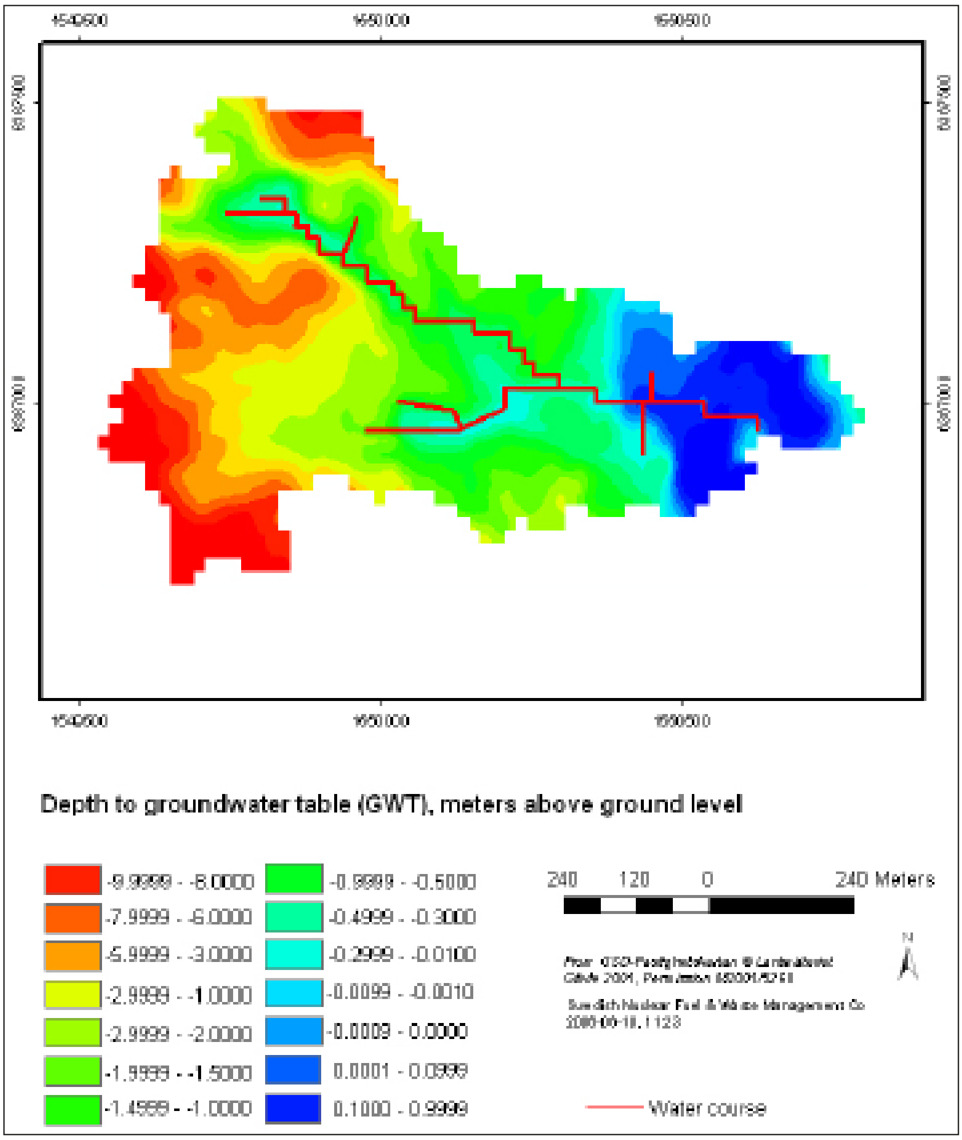

Figure A1-10. *Model-calculated depth to the groundwater table (GWT) in the catchment No. 8. The solid red line represents the stream network computed by ECOFLOW for Pistlanbäcken.*

