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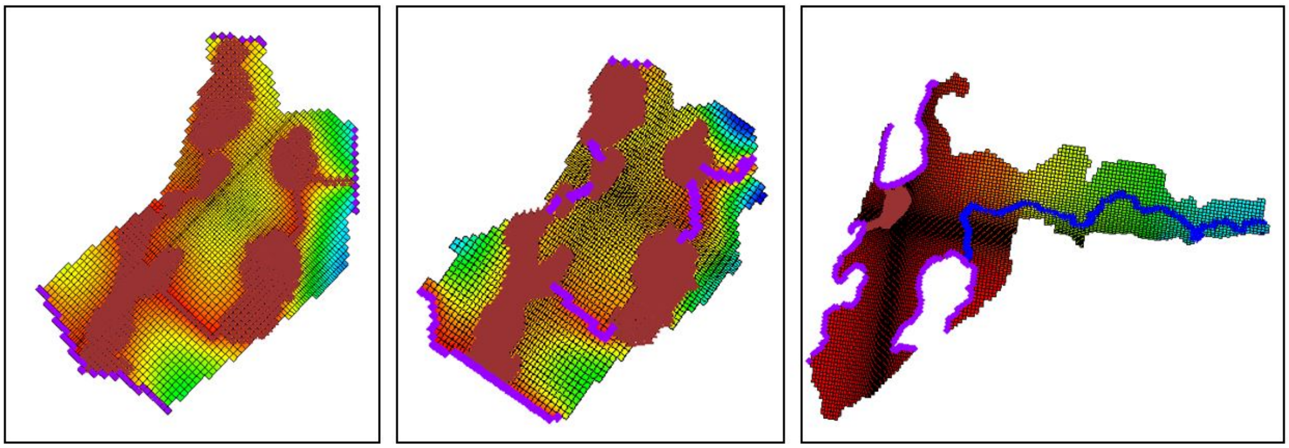

Uncertainties in groundwater modelling

A case study investigating uncertainties from parameters and assumptions in a groundwater modelling process with multiple stochastic numerical models

Master's thesis in Infrastructure and Environmental Engineering

AGNES DANIELSSON

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
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Cover:
Figure of the three numerical models included in this study. Retrieved from the modelling software GMS.

Chalmers Reproservice
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Abstract

Groundwater models are often used as decision support in policy processes. The output of a groundwater model can never be claimed to be totally accurate and it always comes with some degree of uncertainty. This uncertainty needs to be described to allow policy makers to make well informed decisions. The aim of this thesis has been to investigate uncertainties due to assumptions made in the groundwater modelling process and relate these to parameter uncertainties that can be captured with stochastic modelling. Three stochastic numerical groundwater models have been set up based on three different conceptualizations of a case site, the Varnum aquifer in Västergötland, Sweden. The conceptual models were developed by professionals in hydrogeology. Each conceptual model developer also made assumptions about input data and parameter ranges used in the numerical models. The numerical models were run stochastically with inverse calibration (PEST with Null-space Monte Carlo) and resulting calibrated files were used in a water abstraction scenario. The three conceptual model developers chose different approaches of setting boundaries, different material layering and had different assumptions for parameters. In a qualitative self-review they all agree on that uncertainties in the conceptual model and parameterization contributes to model output uncertainties but disagreed on which assumptions that were of most importance. The output from the three numerical models in terms of drawdown and flow from a boundary representing a lake during withdrawal, differed substantially. There was both a big difference between the mean values for each model and big difference between the distributions within each model. The difference between the models was much larger than the spread within the models. This result shows that for this case study, uncertainties from different assumptions play a significant role and that stochastic modelling solely, is not sufficient to capture essential uncertainties.

Keywords: groundwater modelling, uncertainties, conceptual model uncertainties, structural model uncertainties, parameter uncertainties, Monte Carlo analysis, stochastic modelling, PEST

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PREFACE

This thesis was conducted at Chalmers University of Technology in the autumn of 2018 and winter 2019. It covers a subject of importance to all fields of environmental modelling. Models are powerful tools for prognostication of future conditions but just as weather forecasts, they can never come with guaranties. However, with knowledge of how certain the prognosis is, we are better equipped to decide if the raincoat should be packed or not. The thesis has given me insight into the wide spectra of uncertainties and challenges in groundwater modelling. It would not have been possible without my excellent supervisors Jonas Sundell and Johanna Merisalu. Thank you for all guidance and support in times of doubt. Thanks very much to Lars Rosén and Markus Geise for all effort and time spent on this thesis and sharing your experience and knowledge. Also, thanks to Ezra Haaf, Per Sander and SGU employees for providing material as well as to Rolad Bartel for letting me join your field trip. Thanks to Nadja Holtryd and Niklas Ramhöj for being my scripting heroes. Lastly, thanks to Tim and Dan for invaluable lunch pauses and climbing sessions and to Emma-Clara for being at my side in all weathers.

Agnes Danielsson
Gothenburg, Sweden, March 2019

Abbrevations

DEM	Digital elevation map
ET	Evapotranspiration
GMS	Groundwater modelling system
MODFLOW	Modular finite-difference groundwater flow model
NUSAP	Numeral Unit Spread Assessment Pedigree
NWT	Newton formulation
PEST-NSMC	Automated parameter estimation - Null space Monte Carlo
SGU	Sveriges geologiska undersökning (Geological survey of Sweden)
SMHI	Swedish meteorological and hydrological institute
SVD	Singular value decomposition
SVD-A	Singular value decomposition assist

1 Introduction

Groundwater models are commonly used as decision support in policy processes to evaluate effects of external stresses to a groundwater system. Such stresses can for example be groundwater leakage to underground constructions risking damage to buildings in land subsidence sensitive areas where decisions must be taken on appropriate measures to reduce the risks (Sundell, Haaf, Tornborg, and Rosén, 2019). Management of groundwater resources is another concern where decision makers face the task to decide how the resources are used to its optimum while minimizing risks such as declining levels (Roozbahani, Ebrahimi, and Banihabib, 2018), salt water intrusion (Halder, 2019) or contamination (Jafari and Nikoo, 2019). Since groundwater models are just representations of reality, their outcome can never be completely accurate and will always come with some degree of uncertainty (Anderson, Woessner, and Hunt, 2015). To be able to take well-informed decisions where risks are recognized, there is a need to quantify or describe these uncertainties (Refsgaard, van der Sluijs, Højberg, and Vanrolleghem, 2005).

Methods to manage uncertainties from parameters in groundwater models are relatively well-established (Van Der Sluijs et al., 2005; Refsgaard, van der Sluijs, Brown, and van der Keur, 2006). Stochastic modelling is an available tool, where parameters and outcomes are represented by distributions rather than one deterministic value (Anderson et al., 2015). However, uncertainties related to how a natural system is interpreted and is represented in the structure of the model are more complex and are increasingly recognized in research (Van Der Sluijs et al., 2005; Refsgaard et al., 2006; Enemark, Peeters, Mallants, and Batelaan, 2018). These types of uncertainties are often referred to as conceptual or model structure uncertainties and constitute a significant source to uncertainty (Rojas et al., 2010; Højberg and Refsgaard, 2005; Gupta, Clark, Vrugt, Abramowitz, and Ye, 2012). To include these uncertainties, multi-model approaches (Beven, 2006; Refsgaard et al., 2006; Højberg and Refsgaard, 2005; Enemark et al., 2018) or qualitative assessment (Van Der Sluijs et al., 2005), are possible methods.

In the interpretation of the system as input to a groundwater model, assumptions must be done. These assumptions can be based on different amount and quality of field data and incorporates often experience based judgment (Enemark et al., 2018). As a consequence, models that are based on the same field data but are developed by different persons or model teams, can have different assumptions on structures and input data. For a model to be representative, its parameters are calibrated against observed data (Anderson et al., 2015). Since many parameters can be adjusted to calibrate a model, it is possible to reach a well calibrated model with different models structures and parameter sets. This phenomenon is described by Beven (2006) as the equifinality and rises from that environmental models are matematecally ill-posed, meaning that there is not enough information to allow for one unique mathematical solution. Since groundwater models commonly are used in purposes of forecasting, different structures and parameter sets in the calibrated base model can lead to different prognosis, resulting in model output uncertainties (Refsgaard et al., 2012).

In this thesis a multi-model method is used in combination with a qualitative self-review and stochastic modelling, to study uncertainties from assumptions and parameters in groundwater models for a case site, Varnum aquifer, Västergötland, Sweden.

1.1 Aim

The objective of this study is to assess uncertainties originating from assumptions that are made in a groundwater modelling process and relate these to parameter uncertainties that can be modelled stochastically. This is done by means of a case study in Varnum aquifer, Västergötland, Sweden. The study includes different professional hydrogeologists' assumptions for development of conceptual models and input data to numerical models. Based on these assumptions, three numerical models are set up and run stochastically. Model output uncertainties are analyzed in terms of difference between models and spread within models. The involved professional's views on uncertainties in the case study are also investigated by a qualitative self-review and discussed in relation to the modelling result.

The following research questions are aimed to be answered:

- What assumptions are made by different professionals for development of conceptual models and input data to numerical models?
- Are uncertainties from assumptions relevant to include in a groundwater modelling process and how large are they compared uncertainties from parameters included in stochastic modelling?
- What are the professional's view on uncertainties and how does it compile with the differences between the different models?

1.2 Thesis structure

This thesis is divided in five major part except from this introduction. The first part is a theory chapter (chapter 2) where the theory behind used methods is described. It also includes a short description of groundwater processes that are of importance to this study. The second part is the method (chapter 3) where the general method for the thesis is described. Details about how each of the different models are set up is presented in chapter 4. Here is also the case site, Varnum aquifer, described. In the result chapter (chapter 5), the numerical model outcomes and the groundwater professionals qualitative view on uncertainties are presented. In chapter 6 the model results are discussed and related to results from other studies.

2 Theory

2.1 Basic groundwater principles

2.1.1 Groundwater recharge

Groundwater recharge is the refilling of water to aquifers. Recharge is strongly related to the hydrologic cycle which can be represented by a water balance equation for a catchment.

$$P = ET + R + \Delta S \tag{2.1}$$

where P is the precipitation, ET the evapotranspiration consisting of direct evaporation and transpiration by plants, R the runoff and ΔS the change of storage in reservoirs (snow, surface water, groundwater, soil water and water bounded in plants).

Water from precipitation which do not evapotranspirates, so called net precipitation, will thus end up as run off in streams, lakes and oceans. The path the water takes to come there varies and is dependent on geology, topography, land use and vegetation. Precipitation infiltrates the ground and creates soil water. If the soil water zones is saturated more precipitation cannot infiltrate and runs of as surface runoff. Surface runoff can also take place if the infiltration capacity of the ground is bigger than intensity of precipitation. If the so called field capacity of the soil water zone is exceeded, the water can percolate further to the groundwater table and create recharge. These processes are shown in figure 2.1. The capacity of the soil water zone can hold is dependent of several factors such as soil material proprieties, vegetation and groundwater level. In Sweden the infiltration capacity of the soil is generally high so precipitation and evapotranspiration dominates the recharge but geology and land use are also important factors (Eveborn, Vikberg, Thunholm, Hjerne, and Gustafsson, 2017).

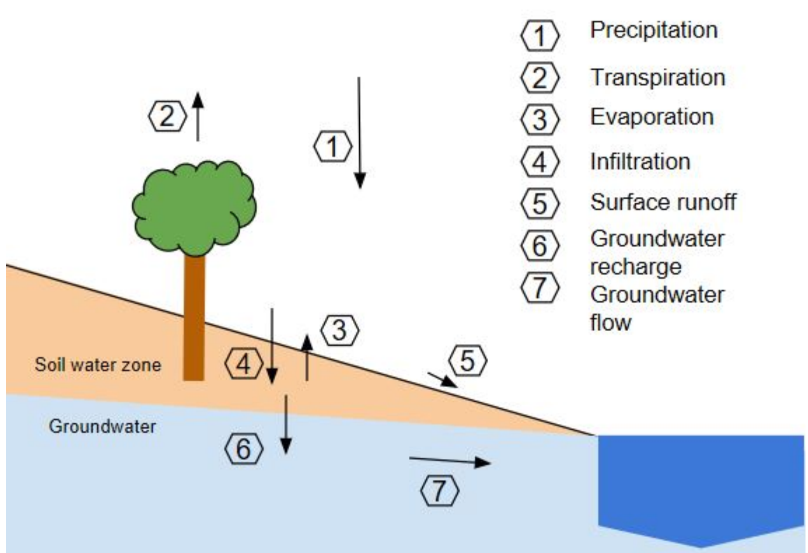


Figure 2.1: Water balance and groundwater recharge

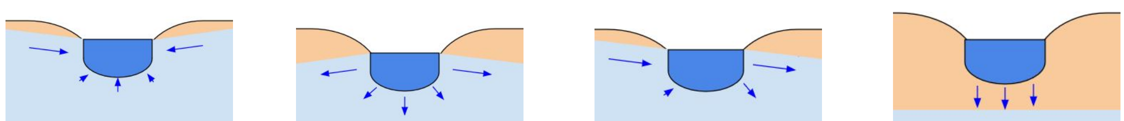
2.1.2 Groundwater flow

The most central law describing groundwater flow is Darcy's law (equation 2.2), It describes that discharge, Q, is proportional to the hydraulic gradient and the cross-sectional area, A, with a proportional constant named hydraulic conductivity, K, which is dependent on the fluid and the material which is flow through. This law is valid under low flow velocities which mostly is the case for natural groundwater (Fetter, 2014).

$$Q = -KA\frac{dh}{dl} \tag{2.2}$$

2.1.3 Groundwater - surface water interaction

Interaction between lakes or streams and groundwater is important in the context of water balance in an aquifer. Lakes and streams can either gain water from the groundwater, loose water to an aquifer or both, see figure 2.2. Which of the situations that occur is dependent on the altitude of the groundwater table adjacent to the stream and can therefore vary both spatially and temporarily. Especially, withdrawal of groundwater through pumping can significantly change this situation. A loosing stream could be connected or disconnected. For a disconnected stream the water percolates from the stream through the unsaturated zone to the groundwater table (Winter, Harvey, Franke, and Alley, 1998).



(a) Gaining stream (b) Loosing connected stream (c) Loosing and gaining stream (d) Loosing disconnected stream

Figure 2.2: Different types of groundwater - surface water interaction

2.2 Groundwater modelling

Models are instruments that represent systems of the real world (Wang and Anderson, 1995). In the management of groundwater resources, models can be used to understand the groundwater system, its prospects and limitations, usually in forecasting of potential future scenarios. Groundwater models can roughly be divided into physical (laboratory) and mathematical models. Mathematical models can further on be divided into data driven or process-based. Mathematical data driven models uses empirical or statistical relations to connect inputs and outputs. Mathematical process-based are based on physical processes and principles. Models and can be either deterministic or stochastic. Deterministic models uses single values parameters and outputs while stochastic includes parameters with probability distributions. To solve mathematical models, analytic or numerical methods exists. Analytic methods are limited to problems that can be extensively simplified (Anderson et al., 2015). In this study mathematical, process-based stochastic models are used, which are solved numerically. A groundwater model can simulate steady state or transient conditions, which differs in being time dependent or not.

2.2.1 The groundwater modelling process

Before any mathematical model can be set up, the purpose of the model needs to be identified and the system interpreted into a conceptual model. Based on purpose and conceptual model, the numerical model, including mathematical model and associated code to solve the equations numerically, can be chosen. The conceptual model needs to be translated into the numerical model which includes discretization and assigning all boundaries, parameters, stresses and initial conditions (if transient). The model is then calibrated against some decided calibration target. This is done by history matching where parameters are adjusted within sound ranges until the difference between field observations and computed values (usually head and/or flux) are within this target. Sometimes it also includes updating of the conceptual model. When a calibrated model has been reached, it can be used for forecasting of future scenarios where some analysis of uncertainty should be included (Anderson et al., 2015). This process is showed in figure 2.3.

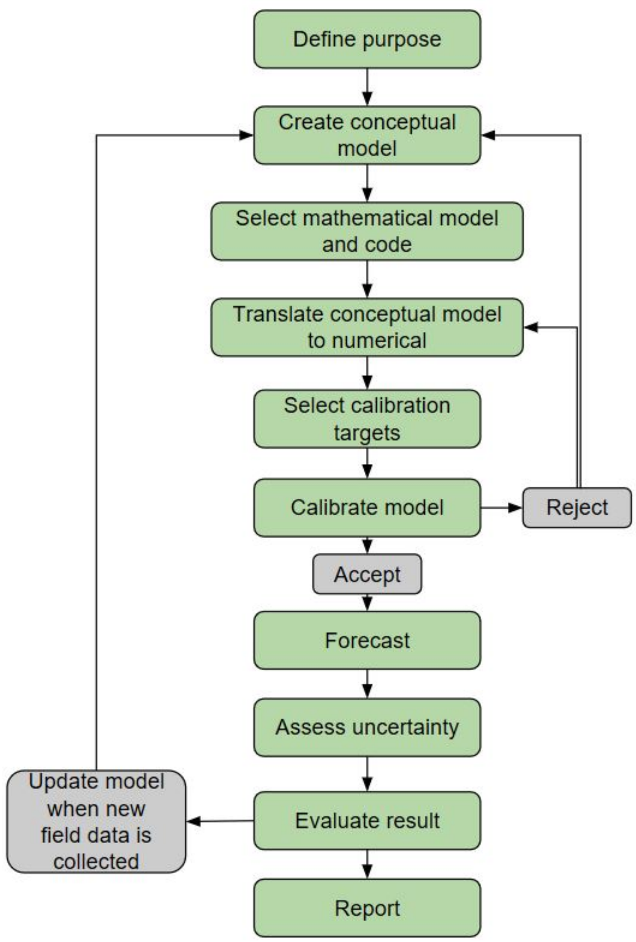


Figure 2.3: Flow chart of the groundwater modelling process. Inspired by Anderson, Woessner, and Hunt (2015).