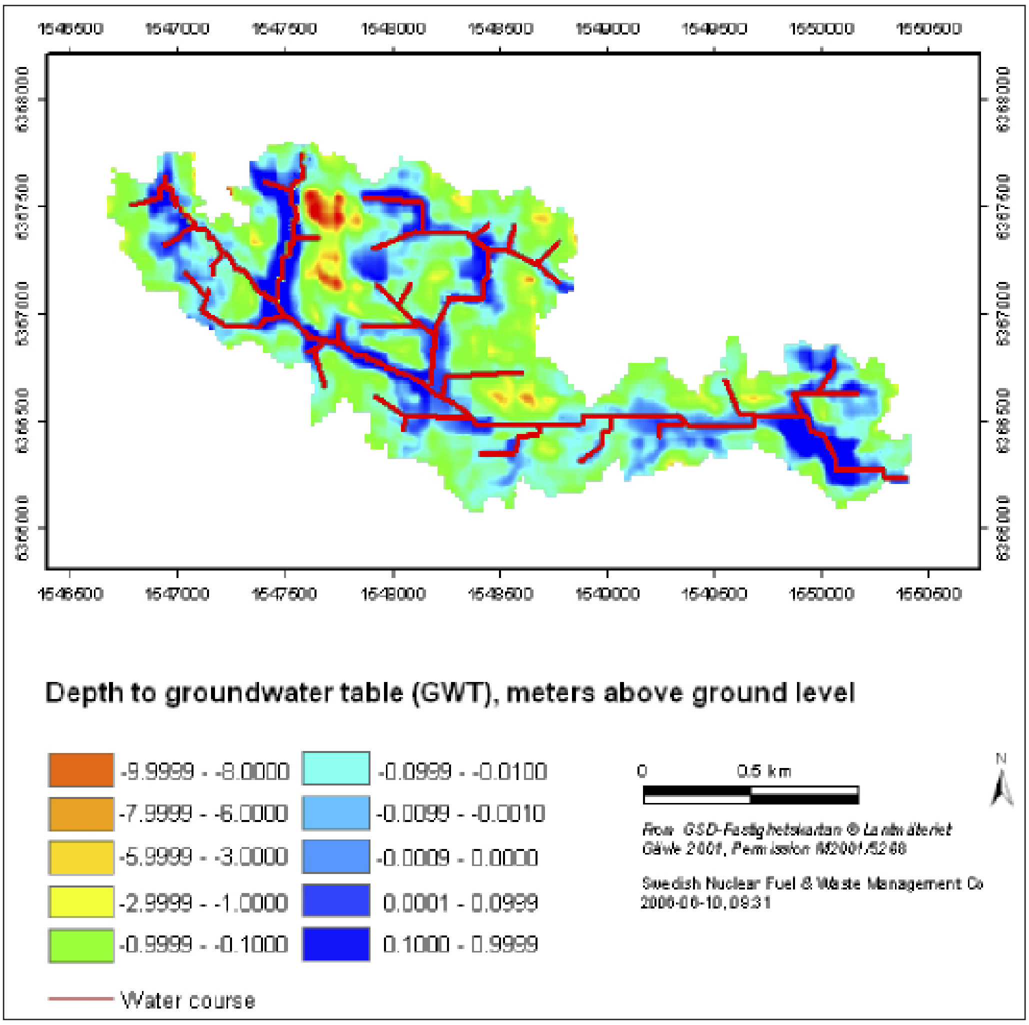

Figure A1-11. *Model-calculated depth to the groundwater table (GWT) in the catchment No. 9. The solid red line represents the stream network computed by ECOFLOW for Ekerumsån.*