2.2.2 Conceptual model

A site-specific conceptual model is a interpretation and description of the site and the processes relevant to the problem. Several definitions of conceptual model exist, which of two are

"a qualitative representation of a groundwater system that conforms to hydrogeological principles and is based on geological, geophysical, hydrological, hydrogeochemical and other ancillary information." (Anderson et al., 2015)

" A conceptual groundwater flow model is a simplification of a real-world groundwater problem such that (1) it captures the essential features of the real world problem and (2) it can be described mathematically" (Haitjema, 1995).

The latter definition is especially true for these conceptual models that are used in numerical groundwater modelling. As an example, physical boundaries needs to be defined both in respect of location but also in terms of mathematical representation.

2.2.3 Numerical model

The basis of most process-based groundwater models is to solve one governing equation, the differential groundwater flow equation, for given boundary conditions and initial conditions (if transient). The groundwater flow equation (equation 2.3) is derived from Darcy's law and the conservation of mass principle. It assumes that water groundwater have a constant density, that flow is saturated and that Darcy's law applies.

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) + W = S_s\frac{\partial h}{\partial t} \tag{2.3}$$

where
K_x, K_y, K_z hydraulic conductivity
h potentiometric head
W volumetric flux per unit volume representing sources and sinks
S_s specific storage
t time

For steady state conditions $S_s\frac{\partial h}{\partial t} = 0$.

In numerical models, equation 2.3 is solved for head but many codes also computes flow. Most commonly, finite difference and finite element methods are used where heads are calculated at discrete nodes within the modelling domain (Anderson et al., 2015).

2.2.4 Boundary conditions

Three types of boundary conditions exist (Anderson et al., 2015).

1) At specified head boundary, also called Dirchlet condition, heads in boundary cells are held constant.

$$h = constant$$

2) At a specified flow boundary, also called Neumann condition, the gradient is specified. For this condition at a $\Delta x \Delta z$ face of a cell

$$\frac{\partial h}{\partial y} = constant$$

When the constant is zero, this boundary is called a no-flow boundary.

3) The third boundary condition is called head-dependent boundary or Cauchy condition. Flux across this type of boundary is calculated with Darcy's law (equation 2.2). At a $\Delta x \Delta z$ face of a cell

$$q_y = -K_y \frac{h_b - h_{i,j,k}}{L} \tag{2.4}$$

where $h_{i,j,k}$ is the computed head of a cell at the boundary, h_b the boundary head, L the distance between the heads and K the hydraulic conductivity.

2.2.5 MODFLOW

The modular finite-difference groundwater flow model (MODFLOW) is a code developed by the U.S Geological Survey (USGS) to simulate groundwater flow (Harbaugh, 2005). It can be run in a variety of different user interfaces, commercial and non-commercial. One of them is Ground Water Modelling Systems (GMS) (Aquaveo, 2019b). MODFLOW solves the groundwater flow equation (equation 2.3) with the finite difference method. In this method nodes are distributed within a rectangular grid, where each grid cell and corresponding node has location i,j,k (for 3D grids) representing rows, columns and layers.

The finite difference form of equation 2.3 can be be derived from the continuity equation (Harbaugh, 2005)

$$\sum Q_i = S_S \frac{\Delta h}{\Delta t} \Delta V \tag{2.5}$$

where

Q_i is the flow rate to the cell
S_S the specific storage of the cell
ΔV the volume of the cell
Δh the change in head over time interval Δt

Flow into a cell from an adjacent cell can be written

$$q_{i,j-1/2,k} = KR_{i,j-1/2,k} \Delta c_i \Delta v_k \frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}} \tag{2.6}$$

where

h is heads at node i,j,k and i,j-1,k

q the volumetric flow rate through the face between two cells i,j,k and i,j-1,k
$KR_{i,j-1/2,k}$ is the conductivity in row direction between nodes i,j,k and i,j-1,k
$\Delta c_i, \Delta v_k$ area of cell faces normal to flow direction
$\Delta r_{j-1/2}$ is the distance between node i,j,k and i,j-1,k

Time derivative is discretezed in MODFLOW with backward difference as

$$\frac{\partial h}{\partial t} = \frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t^m - t^{m-1}} \tag{2.7}$$

where m and $m+1$ are superscripts for the current and next time levels.

Conductance is a combination of grid dimensions and hydraulic conductivity such that

$$CR_{i,j-1/2,k} = \frac{KR_{i,j-1/2,k}\Delta c_i \Delta v_k}{\Delta r_{j-1/2}} \tag{2.8}$$

With equation 2.5,2.6, 2.7 and 2.8, the finite-difference form of equation 2.3 for one cell i,j,k can then be formulated (for more details see Harbaugh, 2005)

$$\begin{aligned} CR_{i,j-1/2,k}(h^m_{i,j-1,k} - h^m_{i,j,k}) + CR_{i,j+1/2,k}(h^m_{i,j+1,k} - h^m_{i,j,k}) + CC_{i-1/2,j,k}(h^m_{i-1,j,k} - h^m_{i,j,k}) + \\ + CC_{i+1/2,j,k}(h^m_{i+1,j,k} - h^m_{i,j,k}) + CV_{i,j,k-1/2}(h^m_{i,j,k-1} - h^m_{i,j,k}) + CV_{i,j,k+1/2}(h^m_{i,j,k+1} - h^m_{i,j,k}) + \\ + P_{i,j,k}h^m_{i,j,k} + Q_{i,j,k} = S_{S\,i,j,k}(\Delta r_j, \Delta c_i, \Delta v_k)\frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t^m - t^{m-1}} \end{aligned} \tag{2.9}$$

where
h is heads at respective node
$\Delta r_j, \Delta c_i, \Delta v_k$ are lengths of the sides of cell
$CR_{i,j-1/2,k}$ is the conductance in row direction between nodes i,j,k and i,j-1,k
$CC_{i-1/2,j,k}$ is the conductance in column direction between nodes i,j,k and i-1,j,k
$CV_{i,j,k-1/2}$ is the conductance in vertical direction between nodes i,j,k and i,j,k-1
$Q_{i,j,k}$ flow to or from external sinks and sources not dependent on head at the node i,j,k
$P_{i,j,k}h_{i,j,k}$ flow to or from external sinks and sources dependent on head at the node i,j,k
$S_{S\,i,j,k}$ specific storage of the cell.

This equation is assigned to each node in the finite difference grid which is not assigned a boundary condition. The equations are written into one global matrix equation which is solved with iterative methods (Harbaugh, 2005). When specific criteria are met (maximum error between iterations for head and flux) during the iteration process, the model has converged.

MODFLOW has been released in different versions which have some different capabilities. The Newton (NWT) formulation of MODFLOW is developed to handle drying and rewetting of cells in an unconfined layer (a layer that is not fully saturated). MODFLOW-NWT contains a flow package that smoothely changes conductance, which is dependent on the saturated thickness, in these cells in contrast to other flow packages. Also, when a cell becomes dry it do not turn into an inactive cell as in other packages but flow is controlled by putting the conductance to zero instead. These features enables easier convergence for models where cell drying and rewetting takes place (Niswonger, 2011).

MODFLOW contains packages which facilitates the mathematical representation of features in the conceptual model. Examples are packages that represent the different type of boundary conditions described in chapter 2.2.4. The River and Drain packages are types of head-dependent boundaries that incorporates bottom elevations. The river package can simulate percolating conditions and the drain package is restricted to only one way flow - out of the aquifer. In packages using head-dependent boundaries a conductance term needs to be specified, which includes the geometrical and conductance term in equation 2.4 so that $C = \frac{KA}{L}$. In GMS this can be specified as $\frac{Kw}{t}$ for features represented by arcs and $\frac{K}{t}$ for features represented by polygons where w is the with of the feature and t is the thickness. GMS then calculates the conductance based on the geometry of the feature (Aquaveo, 2019a). For more information on MODFLOW packages, Harbaugh (2005) is referred to. Zonebuget is an add-on program to MODFLOW which have the capability to calculate sub-regional flow budgets for user-defined zones from the computed flows in the main model (Harbaugh and Peck, 1990).

2.2.6 PEST

Groundwater modelling calibration is an inverse problem since the result, heads and/or fluxes, are known while the parameters resulting in those heads or fluxes are unknown. The basic way of calibrating a model is by manually adjusting parameters in a model so that computed values match observed data by some user defined error. This process can be aided by letting a computer code search for parameters that minimize the error between observed and computed heads or fluxes. One such code is called Automated Parameter Estimation (PEST) (Doherty, 2018). PEST can be used in combination with different codes for groundwater and surface water models. Here, the general concept of PEST for parameter estimation in groundwater modelling is described. PEST can also be used for uncertainty analysis which is described in chapter 2.3.2.

To perform parameter estimation, PEST minimizes the objective function. The objective function is

$$\Phi = \sum_{i=1}^{n} [w_i r_i]^2 \tag{2.10}$$

where r_i is the residual between the ith observation and corresponding simulation and w_i is the weight for this observation. For calibration towards head observation this is written

$$\Phi = \sum_{i=1}^{n} [w_{hi}(h_m - h_s)_i]^2 \tag{2.11}$$

where h_m and h_s are observed and simulated heads and w_{hi} is the weight for the ith measured head and is defined as

$$w_{hi} = \frac{1}{std_i^2 * W_h} \tag{2.12}$$

where std_i is the standard deviation of observation i and W_h the group weigh which is assigned to the type of observation, in this case head.

The objective function depends on the parameters of the model and minimizing the objective function is equivalent to finding the minimum of the multidimensional objective function surface which have has many dimensions as model parameters. This is done with a derivative-based nonlinear technique, which concept is to evaluate the slope of the surface and based on this, adjust the parameters so that the global minimum of the objective function is found. The derivatives of the observations with respect to all calibration parameters are stored in the so called Jacobian matrix. They are calculated with finite difference approximation by incremental variation of parameters and the resulting difference in the output when a forward run is performed with the new parameters.

Since the function is complex, a optimum set of updated parameters in not easily found. Therefore, the objective function is calculated for some sets of updated parameters, and the set that gives the lowest value of the objective function is used to calculate the Jacobian matrix. This procedure is repeated until any of four user specified closure criteria is met. The criteria is either that the objective function cannot be further minimized, the changes to parameters is very small, the maximum number of optimization iterations is reached or the objective function cannot be further lowered (Anderson et al., 2015; Doherty, 2018). To perform a PEST calibration, ranges for parameters to be calibrated are given, in which PEST tries to find the optimal parameter values.

2.2.7 Highly parameterized inversion and regularization methods

Groundwater systems are heterogeneous and complex and have properties with spatial and time dependent variability. To model a system, these properties are represented by parameters which cannot take into account all the complexity of the real world system due to the nature of measure restrictions and computational limitations. The simplification that the parameters are undertaken could result in errors if the simplification is bigger than the detail required for the problem (Doherty, Hunt, and Tonkin, 2010). Traditionally, spatial simplification is made by zonation of parameters. The errors inherited from this subjective process cannot be quantified resulting in uncharacterized uncertainties (Anderson et al., 2015).

To avoid such oversimplification, approaches for highly parameterized models have been developed. This means that a large number of parameters are introduced to avoid the need of division into zones. Since highly parameterized models have much more unknowns (parameters) than knowns (observations), regularization techniques are used to solve the inverse problem. Regularization includes any technique that makes those ill-posed problems, possible to solve (Anderson et al., 2015). One of these is the use of pilot points. Instead of assigning values of parameters to all locations in the modelling domain, parameter values are assigned to discrete points. Values at locations between these points are then interpolated from the values at the points.

Another regularization technique is the use of soft knowledge (expert knowledge). This can for example be that properties at locations close to each other should be similar or the parameter at a specific location should be close to a specified value. In PEST this is incorporated by Tikhonov regularization. Another objective function, a regularization objective function, is then added which PEST aims to minimize additionally minimizing the measurement objective function (equation 2.10). The regularization objective function can be written

$$\Phi = \sum_{j=1}^{q} [f_j(p)] \tag{2.13}$$

where f_j is a function of the parameters p which puts a penalty on deviation of estimated parameters from soft knowledge, also called preferred condition for parameters. Preferred conditions could either be preferred homogeneity condition or preferred value condition (Anderson et al., 2015).

A third regularization method that can be used in PEST, in combination with Tikhonov regularization, is singular value decomposition (SVD). In short terms, SVD decomposes the parameters into sets of independent linear combinations. These sets are ranked from how constrained they are by the calibration targets. Sets that cannot be determined from the calibration targets are assigned to the so-called null space and retains the same as their initial value. To speed up the process, SVD-A can be used. Then the sets of linear independent combinations of parameters are represented by superparameters. The Jacobian matrix is then calculated for this smaller amount of superparameters instead of all original parameters (Anderson et al., 2015).

2.3 Uncertainty in groundwater modelling

Forecasts made from groundwater models could never be guarantied to be accurate, even though a perfectly well calibrated base model is used. This is inherited from several reasons which will be discussed further on. Due to the lack of precise accuracy of result from models, uncertainty related to the result needs be communicated to policy makers that will use the result as decision support (Anderson et al., 2015). With knowledge about uncertainties, decision makers are given insight to the possible risks and outcomes and have the chance to decide if more resources should be spent on improving the quality of information or risk measures should be implemented (Refsgaard et al., 2005).

2.3.1 Definition and types of uncertainty

Two definitions of uncertainty, given in the context of model uncertainty are

"any departure from the unachievable ideal of complete determinism" (Walker et al., 2003)

"A person is uncertain if s/he lacks confidence about the specific outcomes of an event or action. Reasons for this lack of confidence might include a judgment of the information as incomplete, blurred, inaccurate or potentially false or might reflect intrinsic limits to the deterministic predictability of complex systems or of stochastic processes." (Klauer and Brown, 2004)

A big variety of terminology to describe types and sources of uncertainty, can be found in the literature. Refsgaard et al. (2006) means that the key sources of uncertainties are input data, model parameter values and model structure (conceptual model). Van Der Sluijs et al. (2005) distinguish between quantifiable and unquantifiable uncertainties. Quantifiable uncertanties are simply those who can be quantified. Unquantifiable uncertainties relate to model structures, system boundaries, problem framing etc and cannot easily be described by quantitative methods.

In this study the terminology defined by Walker et al. (2003) and modified slightly by Refsgaard, van der Sluijs, Højberg, and Vanrolleghem (2007) will be used. These authors, identifies the sources to uncertainty as:

- **Context uncertainty** which refers to the framing of the problem and system boundaries.
- **Model technical uncertainty** comes from the computer code and can be due to software bugs and numerical approximations.
- **Model structural uncertainty** rising from the interpretation of the reality into the conceptual model and is a result of simplification and limited understanding of the system.
- **Input uncertainty** comes from data describing the system and external forces on the system.
- **Parameter uncertainty** comes from uncertainties in the parameter values

These sources of uncertainties accumulates into the final model outcome uncertainty.

To distinguish between different levels of uncertainty, Walker et al. (2003) uses the scale: determinism, statistical uncertainty, scenario uncertainty, recognized ignorance and total ignorance, where determinism is the ideal scenario and total ignorance the worst. Refsgaard et al. (2007) add qualitative uncertainty in between scenario uncertainty and recognized ignorance.

Walker et al. (2003) also defines two categories describing the nature of uncertainty; epistemic and variability uncertainty. Epistemic uncertainty is all uncertainty relating to knowledge imperfection which can be derived from limited data, measurement errors, subjective judgment etc. This uncertatinty can be reduced by means of more measurements. Variability uncertainty is the natural variation and randomness of a phenomena and cannot be reduced.

2.3.2 Methods for dealing with uncertainty

Several methods to handle uncertainty exist. Primarily, the methods used in this study are presented here. These methods are based on concepts described earlier in this theory chapter.

For parameter uncertainties, stochastic methods that can be based on either linear or non-linear behaviour of the model can be used (Anderson et al., 2015). Monte Carlo is a stochastic method without any need of assumptions of linear behavior. Parameters are defined as probability density functions from which parameter sets are randomly sampled. Each of these sets is called a realization. A large number of realizations are produced and forward run is performed for each of it. The challenge when stochastic methods are used in groundwater modelling is to keep a calibrated model during the sampling. If a standard Monte Carlo method is used, runs that do not fulfill a user specified calibration targets must be removed. To reduce the number of runs needed, Null-space Monte Carlo (NSMC) can be used where the number of realizations are reduced to the ones that can produce a calibrated model (Anderson et al., 2015). NSMC in combination with PEST on highly parametized models with pilot points is a method with the capability to produce multiple random parameter fields (realizations) that calibrates the model. Parameter values at the pilot points are then randomized and values at the rest of the grid, then interpolated from the pilot points. In combination with SVD and SVD-A, the computational burden is reduced. The produced realizations can then be used in forward runs in forecast scenarios which gives the result as a distribution representing the uncertainties (Aquaveo, 2012).

Methods for handling uncertainties origination from the assumptions that has to be made in the conceptualization of the aquifer is by nature not so easily quantifiable. Several authors suggest a multiple model approach where a number of numerical models are developed based on different conceptual models (Beven, 2006; Refsgaard et al., 2006; Højberg and Refsgaard, 2005; Singh, Mishra, and Ruskauff, 2010). Different ways of including these multiple models in the uncertainty analysis have been described. Refsgaard et al. (2006) advocate a qualitative approach with expert reviews to evaluate the different conceptual models and that the plausible set of conceptualisations has been covered. Others suggest a more quantitative approach where model averaging is undertaken which for example can include Monte-Carlo sampling (Singh et al., 2010). In a review by Enemark et al. (2018), a consensus approach has been identified to be a commonly used alternative to the multi-model approach. In this, interpretations are integrated into one model in which complexity is iteratively increased and conceptual uncertainties switches to parameter uncertainties

A system which incorporate qualitative and quantitative uncertainties in a policy making perspective is the Numeral Unit Spread Assessment Pedigree (NUSAP) system (Van Der Sluijs et al., 2005). The first three of these five relates to the quantitative part of uncertainty and includes for example some kind of stochastic method to capture parameter uncertainties. Assessment and predigree includes qualitative approches where experts judgement and multi-criteria evaluation is carried out. The NUSAP system does not primarily include exact instruments to be used for uncertainty analysis, but is rather a framework with proposed methods.

3 Method

To investigate uncertainties originating from assumptions in groundwater modelling, three numerical groundwater models, A, B and C, have been developed. They were based on different conceptualizations and assumptions on input data by three professionals in hydrogeology, for a case aquifer, the Varnum aquifer, Västergötland, Sweden. Stochastic modelling with NSMC simulation was used for the numerical modelling to include uncertainties from parameters. The results of this stochastic modelling and a qualitative self-review of uncertainties were used for analysis of uncertainties in the models. The work process of this thesis is shown in figure 3.1 and in the following sections the different parts are described in detail.

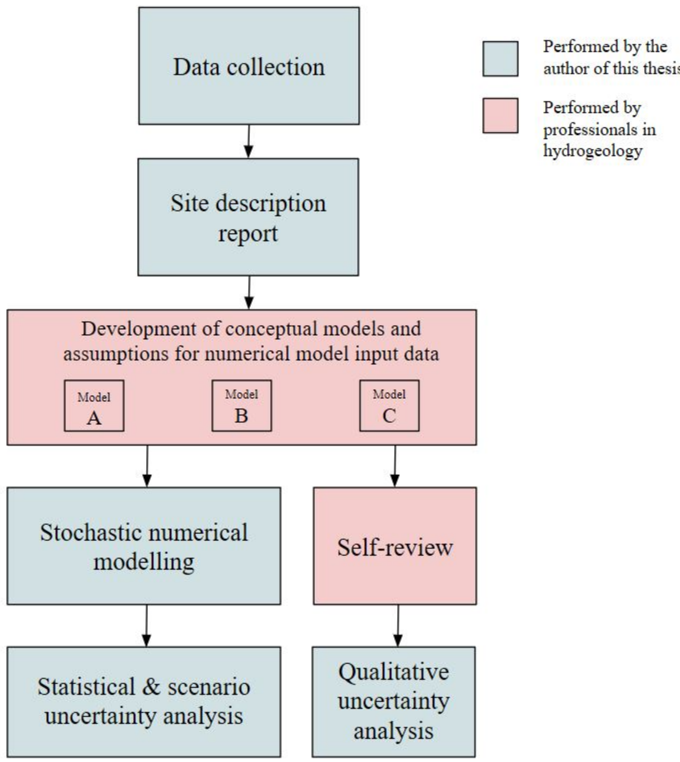


Figure 3.1: Flow chart of the procedure of this thesis.

3.1 Data collection and development of conceptual models

Initially, geologic, hydrogeologic and hydrologic information about the Varnum aquifer was collected and summarized in a report. The main sources for this information was an earlier investigation of drinking water extraction in the area by Scandiaconsult (2003), a description to the geological map by Hilldén (1984) and a description of the aquifer by the Geological Survey of Sweden (Lång and Lindh, 2012). It included for instance a summary of the geology described in the literature, investigation borehole logs and information from test pumpings. The report is found in appendix C. The report was handed to the professional hydrogeologists, which developed one conceptual model each, independent of each other.

The developers of the conceptual model were instructed that the model would be used in a pumping scenario of 50 l/s from two wells situated close to a lake and drawdown in the aquifer and infiltration from the lake would be studied as a consequence of the pumping. They were asked to develop a conceptual model that included description of boundaries and boundary conditions, sources and sinks of water including representation of surface water features, definition of any hydrogeological units with different proprieties of hydraulic conductivity and properties of the grid in the numerical model. Additionally, they were asked to set values for any input variables or intervals for parameters to be inversely calibrated in the numerical model. They were also instructed to chose how available head observations should be used for calibration and which calibration target that should be met for the model to be regarded as sufficiently calibrated. The conceptual models were reported back in text, by drawings on maps and in discussions. Based on this information the conceptual models were converted into numerical models by the author of this thesis. During the numerical modelling procedure, some adjustments were done which deviated from initial assumptions, due to heavy computational burden and/or calibration issues. This is described further in chapter 4.2.

3.2 Numerical modelling procedure

Here, the general numerical modelling procedure is described which the three models have in common. For further details on each of the models see chapter 4.2.

The numerical models were set up and run in GMS 10.3.5/MODFLOW. Layer elevations in the MODFLOW grid was set with assistance of the GMS solid module, where the geological models were built up by boreholes with interpreted material layers and/or TIN 3D surfaces from rasters of elevation data. The models were parameterized with values assumed by each conceptual model constructor. Parameters to be inversely calibrated, were assigned to pilot points which were located according to guidelines by Anderson et al. (2015) and Doherty (2003) with a higher density around head observations. Interpolation for these parameters between pilot points were done with ordinary Kriging. Variograms for the kriging interpolation were based experimental variograms from pilot point values from one initial PEST calibration. In some cases the software did not support the production of experimental variograms and variograms then had to be defined without support of any data. Adjustments were done if non-realistic parameter fields were produced. The variograms were of spherical type and their properties are found in appendix A.

Observation wells were placed 1 m above bottom of borehole reported in the borehole log (appendix B). Calibration data was the one year measurements by Scandiaconsult (2003) found in figure 4.4. Since no information about height coordinate system could be find, all level data for used for lake levels and calibration, was assumed to be in Borås old local coordinate system. It was converted to RH2000 according to Borås Stad (2018), to be in the same coordinate system as other data used. This assumption i supported by the fact that all xy-coordinates from the investigation was reported in Borås old local coordinate system.

The numerical models were run in steady state conditions. They were initially roughly manually calibrated with parameter values in the ranges from the developer of the conceptual models, to identify any problems in the numerical models. If so, changes were discussed with the conceptual model developers. Thereafter the models were run in stochastic inverse calibration mode (PEST-NSMC) with SVD, SVD-A (see chapter 2.2.6 and 2.2.7) and Tikhonov regularization with preferred homogeneity conditions. The MODFLOW-NWT with NWT solver was used for all models. 100 runs were performed for each model. Each run represent one parameter realization. To investigate if the number of runs was enough, one model were tested with 500 runs. Since no major differences were seen in the result, 100 runs were concluded to be enough for this study. The result of this test is reported in appendix F.

The calibration target given by each conceptual model developer were checked in the MODFLOW output files by a scrip written in Python. Realizations that did not meet the criteria were removed. The remaining realizations were then run for the pumping scenario. MODFLOW zonebudget were run in the pumped files with a zone defined for the cells representing Lilla Kleven. The result from these runs were retrieved from the MODFLOW output files by Python scrips reading total water budget data, zonal water budget data and heads for each of the realizations. Drawdowns were then calculated by subtracting the heads for the pumped scenario from each respective calibrated base file for four chosen point locations in the upper layer in all models. These points were chosen to represent some different distances and directions from the pumping wells, but be within a radius where drawdown took place. From the zonebudget output file, inflow from the boundary condition representing Lilla Kleven was retrieved. The data was the plotted in histograms or box-plots and mean and standard deviation calculated for the drawdown.

3.3 Uncertainty analysis

The analyze of uncertainties have been done with three different approaches which in this study are named after the level of uncertainty they result in, defined by Walker et al. (2003) and described in chapter 2.3.1. These are:

- **Scenario analysis** - referring to the method to use different persons assumptions to set up conceptual and numerical models. The three numerical models represent different scenarios for the context, model structural and input uncertainties. The difference in numerical model output from these scenarios is a measure of uncertainty for these sources.
- **Statistical analysis** - referring to the stochastic modelling capturing parameter uncertainties. The distribution of the numerical model output is a measure of parameter uncertainty within each model.
- **Qualitative analysis** - by means of a self-review questionnaire described last in this section. This gives a qualitative description of context, model structural and input uncertainties.

These methods are used to handle different sources of uncertainty. Additionally, there are uncertainties that are recognized but ignored in the uncertainty analysis. For example, uncertainty of the computer code has been ignored since only one code has been used and no comparisons against other codes or analytic calculations have been done. Also, there are uncertainties that are unknown and ignored (total ignorance) but these are by nature not identified. In table 3.1 it is shown which uncertainty analysis method that is used for which sources of uncertainty defined by Refsgaard et al. (2007) and Walker et al. (2003). It is also shown which parts specific for this study, that contribute to each type of source.

Table 3.1: Sources of uncertainty and the method they are handled in this study.

Uncertainty source (Refsgaard et al, 2007; Walker et al., 2003)	Context	Model technical	Model structural	Input	Parameter
Study specific contribution	(1) Model boundaries (2) Problem definition	Computer code, spatial discretization	Representation of the natural system in conceptual models	Invariable parameters and input variables, calibration data, pilot-points and interpolation scheme	Parameters randomized in stochastic modelling
Analysis method	(1) Scenario/ Qualitative (2) Recognized ignorance	Recognized ignorance	Scenario/ Qualitative	Scenario/ Qualitative	Statistical

The self-review referred to as qualitative analysis was done by a questionnaire that the developers of conceptual models were asked to answer after construction of the conceptual models. In general, the questions came from a checklist developed by Risbey, der Sluijs, Ravetz, and Janssen (2001) for quality assistance in environmental modelling within the NUSAP system. Some adjustments were done to the questions to adapt to this study and some questions were added. The questionnaire with answers is found in appendix D.

3.4 Limitations

Some limitations in the method used in this study exist, mainly due to the numerical burden and complexity of the PEST-NSMC method. The models were limited to only be run in steady state conditions even though test pumping data existed which could have been used for transient calibration. The discretization had to be kept at a relatively coarse level. Parameters that could be calibrated in the PEST-NSMC in GMS were restricted to recharge, hydraulic conductivity and anistotropy factor. Other parameters had to be held constant during PEST-NSMC. No formal sensitivity analysis was performed due to the complexity of such task in the PEST-NSMC with SVD/SVD-A method. Due to time restrictions of a master thesis, only three conceptual models have been looked at, which do not capture all plausible conceptualizations resulting in a risk of underestimated uncertainty.

Due to some of these limitations, there were compromises in the setup of the numerical models compared to the professionals' initial assumptions. This and that the numerical modelling was not performed personally by the professionals, probably affect the model results compared to if the whole process were undertaken by individual professionals, which would be the case for most real scenarios. However, such approach was regarded as being outside the frame of the thesis.

4 Case study

4.1 Site description

Varnum aquifer is situated in the South west of Sweden, in the municipality Borås, figure 4.1. The area is rural, and the vegetation is mainly farmland and some forest. Scattered settlement exists, which are summer houses and permanent residents. The aquifer is situated in a valley that has an altitude of approximately 170-175 masl and is surrounded by areas of higher altitudes, approximately 200-270 masl. The aquifer has been in focus of earlier investigations, aiming to explore the possibility to use it as a municipal raw water source (Scandiaconsult, 2003). No such plans have been implemented.

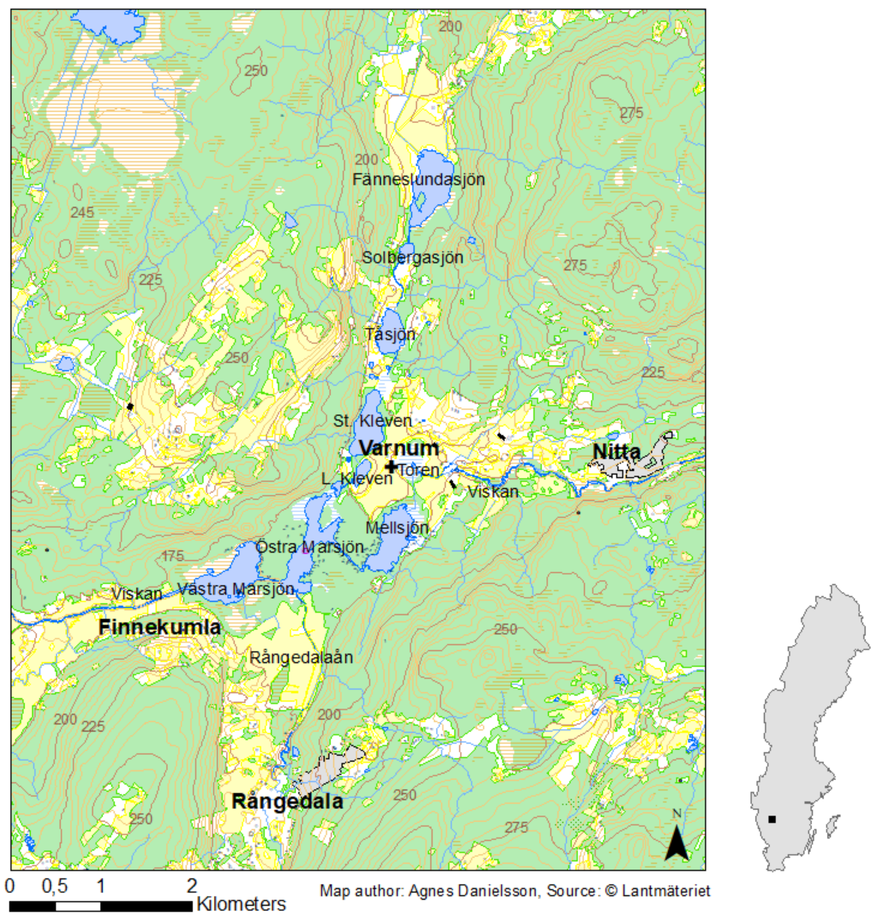


Figure 4.1: Varnum area.

The aquifer consists of glaciofluvial deposits as a part of the Rångedala esker, which stretches north-south in a fracture zone in the same direction. This fracture zone is crossed by another fracture zone going east west, where the glaciofluvial deposits has an extended width. The extension of the Varnum aquifer in plane and general flow pattern, interpreted by Geological Survey of Sweden (SGU), is shown in figure 4.2. Its area is around 8 km^2 (Lång and Lindh, 2012).

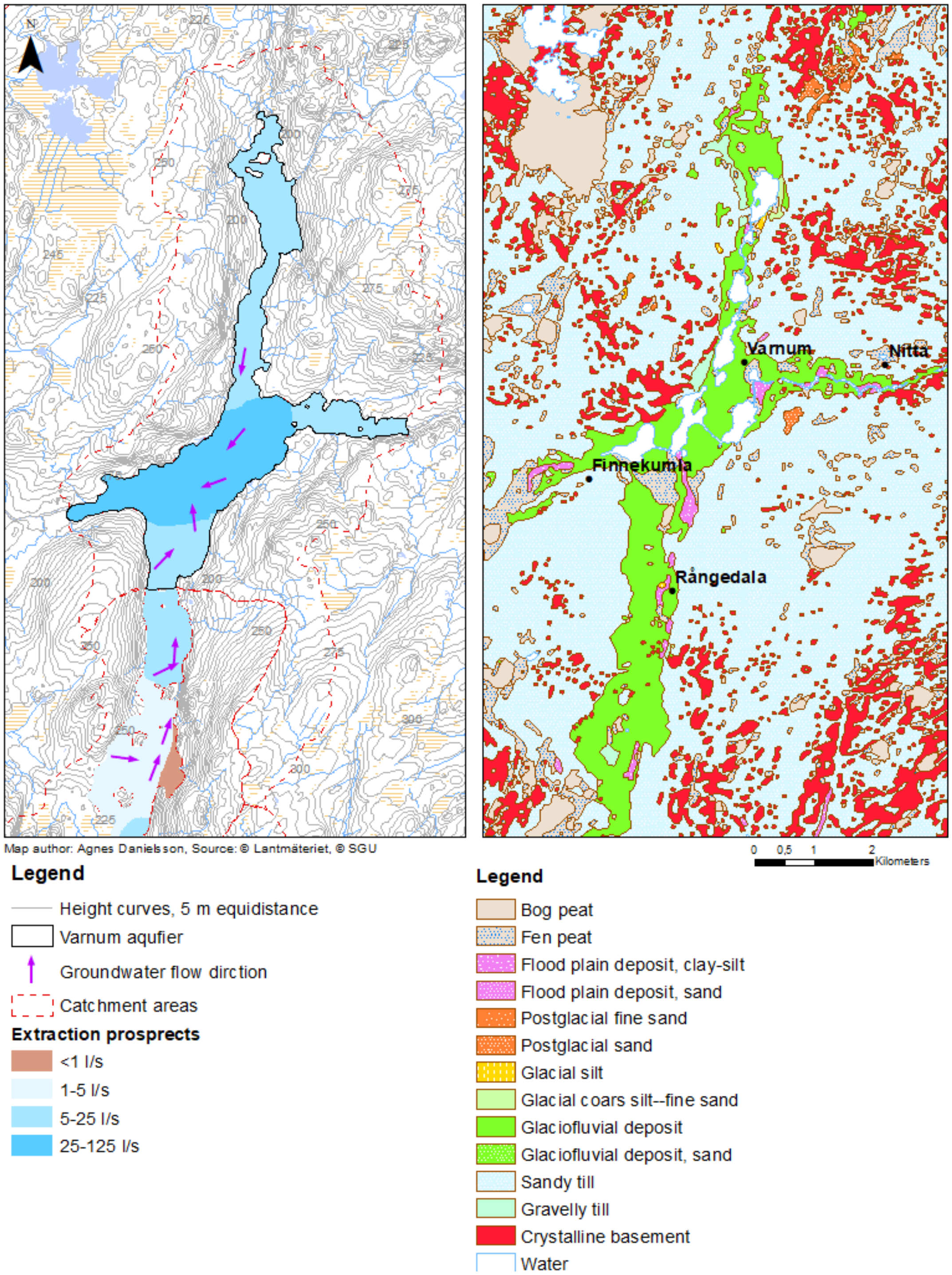


Figure 4.2: Aquifer properties according to SGU and soil map.