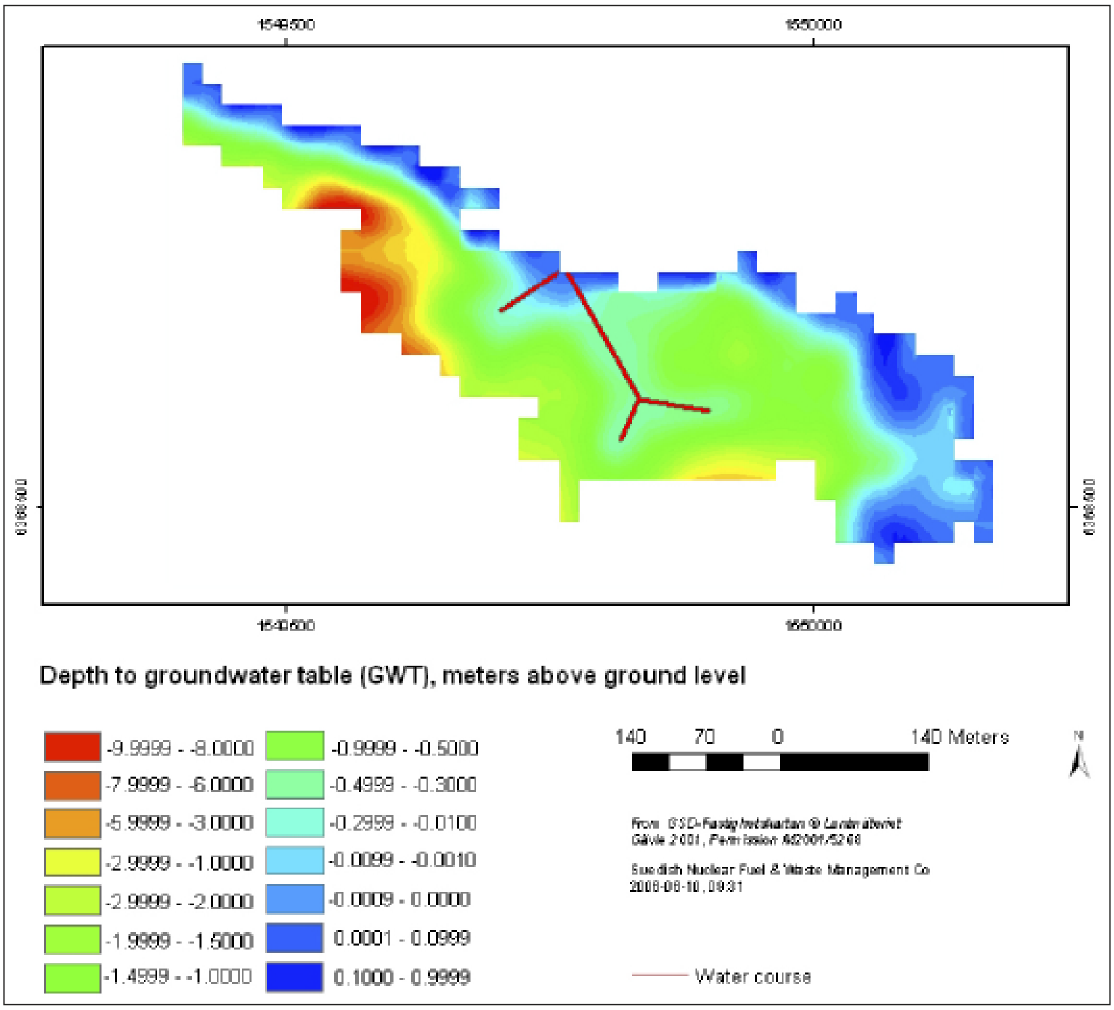

Figure A1-12. *Model-calculated depth to the groundwater table (GWT) in direct runoff area I. The solid red line represents the stream network, as computed by ECOFLOW.*

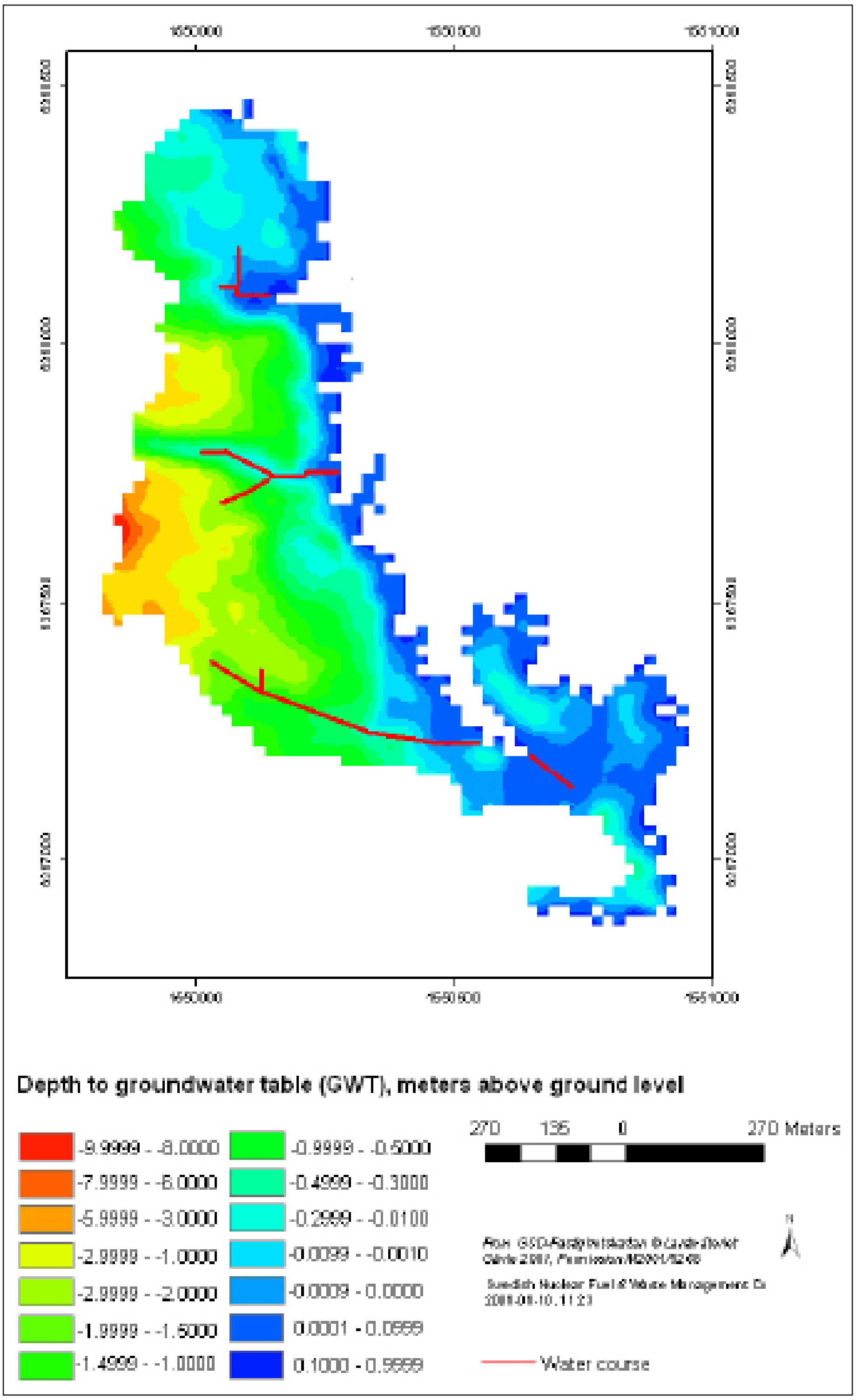

Figure A1-13. Model-calculated depth to the groundwater table (GWT) in direct runoff area II. The solid red line represents the stream network, as computed by ECOFLOW.