The deposits of the aquifer is mainly sand of different grain sizes, sometimes with coarser gravelly material or silt. In the central part of the aquifer a structure, interpreted as a delta, is present (Hilldén, 1984; Scandiaconsult, 2003). Horizontal-subhorizontal layers has been found. They consist of fine to coarse sand and thin layers of silt or gravel (Scandiaconsult, 2003). The glaciofluvial deposits are surrounded by thin layers of till deposited on the bedrock. Location of investigation boreholes are seen in figure 4.5 and borehole logs from the investigation by Scandiaconsult (2003), are found in appendix B. Sesimic investigations and the boreholes shows that the soil depth varies from some few meters up to 57 m. The larges depths has been found beetwen the two lakes Marsjöarna. Soil depth frpm SGU's soil depth model is shown in figure 4.3. The bedrock consists mainly of gneiss with a dominating strike of west-east direction (Lång and Lindh, 2012).

Other processes have also impacted the geology at the site. Hilldén (1984) describes an ice lake that existed during melting of the glacier in the latest ice age. The lake was situated in the north sloping valley south of Finnekummla and embanked by the ice front retrieving north-east. The lake was drained in several steps but fully emptied first when the ice front passed Finnekummla. In the end of the 1900th century, the water level in lake Marjön was lowered some meters to allow for land exploitation, resulting in that the area around the lakes Marsjöarna has been a previous lake bottom.

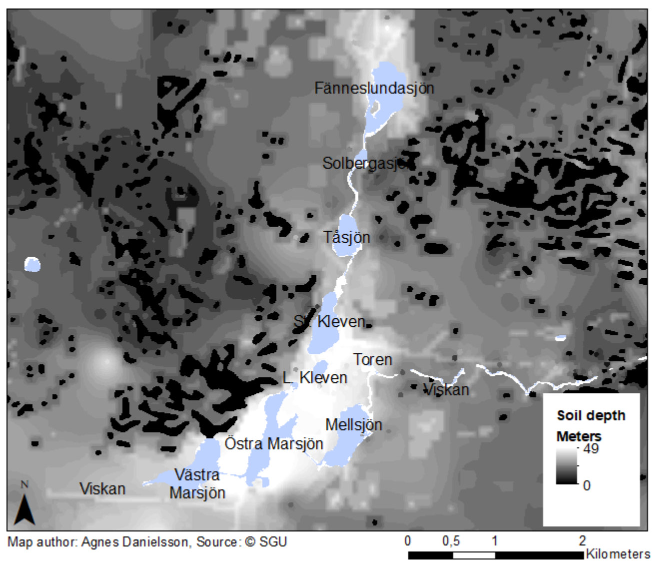


Figure 4.3: Soil depth.

The normal precipitation in the area is around 1000 mm/year and the evapotranspiration approximately 400-500 mm/year (SMHI, 2018). SGU has estimated direct recaharge to the aquifer to 100 l/s over an area of 5.8 km (Lång and Lindh, 2012). There are several streams and lakes in the area, seen in figure 4.1. Three major surface water networks meet in Östra Marsjön. From north, a stream network coming into Fännelundasjön, continues south towards Östra Marsjön. From east the stream Viskan flows into the area. From the south, the stream Rångedalaån flows into Östra Marsjön. The water flows out west to Västra Marsjön and into Viskan.

During the drinking water extraction investigation by Scandiaconsult (2003) heads in observation wells and lake levels were observed during one year. These are shown in figure 4.4. Location of the observation wells are shown in figure 4.5. Also, test pumpings were performed during this investigation. For more information about them, see appendix C and Scandiaconsult (2003).

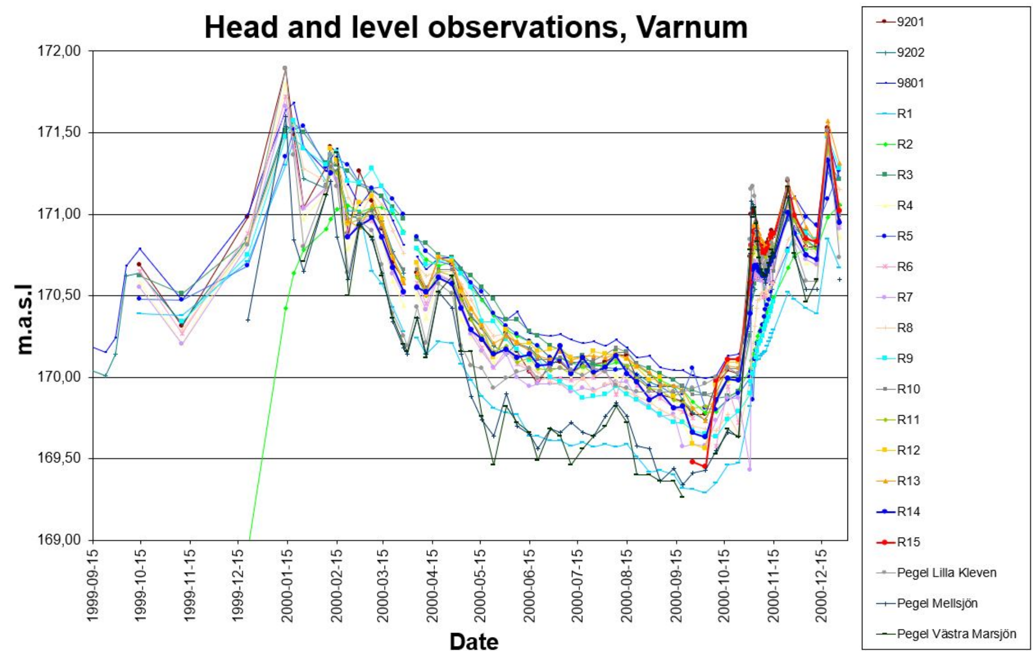


Figure 4.4: Head in observation wells and lake levels recorded during one year in the investigation by Scandiaconsult (2003).

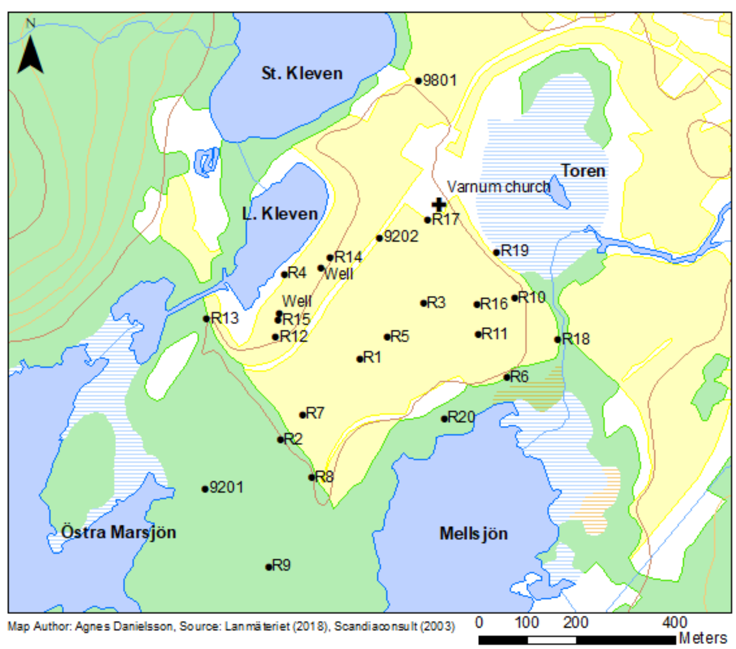


Figure 4.5: Location of boreholes/observation wells. Pumping wells used for pumping in this thesis are also shown and named wells on the map.

4.2 Conceptual models and input assumptions

4.2.1 Model A

In Model A, the aquifer was interpreted to extend over the glaciofluvial material in the two valleys crossing in Varnum. It was assumed to be unconfined and anisotropic in terms of hydraulic conductivity, caused by layers of less permeable materials. Recharge to the aquifer was assumed to be mainly from direct precipitation but some recharge from the surrounding till and bedrock is possible. Also the surface waters could be connected to the aquifer and either lose or gain water from it. The model was constructed in in two steps, first a regional and then a local scale model. The regional model was defined over the catchment area of the aquifer but since this model was to big and computational heavy to be used with PEST-NSMC, a highly parameterized local model where boundaries were extracted from the regional model was developed, see figure 4.6.

Regional model
The domain of the regional model were chosen to be similar to SGU's interpretation (Lång and Lindh, 2012) of the catchment area of the aquifer, see figure 4.2. Boundaries at the sides of the aquifer could then be assumed to be now flow boundaries. It had a area of 38.5 km^2 and a structured grid with a cell size of 40 m $\times$ 40 m.

The model consisted of three layers. The upper layer represented soil and had a top elevation corresponding to the 2 m $\times$ 2 m digital elevation map (DEM) from Lantmäteriet (2016) and a bottom elevation corresponding to soil depth data from SGU (2017) with adjustments were borehole data existed. Recharge was applied at this layer. The layer were divided into two hydraulic conductivity and recharge zones, one where glaciofluvial material is found on the soil map and one were till is found, see figure 4.2. The second layer was a moderately permeable layer corresponding to till and fractured bedrock with a bottom elevation 6 m lower than the soil depth. The third layer represented more competent bedrock and continued down to a constant depth of 60 masl where a no flow boundary was assigned.

Location of lakes and water courses were gained from Lantmäteriets hydrological GIS data and complementary identified at ortophoto of the area. Larger lakes and streams were modelled as head-dependent boundaries and smaller water bodies and smaller streams as drains. Bottom elevation of these were set to 0.5 m below ground elevation and head at ground level. Conductance were chosen to be high for streams and lower for lakes since it was assumed that a low permeable bottom layer is likely to occur in lakes where finer particles could settle but not in streams where higher velocities can be expected. Evapotranspiration (ET) was modelled with the EVT package with a extinction depth of 0.5 m and ET surface equal to ground surface. ET max rate was set equal to yearly potential evapotranspiraton for the normal year in the area reported by SMHI (2017).

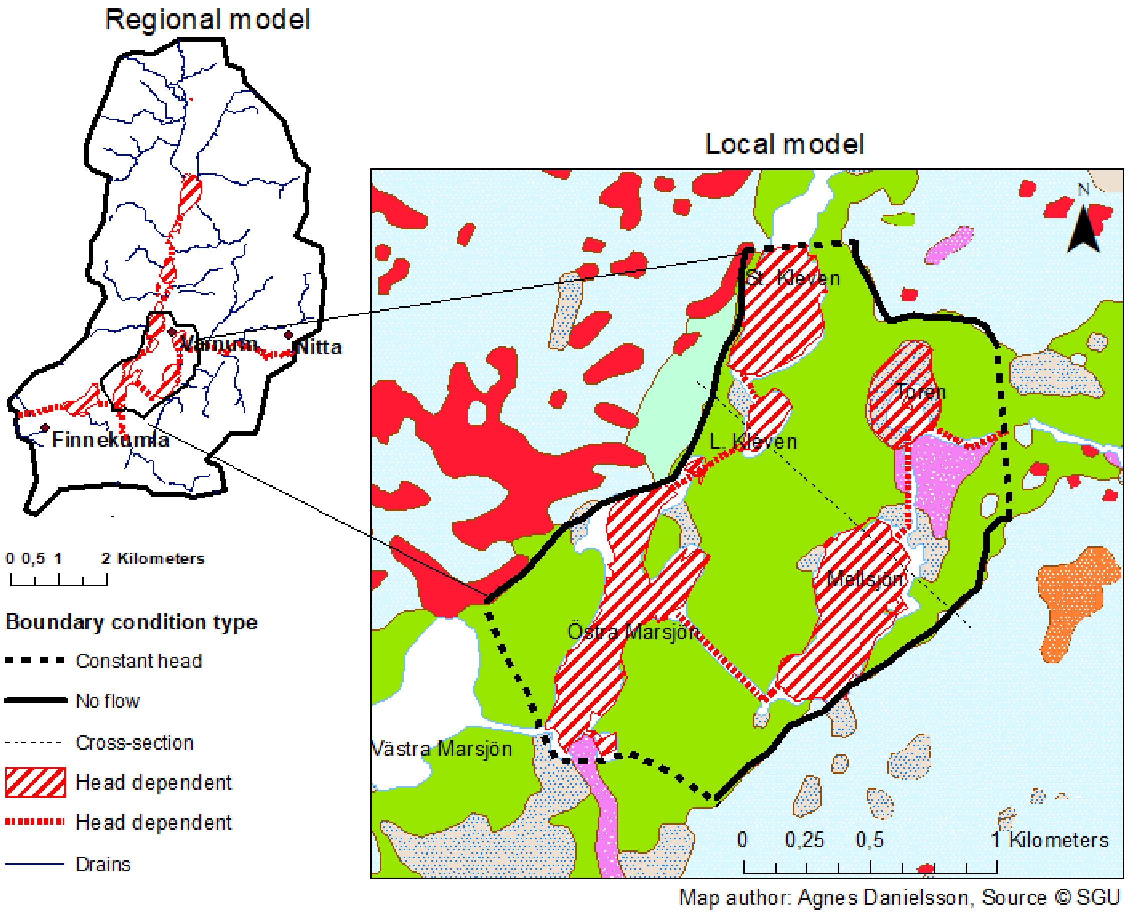


Figure 4.6: Boundaries in plane, Model A

The model was manually calibrated towards observed heads, measured at a single occasion (2000-05-20) where these existed and to not cause unrealistic flooding at other locations. Observations for R1 was excluded since it was seen on head observation and test pumping data that it is probably not well connected to the aquifer (Scandiaconsult, 2003). The reason for choosing observation at one single day for calibration was that fluctuations over the year was big for both lake levels and groundwater levels but differences between observation points and the lakes at specific days were low. Since lake levels could only be represented by one single value it was considered that using groundwater heads occurring at the same time as the chosen lake level would result in the most appropriate picture. The specific date was chosen to represent a non-extreme event over the year. The calibration data is found in appendix A. Where measured lake levels existed, heads at head-dependent boundaries representing these lakes and connected streams, were set to values measured the same day as calibration data used. Heads for lakes where measurements were lacking, were set with the level difference in the ground level DEM (Lantmäteriet, 2016) added to the closest measured lake level. Parameter values in the calibrated model are shown in table 4.1.

Table 4.1: Parameters values in the calibrated regional model A.

	Value in calibrated model
Horisontal hydraulic conductivity [m/s]	
Lay 1 (glaciofluvial zone)	7e-5
Lay 1 (till zone)	1e-5
Lay 2 (till/bedrock)	1e-6
Lay 3 (bedrock)	1e-8
Vertical anisotropy [-]	
Lay 1 (glaciofluvial zone)	3
Lay 1 (till zone)	1
Lay 2 (till/bedrock)	1
Lay 3 (bedrock)	1
Recharge [m/s]	
Lay 1 (glaciofluvial zone)	1.8e-8
Lay 1 (till zone)	4.0e-9
Evapotranspiration max rate [m/s]	2e-8
Conductance	
Streams [m/s]	0.01
Drains [m/s]	0.003
Lakes [s^{-1}]	5e-7

Local model

The local model was constructed to gain a model with finer discretization that was numerically manageable in PEST-NSMC. It had an area of 2.6 km^2 and a structured grid with refinement around the wells with a minimum size of 15 m × 15 m and maximum size of 40 m × 40 m. The model domain consisted of the central part of the aquifer where the sides against the thin till layer was assigned no-flow boundaries. Boundaries at the sides towards glaciofluvial material were assigned constant head boundaries with heads gained from the regional model. The lower bedrock layer was removed and a no-flow boundary assigned directly under the second layer since it was found in the regional model that the flow to this layer was very low (less than 1 % of the inflow to the whole model), resulting in a two layer model, see figure 4.7. Surface waters were modelled as in the regional model. Heads for these are shown in appendix A.