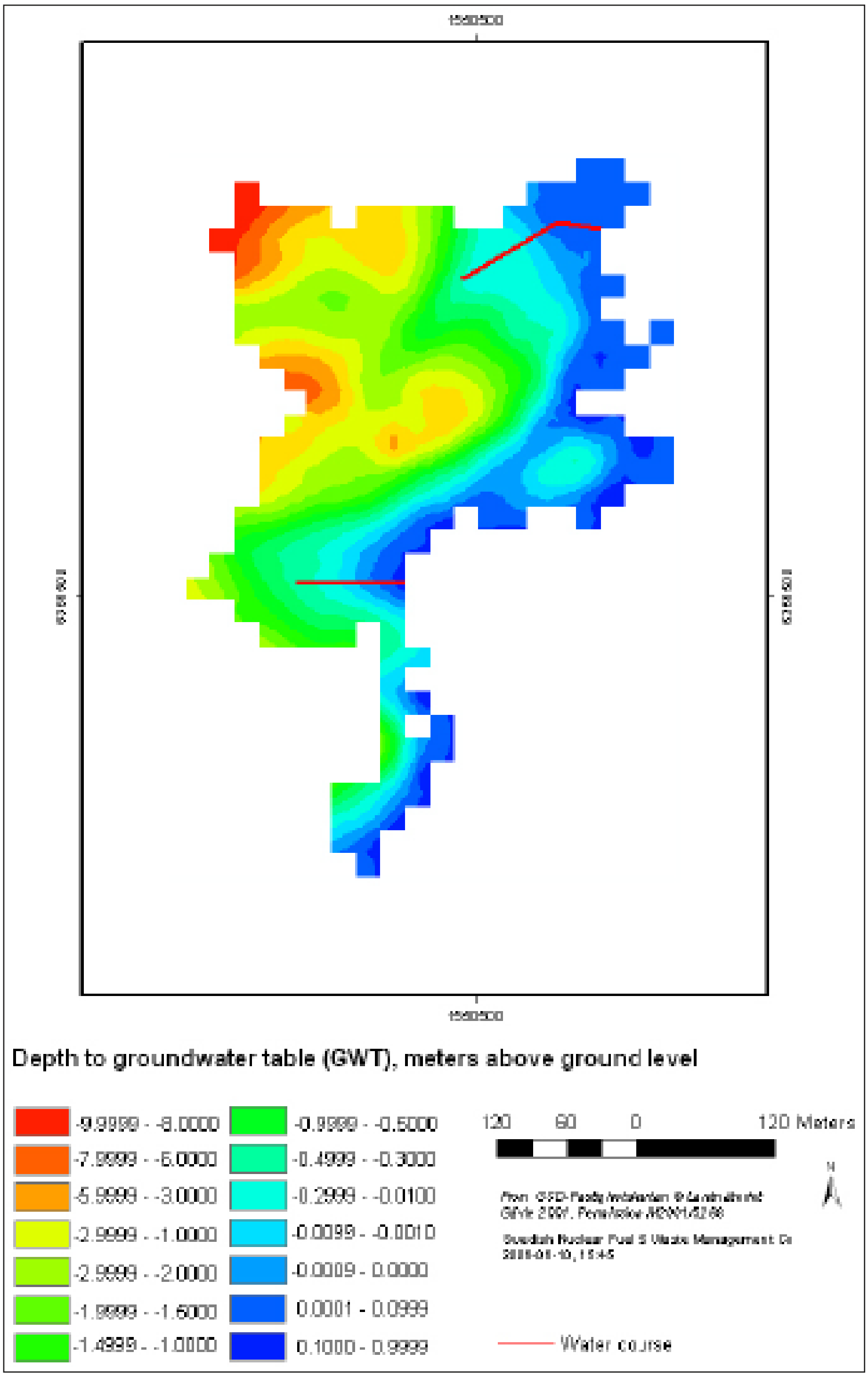

Figure A1-14. Model-calculated depth to the groundwater table (GWT) in direct runoff area III. The solid red line represents the stream network, as computed by ECOFLOW.

Appendix 2

List of input files

Table A2. List of input files.

Initial files	Files used in the modelling	Description
Hms_tr_prec_corr_alx.asc	Pre04.asc	Corrected precipitation records for year 2004
Hms_tr_temperature.asc	Temp04.asc	Air temperature for year 2004
Hms_tr_air_humidity.asc	Def04.asc	Vapour-pressure deficit for year 2004
Hydrografi.shp Vattendrag_indelade_10m.shp Vattendrag_surf_05.shp	Riv_6.asc Riv_7.asc Riv_8.asc Riv_9.asc Riv_s1.asc Riv_s2.asc Riv_s3.asc	Stream network for each catchment
Höjdmodell__.asc	Height_6.asc Height_7.asc Height_8.asc Height_9.asc Height_s1_.asc Height_s2_.asc Height_s3_.asc	Digital elevation data for each catchment
Markanvänning_Fastighetskartan_lager_MY_.shp	Markanvand_6.asc Markanvand_7.asc Markanvand_8.asc Markanvand_9.asc Markanvand_s1.asc Markanvand_s2.asc Markanvand_s3.asc	Digital map of land use for each catchment
Jordarter.shp	Jordarter_6.asc Jordarter_7.asc Jordarter_8.asc Jordarter_9.asc Jordarter_s1.asc Jordarter_s2.asc Jordarter_s3.asc	Digital map of Quaternary deposits for each catchment
z1_modeller.asc z2_modeller.asc z3_modeller.asc m1_modeller.asc m2_modeller.asc	z1, z2, z3_6.asc z1, z2, z3_7.asc z1, z2, z3_8.asc z1, z2, z3_9.asc z1, z2, z3_s1.asc z1, z2, z3_s2.asc z1, z2, z3_s3.asc m1,m2_6.asc m1,m2_7.asc m1,m2_8.asc m1,m2_9.asc m1,m2_s1.asc m1,m2_s2.asc m1,m2_s3.asc	Thickness of every stratigraphic layer for each catchment
Effpor_L4,5,6,7.grd/dat	Por6,7,8,9,s1,s2,s3_4.asc Por6,7,8,9,s1,s2,s3_5.asc Por6,7,8,9,s1,s2,s3_6.asc Por6,7,8,9,s1,s2,s3_7.asc	Effective porosity for each layer

Initial files	Files used in the modelling	Description
Kxy_L4,5,6,7.grd/dat	Khor6,7,8,9,s1,s2,s3_4.asc Khor6,7,8,9,s1,s2,s3_4.asc Khor6,7,8,9,s1,s2,s3_4.asc Khor6,7,8,9,s1,s2,s3_4.asc	Horizontal hydraulic conductivity for each layer
Kz_L4,5,6,7.grd/dat	Kvert6,7,8,9,s1,s2,s3_4.asc Kvert6,7,8,9,s1,s2,s3_4.asc Kvert6,7,8,9,s1,s2,s3_4.asc Kvert6,7,8,9,s1,s2,s3_4.asc	Vertical hydraulic conductivity for each layer
Ss_L4,5,6,7.grd/dat	Stor6,7,8,9,s1,s2,s3_4.asc Stor6,7,8,9,s1,s2,s3_4.asc Stor6,7,8,9,s1,s2,s3_4.asc Stor6,7,8,9,s1,s2,s3_4.asc	Specific storage coefficients for each layer
Z_L7.grd/dat	Stheads_6.asc Stheads_7.asc Stheads_8.asc Stheads_9.asc Stheads_s1.asc Stheads_s2.asc Stheads_s3.asc	Hydraulic head data-starting heads

Appendix 3

List of output files

Table A3. List of output files.

Output files	Description
Hyd_6.rez Hyd_7.rez Hyd_8.rez Hyd_9.rez Hyd_s1.rez Hyd_s2.rez Hyd_s3.rez	Computed stream runoff
Inpcart_6.asc Inpcart_7.asc Inpcart_8.asc Inpcart_9.asc Inpcart_s1.asc Inpcart_s2.asc Inpcart_s3.asc	Soil moisture
Catchment_6.out Catchment_7.out Catchment_8.out Catchment_9.out Catchment_s1.out Catchment_s2.out Catchment_s3.out	Computed groundwater level
Sbalan_6.rez Sbalan_7.rez Sbalan_8.rez Sbalan_9.rez Sbalan_s1.rez Sbalan_s2.rez Sbalan_s3.rez	Accumulated runoff and water balance