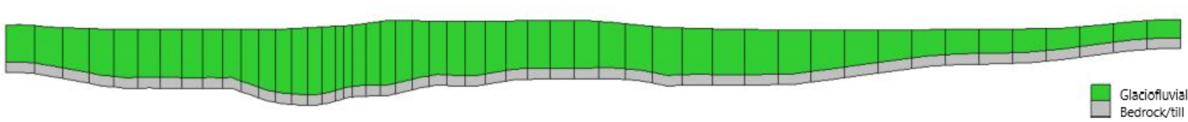


Figure 4.7: Cross-section local model A in NW-SE direction, see figure 4.6 for location. Shown with vertical scale magnification of 2.

The parameters that were considered uncertain and chosen to be randomized and inversely calibrated, were horizontal hydraulic conductivity in the soil and bedrock/till layer, vertical anisotrophy in the soil layer and recharge. Also conductance at head-dependent boundaries was considered uncertain but could not be included in the uncertainty analysis with the method used. Values for lake conductance was based on rough assumptions on sediment thickness of a couple of decimeters and a low permeable material of around 10×10^{-7} m/s, but it was acknowledged that this could vary within large magnitudes. These values and expected intervals for calibration parameters are shown in table 4.2. Values for hydraulic conductivity for the soil was minimum and maximum for test pumpings. For the bedrock/till layer, the interval was taken as literature values for fractured rock and glacial till by Freeze and Cherry (1979) accommodating for that clayey till is not so likely by raising the lower bound to ranges given by Carlsson and Gustafson (1997) for different types of till. Recharge was based on normal precipitation and evapotranspiration data from SMHI (2018) and estimated recharge from Lång and Lindh (2012), see chapter 4.1. It was assumed to have a mean of 500 mm/year that could vary ± 200 mm/year which was assumed to capture precipitation and evapotranspiration fluctuations and some potential extra recharge from the surrounding till. Vertical anisotropy was set so that vertical conductivity was lower than horizontal, which has been shown in test pumpings (Scandiaconsult, 2003) and expected due to layering in the delta formation. To which extent they differ is unknown but the interval given was assumed to cover possible anisotropy factors.

The model was inversely calibrated in stochastic mode towards the same data as the regional model. The calibration target was set so that no computed head should deviate more than ± 0.3 m from the observed value. All observations were weighted equally.

Table 4.2: Parameter values for model A. Values given as min-max are calibration parameters that are randomized during stochastic inverse calibration. Fixed parameters are constant during stochastic inverse calibration.

	Min	Max	Fixed
Horisontal hydraulic conductivity [m/s]			
Glaciofluvial deposit (lay 1)	1e-6	2e-3	
Till/bedrock (lay 2)	1e-9	1e-4	
Vertical anisotropy, K_h/K_v [-]			
Glaciofluvial depsit (lay 1)	1	5	
Till/bedrock (lay 2)			1
Recharge [m/s]	9.5e-9	2.2e-8	
Conductance			
Streams [m/s]			0.01
Lakes [s^{-1}]			5e-7

4.2.2 Model B

In Model B, the conceptualization of the aquifer was built on interpretation of the quatenary geological history. In summary, this conceptual model developer describes that primary glaciofluvial material in the esker and delta formation were overlaid by ice lake sediments of finer material. The aquifer was interpreted to be built up by a esker in the north-south valley, a delta in south of Varnum church formed in the former ice lake and glacial lake sediments. Form this geological interpretation a 3 layer model was constructed with a upper unit of coarse material representing the delta plain south of Varnum church, a interim layer with finer material extending over the whole model domain with a significant thickness in the south and a bottom layer representing esker or delta material with high permeability, see figure 4.9. Soil depth was gained from interpolation of borehole depth and depth extracted from Scandiaconsult Väst AB (1992) interpretation of seismic investigations. This depth formed the bottom of the third layer and was a no flow boundary against bedrock.

The abstraction of water from the wells were assumed to only have impact locally in the Varnum area. Boundaries on the sides was set to now flow boundaries against till/bedrock in west and east. In south and north no clear geological boundaries existed but could be regarded as constant head boundaries since the are far from the abstraction wells. Groundwater heads at these was assumed to be the same as the adjacent lake levels.

The main source of recharge was assumed to be infiltration into the open aquifer and possibly induced water from lakes and streams. Lakes and wetlands was assumed to have some but not full contact to the aquifer and was modelled as head dependent boundaries (initially they were set to specified head boundaries but after some calibration which is described below, this was changed). Streams were modelled as constant head boundaries since they were expected to have good contact to the aquifer. Heads at these features was set to mean lake levels observed during one year, for values see appendix A.

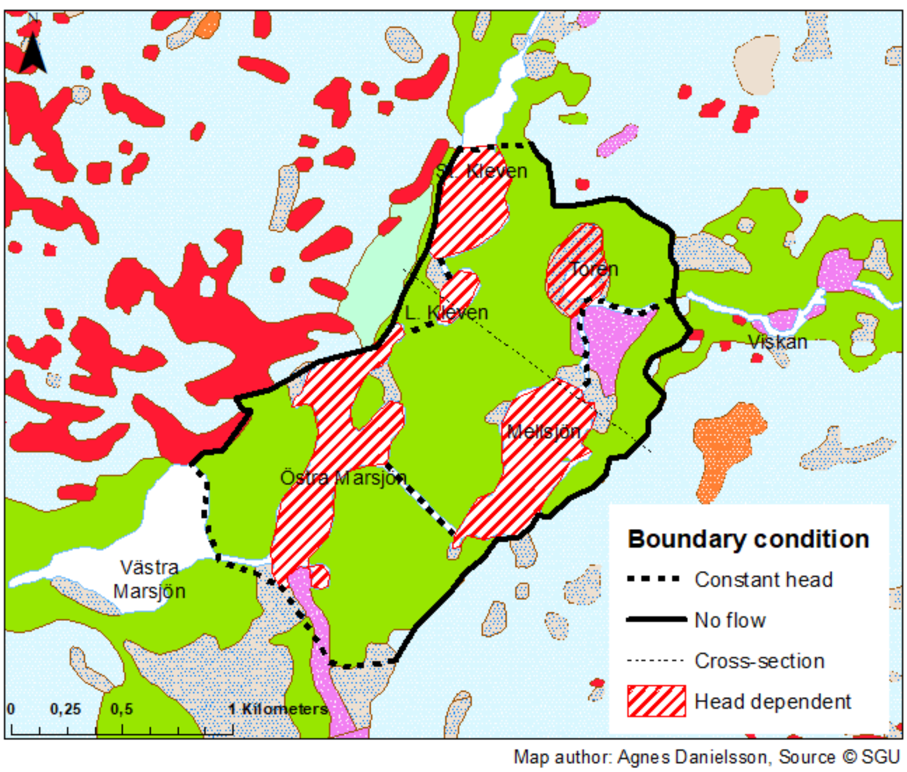


Figure 4.8: Boundaries in plane, Model B

The area of the model was 2.7 km². A structured grid with refinement around the wells was used. A grid size of approximately 5 m × 5 m was requested but due to too long running times a final grid with minimum cell size of 15 m × 15 m and maximum size of 40 m × 40 m was used.

On request from the conceptual model developer, the model was initially manually calibrated and roughly compared against long term test pumping data by running it in a pumping scenario in steady state. The purpose was to evaluate if specified head boundary was applicable for Lilla Kleven and find approximate value of conductance when a head dependent boundary was chosen to be used instead. The observations from this calibration is found in appendix E. Thereafter the model was run in PEST-NSCM and calibrated against mean values of observed heads in observation wells during one year. Observation well R1 was excluded due to the same reason as in model A, and R15 was excluded since it was only measured for a very short period of time. Calibration target was set so that parameter sets that produced computed head that deviated more than ±0.5 m from the observed values was excluded.

Parameters regarded most uncertain was hydraulic conductivity in the three layers and these were used as random parameters in the stochastic inverse calibration. Also recharge was regarded uncertain but to a less extent. It was initially intended to be randomly varied, but due to troublesome simulations it was finally set as a fixed value and excluded from the parameter uncertainty analysis. The initial range for recharge was 450-500 mm/year. Parameter values are shown in table 4.3. The lower bound for the fine material was initially set a bit lower but was raised during manual calibration since unrealistic flooding was caused at locations where this material dominated.

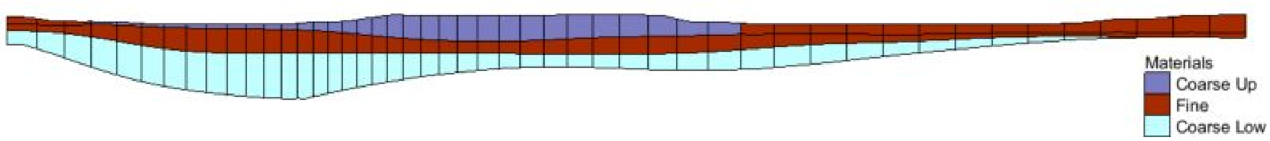


Figure 4.9: Cross-section local model B in NW-SE direction, see figure 4.8 for location. Shown with vertical scale magnification of 2.

Table 4.3: Parameter values for model B. Values given as min-max are calibration parameters that are randomized during inverse calibration within the given interval. Fixed parameters are constant during inverse calibration.

	Min	Max	Fixed
Horisontal hydraulic conductivity [m/s]			
Lay 1 (coarse)	1e-4	7e-4	
Lay 2 (fine)	9e-6	5e-5	
Lay 3 (coarse)	1e-4	7e-4	
Vertical anisotropy [-]			
All layers			3
Recharge [m/s]			1.5e-8
Conductance			
Lakes [s^{-1}]			1e-7

4.2.3 Model C

In Model C, the boundaries of the model was set to a constant head boundary along the major lakes surrounding the Varnum area. This was based on the assumption of hydraulic connection between these lakes and the aquifer which, at least for Mellsjön, could be supported by test pumping data where Mellsjön and the closest observation well shows increasing levels in contrast to the other head observations (Scandiaconsult, 2003). Heads for these boundaries was set equal to the mean of the lake level observations by Scandiaconsult (2003). For Stora Kleven no such observations existed so head was set to the mean head in Lilla Kleven with addition of the head difference between these lakes at the ground DEM (Lantmäteriet, 2016). No-flow boundaries were set along the boarder of glaciofluvial material and till since only a minor flow was expected from the till to the aquifer. The possible recharge from the till was instead included in the range given for recharge.

The lake Lilla Kleven and the attached streams were conceptualized as head dependent boundaries with heads equal to the mean of the observations by Scandiaconsult (2003). The stream Viskan from Mellsjön to the eastern part of the model was represented by MODFLOW River package. The bottom elevation was set equal to the ground DEM from Lantmäteriet (2016) and the stage to 0.1 m above. The wetland Toren was reprezented with a zone with hydraulic conductivity of peat.

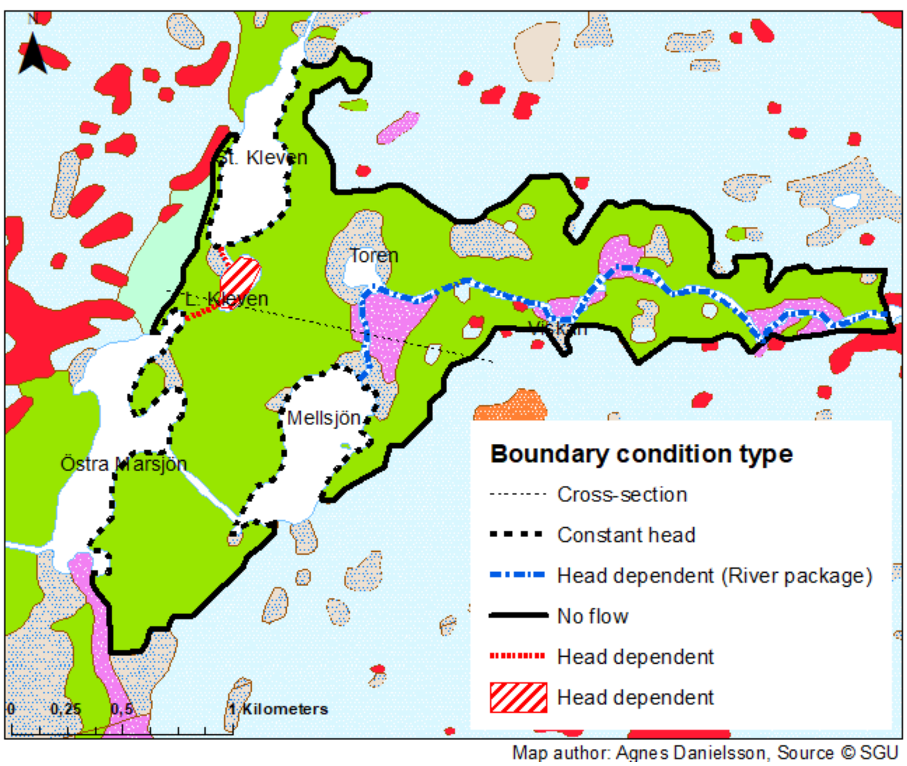


Figure 4.10: Boundaries in plane, Model C

For stratification, the developer of the conceptual model requested the materials in the borehole logs to be grouped into three groups of (1) gravel/gravelly sand, (2) sand and (3) silty sand/silt but since these materials occurred in a great variety of orders in the boreholes, this would result in a model with a large amount of layers which would have been too computational demanding for this project. Instead all glaciofluvial material was lumped into one single layer with top elevation equal to ground DEM (Lantmäteriet, 2016) and bottom elevation corresponding to soil depth data from SGU (2017) with adjustments were borehole data existed. Se cross-section figure 4.11

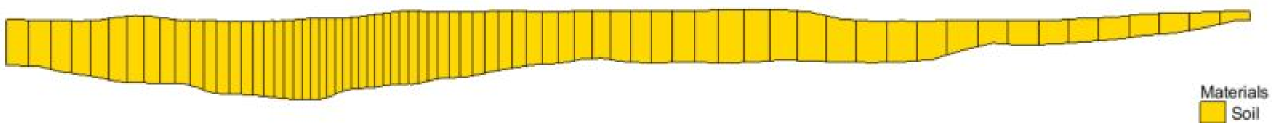


Figure 4.11: Cross-section local model C in W-E direction, see figure 4.10 for location. Shown with vertical scale magnification of 2.

The model had an area of 2.8 km^2 and a grid with 30 m × 30 m m with refinement around the wells down to 8 m × 8 m. The grid size requested by the conceptual model maker was 10 m × 10 m with refinement down to 1 m × 1 m. However, this was not possible due to the numerical burden.

The parameters for this model is shown in table 4.4. The interval for hydraulic conductivity was set to minimum and maximum of conductivity estimated from grain size analysis. The mean recharge was assumed to be equal to SGU's estimations of groundwater recharge (Lång and Lindh, 2012), see chapter 4.1, which corresponds to 1.7×10^{-8} m/s or 544 mm/year with the possibility to be half as low or two and a half times bigger due to possible extra recharge from the surrounding till. The conceptual model developer emphasized strongly that stream and lake conductance should be pure calibration parameters and do not correspond to any physical properties but since that could not be done, values were given but with extreme caution. The model was calibrated toward mean values with exclusion of observation well R1 and R15 with a calibration target that no computed head should deviate more than ±0.25 m from the observed value.

Table 4.4: Parameter values for model C. Values given as min-max are calibration parameters that are randomized during inverse calibration within the given interval. Fixed parameters are constant during inverse calibration.

	Min	Max	Fixed
Horisontal hydraulic conductivity [m/s]			
	6e-7	8e-3	
Recharge [m/s]	8.6e-9	4.3e-8	
Conductance			
Streams [m/s]			1e-4
Lakes [s^{-1}]			1e-3

5 Result

The numerical model outcome in terms of drawdowns at four different locations during the pumping scenario with extraction of 50 l/s as well as total water budget and flow from the boundary representing Lilla Kleven is presented here. The modellers answers to the uncertainty questionnaire are summarized and presented.

5.1 Numerical model outcome - statistical and scenario analysis

In the three models, all 100 runs converged in the undisturbed base model. In model B all of these realizations also met this model's calibration target. For model A and C some realizations were removed since they did not meet the calibration target and 88 and 94 realizations respectively was used for further analysis, see table 5.1.

Table 5.1: Number of realizations converging and number of converged realizations that meet calibration target.

	Number not convering	Number not meeting calibration target	Number remaining
Model A	0	12	88
Model B	0	0	100
Model C	0	6	94

The drawdown at pumping at the four locations is shown in figure 5.1 and table 5.2. It can be seen that the drawdown differs extensively between models and that the spread in model result within each model is very dissimilar to the other models. The drawdown in model A is much larger than model B and C at all four locations. Also the spread in model A is larger than the other two models. Model C shows the smallest drawdown at all locations.

Table 5.2: Mean and standard deviation at the four locations shown in figure 5.1.

		Model A	**Model B**	**Model C**
Location 1				
	Mean	6.11	1.58	0.37
	Std	1.18	0.15	0.23
Location 2				
	Mean	1.47	0.70	0.09
	Std	0.25	0.07	0.04
Location 3				
	Mean	1.88	0.72	0.11
	Std	0.27	0.07	0.04
Location 4				
	Mean	1.09	0.44	0.06
	Std	0.17	0.04	0.02

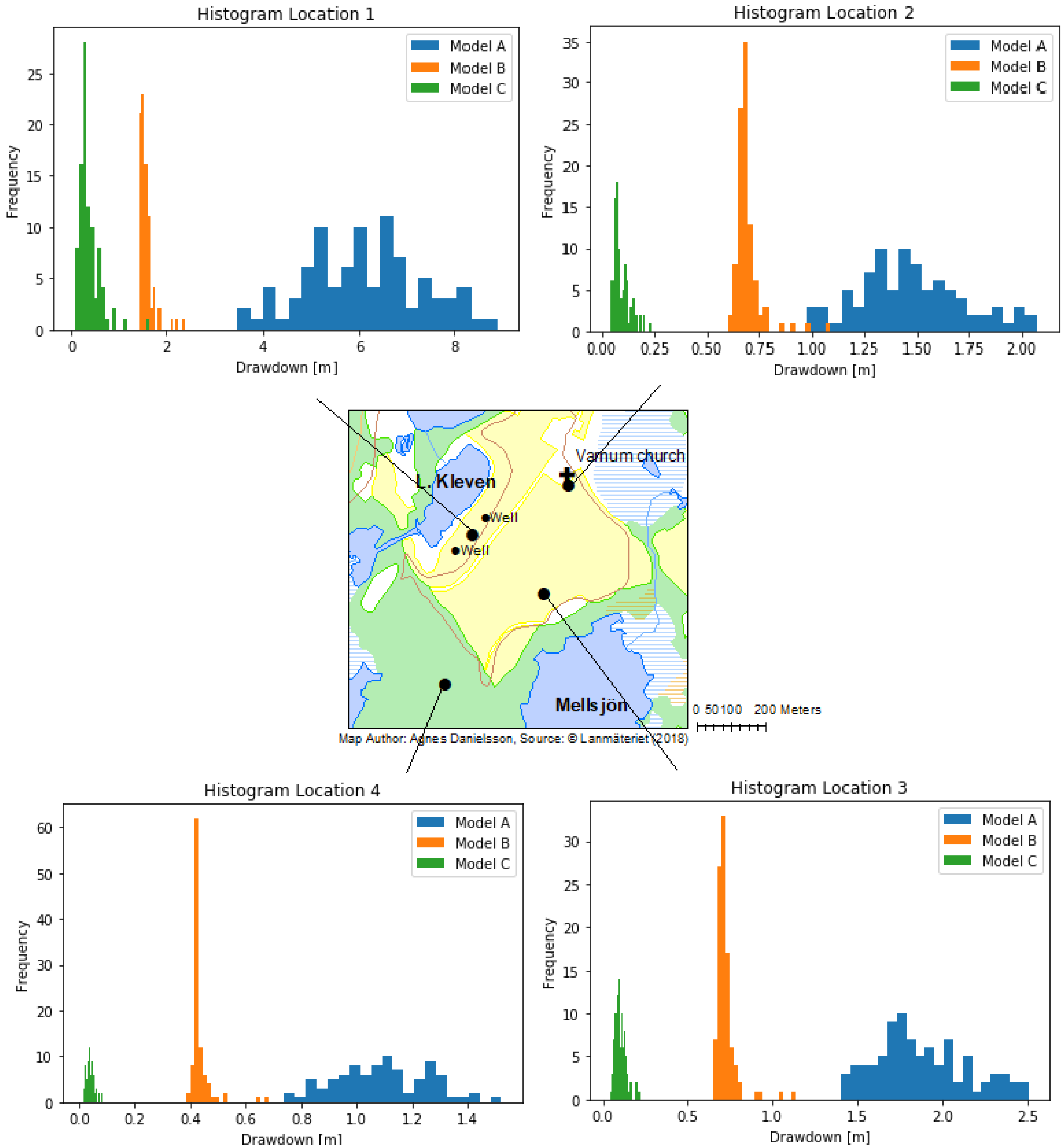


Figure 5.1: Drawdown at some locations in the models with 50 l/s of pumping equally divided between the two wells

In figure 5.3 the total water budget for each model in undisturbed and pumped scenario, is shown. In this water budget, all boundaries or sources and sinks of the same type is represented by one value even if they are not spatially connected in the model. It can be seen that for Model A, the major difference between undisturbed and pumped scenario is an increased inflow and a decreased outflow of water from head-dependent boundaries. In model B, inflow from constant head and head-dependent boundaries increases while outflow from these boundary types decreases. In model C, the major difference is a big increase of inflow from head-dependent boundaries.

The inflow from the boundary representing Lilla Kleven for each respective model is shown in figure 5.2. The models show very different result also for this model output. The inflow is high for model A and C. For model C it accounts for almost all withdrawal from pumping and have a much wider spread than the other models. For model B it is remarkably low. This can be understood when looking at the total water budget for this model in figure 5.3. As mentioned, a big difference between pumped and undisturbed scenario is the inflow from constant head boundaries. Since the streams connected to Lake Lilla Kleven are represented by constant head boundaries (see figure 4.8) and these streams are situated close to the pumping well, it is very likely that much of the withdrawn water comes from these streams.

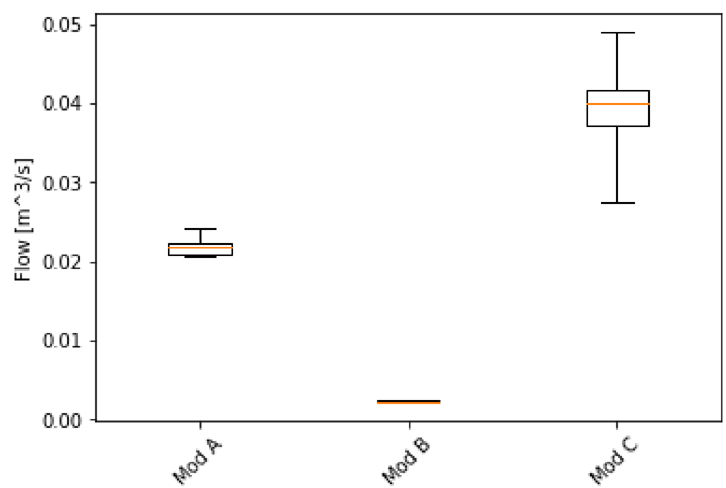


Figure 5.2: Flow into the models from the boundary representing lake Lilla Kleven in pumped scenario. Red lines showing median, boxes showing first and third quartiles and whiskers showing total range.

Mean and standard deviation for the parameter fields for the realizations from the inverse calibration that met the calibration criteria is found in appendix G. It can be seen that mean hydraulic conductivity is generally higher in model C than in the glaciofluvial material layer in model A. The coarse up and coarse low layers in model B are fairly equal to the mean conductivity in model C but model B also have a interim layer with lower conductivity. The spatial variation for conductivity is low in model B as well as the variation in each cell (low standard deviation in relation to the mean) in the fine and lower coarse layers. The variation in each cell for conductivity is higher for model C than the glaciofluvaial layer in model A. Mean recharge is higher in model C than A and the variation in each cell is bigger in model C.

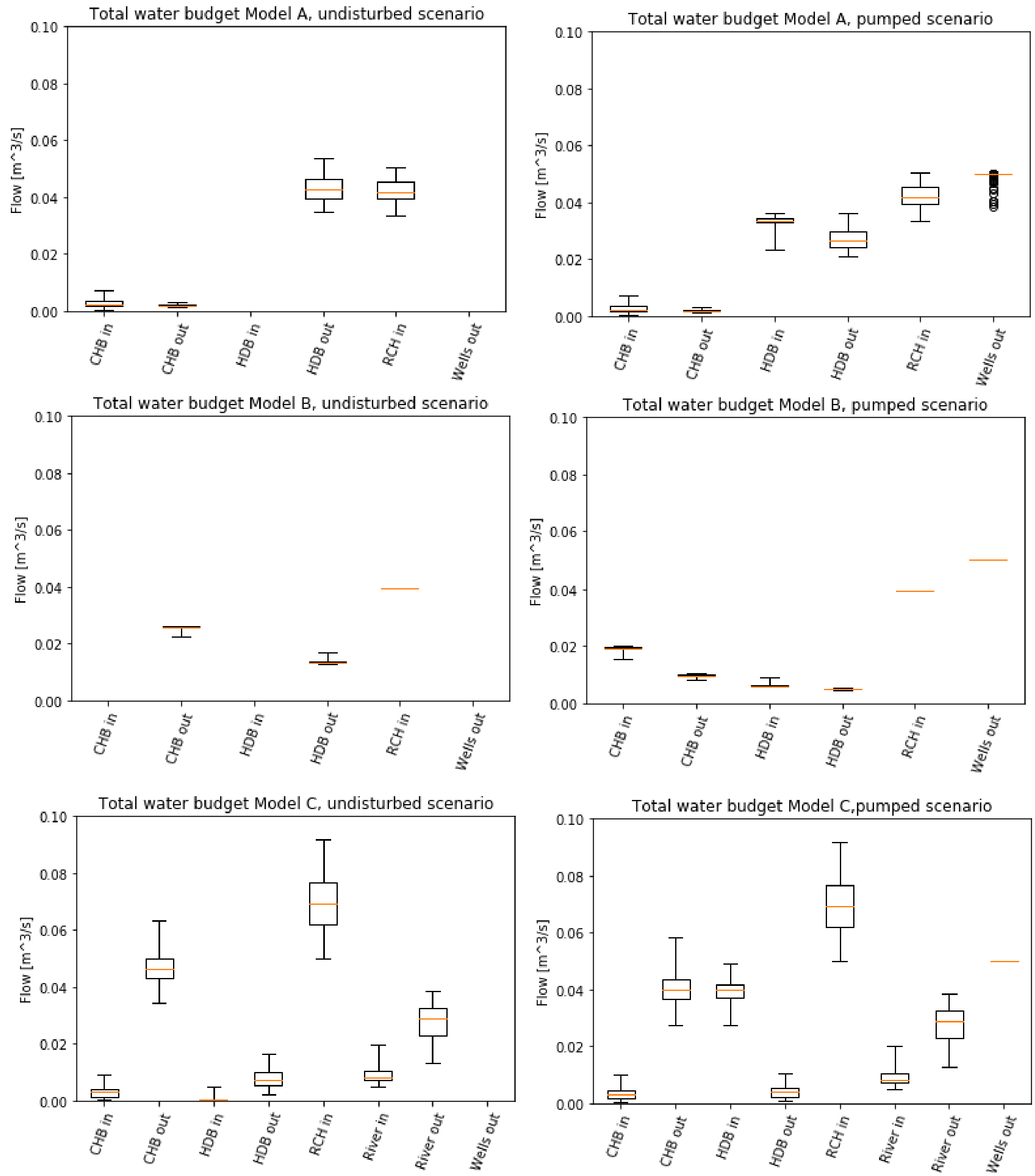


Figure 5.3: Total water budget of the models in undisturbed conditions and pumped scenario. Red lines showing median, boxes showing first and third quartiles and whiskers showing total range. The circles for wells out in model A, pumped scenario are outliers which are a result of decreased pumping rate in some realizations as a consequence of large drawdowns in the wells. CHB - constant head boundary, HDB - head-dependent boundary, RCH -recharge.

5.2 Qualitative analysis

The conceptual model developers' answers to the questionnaire, are found in Appendix D. The answers were given before seeing the result of the models. In summary, the modellers have the same idea that models in general can be used as a guide for policy making for this type of problem but have different opinions about how accurate the model outputs need to be to be useful and with which confidence the result of the models in this study can be used. One modeller thinks the result can be used with confidence whilst another thinks it should be used with caution. The third did not answer this question, considering it was hard prior to seeing the result. The modellers thinks the result needs an accuracy of 10% to a factor of 2 to be useful in a policy process.

All modellers acknowledge the possibility of alternative conceptual models. Two modellers describes that other plausible conceptual models could include different geological interpretations and complexity. One mention that other conceptualizations for the connection between surface water and the hydrogeological system is possible. Two modellers describes that the size of the modelling domain could be different, one describing a smaller domain with perfect connection between lakes and the aquifer and one a larger model bounded by a no-flow boundary. There is a consensus that different conceptualizations will have implications on the modelling result. Questions on how much the conceptual model, geological interpretation and boundaries would affect the result were all answered moderately or radically. However, the modellers have some different thoughts about which assumptions in the conceptual model that was most uncertain and have most implications for the result. Two modellers think the hydraulic connection between lakes and and the aquifer is one of the most uncertain factors. Two mention the stratigraphy and one the boundary conditions.

Considering parameter and input data, there is disagreement in the view on uncertainties and sensitiveness. One modeller finds recharge and conductance of lakes and streams to be most uncertain, one thinks hydraulic conductivity and conductance and one thinks conductivity and hydraulic heads. Their expectations on which parameter and input variables that are most sensitive to model output are even more spread.

6 Discussion

The result of this study showed that there was a substantial difference between model outputs from numerical models based on different assumptions, both in terms of drawdown and induced infiltration from the lake closest to the pumping wells. For both type of numerical model outputs, there was a much bigger difference between the models than there was spread within each model, implying that uncertainty sources analyzed through the scenario modelling dominated over statistical uncertainties. Uncertainty sources included in the scenario modelling were context, model structural and input data uncertainties. Statistical analysis covered parameter uncertainties. This means that uncertainties from assumptions on context, model structural and input data was not covered by statistic result from the stochastic modelling. If decisions would be made with only one model, including only parameter uncertainties, important uncertainties would be ignored and support to take well-informed decisions limited.

The difference in output between the models coincides with the different conceptual model developers' comprehension that model result would vary when using different conceptual models. The large difference between model output lied far from the conceptual model developer's perception on required model accuracy. For example, the induced infiltration from Lilla Kleven was around twenty times bigger in Model C than in model B. Hence, depending on the specific decision to be taken, this indicate that there can be a risk to apply results from these models directly in the policy process. However, this should not be seen as a failure and rejection of the models, but instead as an evidence of the power of including uncertainties in the modelling process. For some types of decisions, the result could indicate that more resources might need to be spend on model improvement and field data collection, which is to prefer over not knowing anything about the uncertainties where decisions can be made on completely wrong basis, as is highlighted by Refsgaard et al. (2005) (see chapter 2.3).

Without any formal sensitivity testing, it is not possible to explicitly state which study specific parts of context, model structural and input uncertainties (see table 3.1) that contributed most to uncertainties. It can neither be specified which specific parameters that contributed most to the spread within each model. However, some comments can be done about difference between the models in the numerical model result. The larger drawdown in model A might be explained by the generally lower hydraulic conductivity in this model as compared to the others (for Model B looking at the lower layer where most of the observation wells are located, which could be seen in simple model testing with forward runs to have a large impact of the drawdown). The lower conductivity probably have several explanations such as parameter assumptions, assumptions on pilot points and variograms and possibly that the gradient between heads representing lakes and calibration data is somewhat larger for model A (see appendix A). In model C, both recharge and conductivity is high, which is reasonable to give low drawdowns during pumping. Additionally, in model C, model testing in a forward run showed that drawdown to some extent, was sensitive to the conductance assigned to the head dependent boundary of Lilla Kleven. Since this model have relatively high conductance it result in lower drawdowns during pumping.

The big spread in model A is not easily explained. It do not seem to have a relation to parameter spread in the final realizations since variation is generally bigger in Model C. It might be a result of that there are more distributed parameters in model A. For model B it is not unexpected that the spread is low since only hydraulic conductivity is included as a randomized parameter and not recharge as in the other models. Interesting to note is that Model C have a large spread for flow from Lilla Kleven compared to the other models but a small distribution for heads. The reason is probably that recharge have a large variation and therefore the other components in the flow budget must vary accordingly to make the flow budget to sum up in each realization. But when it comes to heads these are constrained by the calibration so other parameters (mainly hydraulic conductivity) will compensate for the recharge variation, resulting in smaller variation for heads. The lower median values for the inflow from Lilla Kleven in model A and B can probably simply be explained by the smaller conductance of Lilla Kleven in these models compared to model C. This model output must however be interpreted carefully since the conductance of of head-dependent boundaries could not be included as an uncertain parameter (calibration parameter) in the NSMC simulations. To do so would have been desirable, since the inflow from Lilla Kleven was sensitive to this parameter (eg supported by findings in the manual calibration of model B, appendix E).

As described, no transient calibration against test pumpings have been performed. Some comments can however be made about the model outputs in relation to test pumping data. It must though be mentioned that such comparison is very rough due to different pumping rates, different pumping well locations and different locations of observations wells and locations for presented drawdowns in this thesis. In long term test pumps with 20 l/s from one well located at the same place as the south west well in figure 4.5, maximum drawdown measured after 23 days were between 0.6-1 m, in the closest observation wells (R15, R12, R4 in figure 4.5) (Scandiaconsult, 2003). Drawdowns smaller than or equal to this for location 1 in figure 5.1, such as in model C, does not seem realistic. For model A and B, it is hard to tell if the drawdown is reasonable based on this comparison. No conclusions about the best performing model can be drawn from these reflections, which has neither been the aim of this thesis, but it contributes to the understanding that transient calibration or other refinement of the models could contribute to less uncertainties in the scenario analysis.

The result of the numerical modelling in this study should be read with awareness of the relatively simple construction of the models, coarse discretization and limitations in the calibration and uncertainty analysis. For some real policy processes, increased complexity would probably be needed for the models. This is well reflected in the professionals' initial suggestions for the models. As an example, a finer grid size and more complex stratigraphy than was used in the final numerical models, was demanded from all conceptual model developers. The result should instead be seen as an indicator that assumptions in the groundwater modelling process plays a big role in model result uncertainties and supports other findings that the conceptual model is a major contributor to uncertainties. Among others, this has been found by Højberg and Refsgaard (2005) showing that different geological conceptual models contributed significantly to uncertainty and could not be compensated by parameter uncertainties, especially when the output type was not the same as the calibration data. Seifert, Sonnenborg, Scharling, and Hinsby (2008) found that two conceptual models, with and without a buried valley, had important implications for predictions of groundwater ages, fluxes and travel paths. Harrar, Sonnenborg, and Henriksen (2003) showed that different geological and flow models simulated similar capture zones but very different concentration breakthroughs and travel times. A last striking example is given by Refsgaard et al. (2006), where five different consultants were given the same commission regarding groundwater contamination vulnerability. The consultants used very different model structures and solutions differed widely.

Thus, it is important to recognize that assumptions in the groundwater modelling process result in model output uncertainties and these uncertainties need to be dealt with. For parameter uncertainties, stochastic methods can be used with parameter distributions covering their uncertainties. For context and model structural uncertainties there is still the problem that an unlimited amount of models can be defined and no project have resources to test them all. As in this study, only three models were incorporated but as recognized by the conceptual model developers, there are certainly other plausible conceptual models. Methods for these types of uncertainties is fortunately an emerging research field. Enemark et al. (2018) reviews different approaches used in previous research and discusses methods for dealing with conceptual model uncertainties and the ability to overcome what is describes as "surprises". Surprises occur when new data shows that the current conceptual model is inaccurate (Bredehoeft, 2005). Enemark et al. (2018) means that a multi-model approach where models are mutually exclusive and collectively exhaustive (independent hypotheses are represented and all plausible models are included) could handle these challanges but recognizes also the practical difficulties in such an approach. Based on that study and experiences from this thesis the following approaches are suggested, separate or in combination.

- A multi-model approach is probably indispensable to account for conceptual uncertainties. To limit the number of numerical models to be set up, different hypothesizes of the system that cannot be rejected by data and that are believed to significantly affect the result for the specific model aim, should be included as different conceptual models but less important or duplicate hypotheses excluded. This process could rather benefit from being performed by one modelling team or cooperating teams, than being set up by independent teams where there is a risk that all models strives to be "the most likely" and not incorporate important hypotheses.

- If the model is included in a policy process, the transparency and qualitative description of uncertainties could benefit from self-reviews such as the quality assistance checklist by Risbey et al. (2001). It can be useful for increased awareness and reflection in the modelling team but also important in the communication to the decision makers. It should however be emphasized that such checklists or questionnaires should be adapted to subject specific and local context (type of modelling, language etc) and needs to be well defined and have a clear purpose.

- Include essential complexity in the models and use methods so that uncertainty types that can be handled by with stochastically are included in this type of analysis. Handle the resulting numerical burden in stochastic simulations by eg increased computer power or accounting for long running times. Oversimplification in it self leads to uncertainties.

- Do more field measurements for parts where assumptions are most uncertain and have relevance for the model output. Collect more data field to improve the calibration data or/and perform transient calibration.

Regardless of the increasing awareness of this topic, the unquantifiable nature of conceptual uncertainties will continue to be a considerable challenge and there is no quick-fix to deal with these type of uncertainties. The research of today searches for new strategies and will probably contribute to that tomorrows modeller handle these uncertainties in a more structured manner.

7 Conclusion

This study exemplifies that different professionals make different assumptions for conceptual models and numerical model input data, for the same groundwater modelling problem. Three numerical models based on these different assumptions gave substantially different output. Output distributions within each model from stochastic numerical modelling was smaller than these differences. Hence, uncertainties originating from assumptions were of high relevance and could not be ignored in favour of parameter uncertaintes. Professionals in hydrogeolgy included in this study as developer of conceptual models, are aware of that their assumptions contributes to uncertainties even if they had different views on which assumptions that were of major importance. The numerical models in this study have been of simple character and there have been limitations in how methods for parameter uncertainties have been used. Nevertheless, it contributes to support the research claiming that uncertainties in groundwater modelling not exclusively have quantitative properties and that methods for incorporating structural and conceptual uncertainties should be included in groundwater modelling in addition to parameter uncertainties.

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A Calibration data, boundary heads and properties of variograms

Table A.1: Values for head observations used as calibration data

	Model A [masl]	Model B & C [masl]
9201	170.40	170.73
9202	170.27	170.62
9801	170.48	170.78
R2	170.42	170.53
R3	170.48	170.74
R4	170.32	170.61
R5	170.44	170.63
R6	170.30	170.62
R7	170.27	170.56
R8	170.40	170.58
R9	170.36	170.56
R10	170.39	170.67
R11	170.32	170.63
R12	170.42	170.68
R13	170.38	170.61
R14	170.30	170.56

Table A.2: Heads at boundaries. CHB-Constant head boundary, HDB-Head dependent boundary

Model A	Boundary heads [masl]
CHB north	170.19-170.92
CHB east	171.43-173.05
CHB south	169.97-171.45
HDB Ö. Marsjön	169.97
HDB Mellsjön	170.03
HDB St. Kleven	170.16
HDB L. Kleven	170.12
HDB Toren	170.05

Model B	Boundary heads [masl]
CHB north	170.63
CHB south	170.38
HDB Ö. Marsjön	170.38
HDB Mellsjön	170.42
HDB St. Kleven	170.63
HDB L. Kleven	170.63
HDB Toren	170.42

Model C	Boundary heads [masl]
CHB Ö. Marsjön	170.40
CHB Mellsjön	170.42
CHB St. Kleven	170.67
HDB L. Kleven	170.63

Table A.3: Properties for variograms used for pilot point interpolation

	Range	**Contribution**	**Nugget**
Model A			
HK Glaciofluv	489	0.43	0.32
HK Bedrock/till	500	0.5	0.3
Vanis Glaciofluv	500	0.5	0.07
RCH	1000	0.003	0.002
Model B			
Coarse up	228	0.008	0.003
Fine	433	0.010	0.003
Coarse low	340	0.015	0.004
Model C			
HK	566	2.1	1
RCH	500	0.015	0.003

B Borehole data

	BorrID	R1 mtrl	Grain size analysis	R1 water	R1 cond, Hz	BorrID	R2 mtrl	Grain size analysis	R2 water	R2 cond, Hz
Tot depth		28.5					31.2			
1	R1	grSa				R2	grSa			
2	R1	grSa				R2	grSa			
3	R1	grSa				R2	mSa			
4	R1	grSa				R2	mSa			
5	R1	grSa				R2	fSa/mSa			
6	R1	grSa	sand		8.6E-05	R2	fSa/mSa			
7	R1	fSa/mSa				R2	fSa/mSa			
8	R1	fSa/mSa				R2	fSa/mSa	mellansand/fin sandsand		9.2E-05
9	R1	fSa/mSa				R2	fSa/mSa			
10	R1	fSa/mSa				R2	fSa/mSa			
11	R1	fSa				R2	fSa/mSa			
12	R1	fSa	fin sand			R2	fSa/mSa			
13	R1	fSa			7.2E-05	R2	fSa/mSa			
14	R1	fSa/Si				R2	fSa/mSa			
15	R1	fSa/Si				R2	Si			
16	R1	fSa/Si				R2	Si			
17	R1	fSa/Si				R2	Si			
18	R1	fSa/Si	sandig silt		4.6E-06	R2	Si			
19	R1	fSa/Si				R2	Si			
20	R1	fSa/Si				R2	Si			
21	R1	fSa/Si				R2	Si	sandig silt		5.7E-07
22	R1	fSa/Si				R2	fSa/Si			
23	R1	fSa/Si				R2	fSa/Si			
24	R1	fSa/Si				R2	fSa/Si			
25	R1	fSa/Si				R2	fSa/Si			
26	R1	fSa/Si				R2	fSa/Si			
27	R1	fSa/Si				R2	fSa/grSa		60	
28	R1	grSa		30		R2	fSa	sand	60	9.2E-05
29	R1	grSa		1		R2	grSa		70	
30						R2	grSa		5	
31						R2	grSa	fin sandsand/mellansand	0.5	1.1E-04
32										
33										
34										
35										
36										
37										
38										
39										
40										
41										
42										
43										
44										
45										
46										
47										
48										
49										
50										

	BorrID	R3	Grain size analysis	R3 water	R3 cond, Hz
Tot depth		23.7			
1	R3	grSa			
2	R3	grSa			
3	R3	grSa			
4	R3	fSa/mSa			
5	R3	fSa/mSa			
6	R3	grSa			
7	R3	mSa		0.5	
8	R3	mSa		0.5	
9	R3	grSa		1	
10	R3	mSa/grSa		1	
11	R3	fSa/mSa/Si		0.5	
12	R3	fSa/mSa/Si		0.5	
13	R3	fSa/mSa/Si			
14	R3	fSa/mSa/Si			
15	R3	fSa/mSa/Si	siltig sand		7.2E-06
16	R3	fSa/mSa/Si			
17	R3	fSa/mSa/Si			
18	R3	fSa/mSa/Si			
19	R3	fSa/mSa/Si			
20	R3	fSa/grSa		30	
21	R3	fSa/grSa		60	
22	R3	fSa/grSa	mellansand	60	2.6E-04
23	R3	fSa/grSa		23	
24	R3	grSa		4	
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40					
41					
42					
43					
44					
45					
46					
47					
48					
49					
50					

	BorrID	R4	Grain size analysis	R4 water	R4 cond, Hz	BorrID	R5	Grain size analysis	R5 water	R5 cond, Hz
Tot depth		41					10			
1	R4	mSa		2		R5	grSa			
2	R4	mSa		2		R5	grSa			
3	R4	fSa/grSa		1		R5	grSa			
4	R4	fSa/grSa		5		R5	fSa/mSa			
5	R4	fSa/grSa		0.3		R5	fSa/mSa	siltig sand		2.8E-05
6	R4	fSa/mSa		0		R5	fSa/mSa			
7	R4	fSa/mSa/Si	siltig fin sandsand	0	3.1E-05	R5	fSa/mSa		1	
8	R4	fSa/mSa/Si		80		R5	fSa/mSa		1	
9	R4	fSa/grSa		90		R5	fSa/grSa		1	
10	R4	grSa		90		R5	fSa/grSa	fin sandsand	0.5	6.2E-05
11	R4	grSa		90		R5	Not driven			
12	R4	grSa		90		R5	to bedrock			
13	R4	grSa		90						
14	R4	grSa/Le	grusig sand	90	2.3E-03					
15	R4	grSa		90						
16	R4	grSa		90						
17	R4	fSa/grSa		90						
18	R4	fSa/grSa								
19	R4	fSa/grSa								
20	R4	fSa/grSa								
21	R4	fSa/grSa		25						
22	R4	fSa/grSa		80						
23	R4	fSa/grSa								
24	R4	fSa/grSa		100						
25	R4	fSa/grSa		90						
26	R4	fSa/grSa		90						
27	R4	fSa/grSa		90						
28	R4	fSa/grSa		90						
29	R4	fSa/grSa		90						
30	R4	fSa/grSa		90						
31	R4	mSa/Gr		100						
32	R4	mSa/Gr		100						
33	R4	mSa/Gr		100						
34	R4	mSa/Gr		100						
35	R4	mSa/Gr	grusig sand	100	5.7E-03					
36	R4	mSa/Gr		100						
37	R4	mSa/Gr		100						
38	R4	mSa/Gr		100						
39	R4	mSa/Gr		100						
40	R4	mSa/Gr		100						
41	R4	mSa/Gr		100						
42										
43										
44										
45										
46										
47										
48										
49										
50										

BorrID	R6	Grain size analysis	R6 water	R6 cond, Hz	BorrID	R7	Grain size analysis	R7 water	R7 cond, Hz	BorrID	R8	Grain size analysis	R8 water	R8 cond, Hz	BorrID	R9	Grain size analysis	R9 water	R9 cond, Hz	BorrID	R10	Grain size an	R10 water
	23.25					32.25					10					10					25.7		
R6	grSa				R7	fSa/grSa				R8	grSa				R9	grSa				R10	grSa		
R6	mSa/grSa				R7	fSa/grSa				R8	mSa/grSa				R9	grSa	grusig sand			R10	grSa		
R6	fSa/mSa				R7	fSa/mSa				R8	grSa		1		R9	grSa		4	3.5E-04	R10	grSa		
R6	fSa/mSa		0.2		R7	fSa/mSa				R8	mSa/grSa		1		R9	grSa		2		R10	grSa		
R6	fSa/mSa	fin sandsand/mellansand	0.2	8.6E-05	R7	fSa/mSa				R8	fSa/mSa	fin sandsand/mellansand	1	1.4E-04	R9	fSa/mSa		0.5		R10	grSa		
R6	grSa		12		R7	fSa/mSa		1		R8	fSa/mSa		1		R9	fSa/mSa		0.5		R10	grSa		
R6	grSa		36		R7	fSa/mSa		1		R8	fSa/mSa		0.5		R9	fSa/mSa		2		R10	grSa		
R6	grSa		36		R7	fSa/mSa		1		R8	fSa/mSa		0.5		R9	fSa/mSa		0.5		R10	grSa/mSa		
R6	fSa/mSa	sand	36	3.0E-04	R7	fSa/mSa		1		R8	fSa/mSa	fin sandsand	0.5	6.7E-05	R9	fSa/mSa		0.5		R10	grSa/mSa		
R6	fSa/grSa		70		R7	fSa/mSa	mellansand/fin sandsand	1	9.2E-05	R8	fSa/mSa		0.5		R9	fSa/mSa	siltig fin sandsand	0.5	2.3E-05	R10	grSa/mSa	sand	
R6	fSa		0		R7	fSa/mSa		0.5								Not driven				R10	grSa/mSa	sand	10
R6	fSa		0		R7	fSa/mSa		0.5			Not driven					to bedrock				R10	grSa/mSa		10
R6	fSa		0		R7	fSa/mSa		0.5			to bedrock									R10	grSa/mSa		10
R6	fSa/mSa		5		R7	fSa/mSa		0.5												R10	grSa/mSa		5
R6	mSa/grSa		60		R7	fSa/mSa		0.5												R10	grSa/mSa		5
R6	grSa		60		R7	fSa/mSa		0.5												R10	grSa/mSa		5
R6	mSa/grSa		60		R7	fSa/mSa/Si		0												R10	grSa/mSa		10
R6	grSa		60		R7	fSa/mSa/Si		0												R10	grSa/mSa	sand	50
R6	grSa		60		R7	fSa/mSa/Si		0												R10	grSa/mSa	sand	50
R6	mSa/grSa		30		R7	fSa/mSa/Si		0												R10	grSa/mSa		4
R6	fSa/grSa		8		R7	fSa/mSa/Si		0												R10	mSa/fSa	sand	5
R6	fSa/grSa		2		R7	fSa/mSa/Si		0												R10	mSa/fSa	sand	2
R6	BMn		0		R7	fSa/mSa/Si	sandig silt	0	1.7E-06											R10	mSa/fSa	sand	2
					R7	fSa/mSa/Si		0												R10	grSa	sand	7
	Röret fördjupat maj 2001, tid 10 mete				R7	fSa/mSa		0												R10	grSa	sand	10
					R7	fSa		0												R10	grSa		20
					R7	fSa		0															
					R7	fSa		0															
					R7	mSa/grSa		60															
					R7	fSa/mSa		5															
					R7	fSa/mSa		12															
					R7	BMn																	

R10 cond, H	BorrID	R11	Grain size analysis	R11 water	R11 cond, H	BorrID	R12	Grain size analysis	R12 water	R12 cond, H	BorrID	R13	Grain size analysis	R13 water	R13 cond, H	BorrID	R14	Grain size analysis	R14 water	R14 cond, H	BorrID	R15	Grain size analysis	R15 water
		28.45					32.9					38 (39.25)					35.6					30.65		
	R11	grSa				R12	grSa				R13	grSa				R14	grSa				R15	Sa		
	R11	grSa				R12	grSa				R13	grSa				R14	grSa				R15	Sa		
	R11	grSa				R12	grSa		5		R13	grSa/mSa				R14	grSa				R15	grSa		
	R11	grSa				R12	grSa		5		R13	grSa/mSa				R14	mSa/fSa				R15	grSa		
	R11	grSa				R12	grSa		8		R13	grSa/mSa		10		R14	mSa/fSa				R15	mSa/fSa		
	R11	grSa				R12	grSa		4		R13	grSa/mSa		20		R14	mSa/fSa				R15	mSa/fSa		
	R11	grSa		0.5		R12	mSa/fSa				R13	grSa/mSa		20		R14	mSa/fSa				R15	mSa/fSa		
	R11	grSa		0.5		R12	mSa/fSa				R13	grSa/mSa		20		R14	mSa/fSa				R15	mSa/fSa		
	R11	grSa	sand	15	8.4E-04	R12	mSa/fSa				R13	grSa/mSa	sand	30	9.1E-04	R14	mSa/fSa				R15	mSa/fSa		
4.9E-05	R11	grSa		2		R12	mSa/fSa	fin sandsand		4.6E-05	R13	grSa/mSa		30		R14	mSa/fSa	sand		4.6E-05	R15	mSa/fSa		
2.0E-04	R11	grSa		1		R12	mSa/fSa	fin sandsand		4.6E-05	R13	fSa/mSa		15		R14	mSa/fSa				R15	mSa/fSa/Si		
	R11	mSa				R12	mSa/fSa				R13	fSa/mSa		20		R14	mSa/fSa				R15	mSa/fSa/Si		
	R11	mSa				R12	mSa/fSa				R13	fSa/mSa		5		R14	fSa/mSa/Si				R15	mSa/fSa/Si	sandig silt	
	R11	mSa/fSa				R12	mSa/fSa/Si				R13	fSa/mSa		2		R14	fSa/mSa/Si				R15	mSa/fSa/Si		
	R11	mSa/fSa				R12	mSa/fSa		4		R13	fSa/mSa		2		R14	fSa/Si				R15	mSa/fSa/Si		
	R11	mSa/fSa				R12	mSa/fSa		4		R13	fSa/mSa		2		R14	fSa/Si				R15	mSa/fSa/Si		
	R11	mSa/fSa/Si	fin sandsand		3.9E-05	R12	fSa/grSa		10		R13	fSa/mSa/Si				R14	fSa/Si				R15	mSa/fSa/Si		
4.6E-04	R11	mSa/fSa/Si				R12	grSa		10		R13	fSa/mSa/Si				R14	fSa/Si				R15	grSa/mSa	sand	30
3.0E-04	R11	mSa/fSa/Si				R12	mSa/grSa		50		R13	fSa/mSa/Si				R14	fSa/Si				R15	grSa	sand	30
	R11	mSa/fSa/Si				R12	mSa/grSa		60		R13	fSa/Si				R14	fSa/Si				R15	grSa	sand	60
	R11	mSa/fSa/Si				R12	mSa/grSa	sand	60	5.1E-04	R13	fSa/Si				R14	fSa/Si				R15	grSa	sand	60
	R11	mSa/fSa/Si				R12	mSa/grSa	sand	60	5.6E-04	R13	fSa/Si				R14	mSa/fSa/Si				R15	grSa/mSa/fSa	sand	30
	R11	mSa/fSa/Si				R12	mSa/grSa		30		R13	fSa/Si				R14	mSa/fSa/Si				R15	grSa/mSa/fSa	sand	20
4.7E-05	R11	mSa/fSa/Si	siltig sand		2.3E-05	R12	mSa/grSa		5		R13	fSa/Si	fin sandsandig silt			R14	grSa/mSa		40		R15	grSa/mSa/fSa	sand	30
1.7E-04	R11	mSa/grSa	siltig sand	40	2.3E-05	R12	mSa/grSa		5		R13	fSa/Si			1.0E-05	R14	grSa/mSa	sand	50	2.3E-04	R15	grSa/mSa/fSa	sand	30
	R11	mSa/grSa	sand	50	2.3E-04	R12	mSa/grSa		5		R13	fSa/Si				R14	grSa/mSa		50		R15	grSa/mSa/fSa	sand	30
	R11	mSa/grSa	sand	50	6.5E-05	R12	Si/Le		0		R13	fSa/Si				R14	grSa/mSa		20		R15	grSa/mSa/fSa	sand	50
	R11	mSa/grSa	sand	10	8.4E-05	R12	Si/Le	sand	0	3.5E-05	R13	fSa/Si				R14	grSa/mSa		20		R15	grSa/mSa/fSa	sand	5
	R11	mSa/grSa		10		R12	Si/Le	sandig silt	0	3.3E-06	R13	fSa/Si				R14	grSa/mSa		2		R15	Mn	grusig sand	0
						R12	Si/Le		0		R13	fSa/Si		2		R14	mSa/fSa		2		R15	Mn		0
						R12	Si		0		R13	fSa/Si		2		R14	mSa/fSa/Si		2		R15	grSa		10
						R12	grSa/Si		30		R13	fSa/Si		2		R14	mSa/fSa/Si		2					
						R12	grSa/Si		5		R13	grSa/Si		20		R14	mSa/fSa/Si	sand	2	4.9E-05				
											R13	grSa/Si		50		R14	grSa/mSa/fSa		10					
											R13	grSa/Si		5		R14	grSa/mSa/fSa		10					
											R13	grSa/Si	grusig sand			R14	grSa/mSa/fSa		10					
											R13	grSa/Si		50	6.7E-04									
											R13	grSa/Si		80										

R15 cond, Hz	BorrID	R16	Grain size analysis	R16 water	R16 cond, Hz	BorrID	R17	Grain size analysis	R17 water	R17 cond, Hz	BorrID	R18	Grain size analysis	R18 water	R18 cond, Hz	BorrID	R19	Grain size analysis	R19 water	R19 cond, Hz	BorrID	R20	Grain size analysis
		25.75					25.7					14.7					22.05					26.6	
	R16	grSa				R17	grSa				R18	Dy				R19	grSa				R20	grSa	
	R16	grSa				R17	grSa				R18	Dy				R19	grSa		5		R20	grSa	
	R16	grSa				R17	grSa				R18	Dy				R19	grSa		10		R20	grSa/fSa	
	R16	grSa				R17	grSa				R18	Dy				R19	grSa		30		R20	mSa/fSa	
	R16	grSa				R17	grSa/fSa				R18	Dy				R19	grSa		30		R20	mSa/fSa	
	R16	grSa				R17	mSa/fSa				R18	Dy				R19	grSa/mSa/fSa		30		R20	mSa/fSa/Si	
	R16	grSa		water		R17	mSa/fSa				R18	Dy				R19	grSa/mSa/fSa		10		R20	mSa/fSa/Si	
	R16	grSa		2		R17	mSa/fSa				R18	Dy/grSa				R19	grSa/mSa/fSa		10		R20	mSa/fSa/Si	
	R16	grSa	sand	5	1.0E-03	R17	mSa/fSa				R18	grSa		60		R19	grSa/mSa/fSa		30		R20	mSa/fSa/Si	
	R16	grSa/fSa				R17	mSa/fSa				R18	grSa		60		R19	grSa/mSa/fSa		30		R20	mSa/fSa/Si	
	R16	fSa				R17	mSa/fSa				R18	grSa		60		R19	grSa		60		R20	mSa/fSa/Si	
	R16	fSa				R17	mSa/fSa				R18	grSa		60		R19	grSa		60		R20	mSa/fSa/Si	
1.0E-05	R16	fSa				R17	mSa/fSa		30		R18	grSa/Le		30		R19	grSa	grusig sand	60	2.9E-03	R20	mSa/fSa/Si	
	R16	fSa/Si				R17	grSa/mSa/fSa		40		R18	grSa/Le		5		R19	Sa		60		R20	mSa/fSa/Si	
	R16	fSa				R17	mSa/fSa		3		R18	grSa/Le		1		R19	Sa		60		R20	mSa/fSa/Si	
	R16	fSa				R17	mSa/fSa									R19	grSa		60		R20	mSa/fSa	
	R16	fSa	sand		4.2E-05	R17	mSa/fSa									R19	Sa	sand	60	4.60E-04	R20	mSa/fSa	
1.4E-04	R16	fSa				R17	mSa/fSa		3							R19	Sa		40		R20	mSa/fSa	
4.6E-04	R16	mSa/fSa				R17	mSa/fSa									R19	Sa		20		R20	mSa/fSa	
2.3E-04	R16	mSa/fSa				R17	mSa/fSa		3							R19	Sa		10		R20	mSa/fSa	
5.1E-04	R16	mSa/fSa/Si				R17	mSa/fSa									R19	grSa/Mn		5		R20	mSa/fSa	
2.3E-04	R16	mSa/fSa/Si				R17	mSa/fSa		5							R19	grSa/Mn		1		R20	mSa/fSa	sand
8.4E-05	R16	grSa/Le		1		R17	grSa/mSa/fSa		40												R20	mSa/fSa	
2.0E-04	R16	grSa/Le	grusig sand	5	8.4E-05	R17	grSa/mSa/fSa		5												R20	grSa/mSa/fSa	sand
2.8E-04	R16	grSa/Le		5		R17	grSa/mSa/fSa		5												R20	mSa/fSa	
2.4E-04	R16	grSa/Le																			R20	Mn	
7.8E-04																					R20	Mn	
6.7E-04																							
2.6E-04																							

R20 water	R20 cond, Hz	BorrID	9201	Grain size analysis	9201 water	9201 cond, Hz	BorrID	9202	Grain size analysis	9202 water	9202 cond, Hz	BorrID	9801	Grain size analysis	9801 water	9801 cond, Hz	BorrID
			50		Malmbergs			28.4		Malmbergs			12				
		9201	grSa/Si				9202	Sa				9801	fSa				
water		9201	grSa/Si				9202	Sa				9801	fSa				
		9201	grSa/Si				9202	Sa				9801	fSa				
		9201	siSa				9202	siSa				9801	fSa				
		9201	siSa				9202	siSa				9801	mSa/fSa				
		9201	mSa/fSa/Si		God		9202	siSa				9801	mSa/fSa				
		9201	grSa/mSa		Mkt god		9202	fSa/mSa				9801	mSa/fSa				
		9201	grSa/mSa		Mkt god		9202	fSa/mSa				9801	fSa/mSa		2		
		9201	grSa/mSa/fSa		God		9202	fSa/mSa				9801	fSa/mSa		5		
		9201	fSa/mSa		Måttlig		9202	fSa/mSa				9801	fSa/mSa		10	3.15E-04	
		9201	fSa/Si		Liten		9202	fSa/mSa				9801	mSa/fSa		6		
		9201	fSa/Si				9202	fSa/mSa				9801	mSa/fSa		20		
		9201	fSa/Si				9202	fSa/mSa									
		9201	fSa/Si				9202	fSa/mSa					Not driven				
		9201	fSa/Si				9202	fSa/Si					to bedrock				
30		9201	fSa/Si				9202	fSa/Si									
30		9201	fSa/Si				9202	fSa/Si									
4		9201	fSa/Si				9202	fSa/Si									
5		9201	fSa/Si				9202	fSa/Si									
5		9201	fSa/Si				9202	fSa/Si									
40		9201	fSa/Si				9202	fSa/Si									
40	5.6E-04	9201	fSa/Si				9202	fSa/Si									
30		9201	fSa/Si				9202	grSa/mSa		Måttlig							
30	9.4E-05	9201	fSa/Si				9202	grSa/mSa		Mkt god							
10		9201	Si				9202	fSa/mSa									
0		9201	Si				9202	fSa/Si									
0		9201	Si				9202	fSa/Si									
		9201	Si				9202	grSa/mSa/fSa		Mkt god							
		9201	Si				9202	grSa/mSa/fSa		God							
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		9201	inget prov														

C Report to developers of conceptual models

The following report was handed to the professionals in hydrogeology for developement of conceptual models. During the advance of this thesis, some changes has been undertaken from what is stated in this report. The outcome of the models have been changed from not looking at drawdown specifically near the wetland Toren but to some different locations in the modelling domain in addition to the induced infiltation from Lilla Kleven. Point 6 and 7 in chapter 3.1 in the following report, have mainly been undertaken by the author of this thesis. Figures and appendices has been removed due to copyright reasons. The most relevant figures, such as locations of boreholes and borehole log data can however be found in the main report and its appendices.

Agnes Danielsson
Chalmers University of Technology
31 oktober 2018

Description of Varnum aquifer for construction of conceptual models

1 Background

This report is produced within a master thesis at the department of Architecture and civil engineering at Chalmers technical university, which aims to investigate the uncertainties in groundwater modelling. Specifically, the thesis investigates uncertainties originating from assumptions made in constructing the conceptual model, that is the basis for numerical models. The method of the thesis is to let some experts on ground water modelling construct one conceptual model each. These will be turned into numerical models by the author of the thesis, calibrated and run for a future scenario for which the result will be compared. You as a reader of this report is one of the groundwater modelling experts that will construct one of these conceptual models.

In this report, the geological and hydrogeological conditions for the case aquifer Varnum in South west of Sweden, are described. The intention has been to include a summary of all relevant material from previous investigations that have been made in the area. On this information, your conceptual model will be built on. The data needs to be interpreted into your conceptual model. What should be specifically included in the conceptual model is described later in this report. Additionally, a self-review formulary about the model's uncertainties is asked to be filled in.

2 Site description

Varnum is situated in the South west of Sweden, in the municipality Borås, figure 1. The area is rural, and the vegetation is mainly farmland and some forest. Several lakes and streams are present. Scattered settlement exists, which are summer houses and permanent residents. The aquifer of Varnum is situated in a Valley that has an altitude of approximately 170-175 m.a.s.l. and is surrounded by areas of higher altitudes, approximately 200-270 m.a.s.l. The area has consequently not been under the highest coastline. The topography can be seen in maps in appendix 1 and 6. The aquifer has been in focus of earlier investigations, aiming to explore the possibility to use it as a municipal raw water source (Scandiaconsult, 2003). No such plans have been implemented. Neither any other major extraction is made from the aquifer.

This investigation together with other descriptions of the area have been the basis for the following description of the geology, hydrogeology and hydrology. See the bibliography list for detailed references.

Figure 1 Location of the Varnum aquifer at a geological map where green is glaciofluvial material

2.1 Geology

2.1.1 Description in literature

The Varnum aquifer consists of glaciofluvial deposits as a part of the Rångedala esker, which stretches north-south in a fracture zone in the same direction, and ice lake sediment. This fracture zone is crossed by another fracture zone going east west, where the glaciofluvial deposits has an extended width. The extension of the Varnum aquifer in plane and general soil types, interpreted by SGU are shown in appendix 1, 4 and 5. Its area is around 8 km^2 (Lång & Lindh, 2012). South of their definition of the aquifer, the glaciofluvial deposits continues.

In the description to the earth deposit map Borås SO by Hilldén (1984), the following is found (for referred locations see appendix 4 and 6). The esker goes superficial in the north part of the glaciofluvial formation and between the lakes Tåsjön and Stora Kleven. North of Tåsjön, very coarse gravel has been found. In the central parts, by Varnum church, a glaciofluvial delta formation is present in a plane at a level of 175 m. 0,3-1 m gravel above stratified sand and some few gravel layers has been registered in an extraction pit 400 m south of Varnum church. In the valley south of the aquifer, the esker has ridge formations. Between Finnekumla and Rångedal, the esker is wide and rises maximum 10 m above its surroundings. It has been seen in an extraction pit that esker material is here covered by partly significant thick layers of sand and coarse silt.

Further, a lake named Toarpsissjön, embanked by ice during the time of glacial melting, is described. The lake was situated in the north sloping valley south of Finnekummla and embanked by the ice front retrieving north-east. The lake was drained in several steps but fully emptied first when the ice front passed Finnekummla (Hilldén, 1984). Finnekummla is situated in the southern part of the aquifer. A map of the lake at some different stages, is shown in appendix 9.

In the end of the 1900th century, the water level in lake Marjön was lowered some meters to allow for land exploitation. This results in that the area around the lakes Marsjöarna has been a previous lake bottom, consisting mainly of sand with a depth of one meter. Under the sand, coarse silt/fine sand is reported (Hilldén, 1984).

The soil depth in the aquifer varies, with the central part of the aquifer being deepest. Surrounding the aquifer, the soil depth is shallower, mainly consisting of till. A soil depth map is shown in appendix 3. A bedrock map with fracture zones is found in figure 2. The bedrock consists mainly of gneiss with a dominating strike of west-east direction (Lång & Lindh, 2012).

2.1.2 Investigations

Several investigation boreholes and some trial pits have been made. Locations of these has been marked in appendix 5, 7 and 8. Boreholes named R1-R20 were drilled as a part of the investigation by Scandiaconsult in 1999. Boreholes 9201, 9201 9801 were drilled earlier in the same decade but described in the same report (Scandiaconsult, 2003). The remaining locations has been found in SGU's map generator or in SGU's description of the aquifer (Lång & Lindh, 2012). Observed materials are presented in the attached excel-file *Boreholes*. Majorly, sand of different grain size and silt has been recorded. Most borings have been driven to expected solid ground. When not, this is stated. It must be noticed that the materials reported has been classified ocular in field by the drill operator on samples gained by flushing. For samples from some holes and depths it has also been made grain size analysis. The soil classifications from these are reported in the attached *Borehole* file at their corresponding depth next to the ocular classification. Some additional geologic information exists from private wells in SGU's well archive. This information is found in the attached GIS-files (some of the information from the investigation boreholes is also attached in this format).

In figure 2, one of the trial pits, which is located close to R20, is shown. Some trial pits north of Fännelundasjön (depth of 3-4,8 m) shows sandy sediments. In a trial pit west of Fännelundasjön, till was found on a depth of 4,5 m.

Six seismic investigations from which documentation has been found that have been made in the area. The location of these are shown in appendix 7. Profile interpretations received from SGU for sm19_boras, sm17_boras and s112_83014 is shown in appendix 16, 17 and 18. Investigation P1, P2 and P3 was performed in 1991 in the beginning Borås raw water resource investigation. No data from these has been found but an interpretative report by (Scandiaconsult Väst AB, 1992). They have not been able to draw any strong conclusions about the soil type or location of potential coarser esker sediments embedded in the finer sandy deposits from these investigations. A maximum soil depth of 60 m was found. Their interpretation of soil depths from the investigations is shown in appendix 11. In the report it is described that the south-north and east-west directed valleys crossing at Varnum, most probably are caused by fracture zones. At their crossing, the bedrock is probably further weakened which causes the substantial large soil depths at this location.

Figure 1.Trial pit close to R20.

The borings in the central part of the aquifer R1-R20 and 9201, 9201 9801 showed depths between 15 to 50 m, where the depth increases south towards the Marsjö lakes and west from Mellsjön to Lilla Kleven (Lång & Lindh, 2012; Scandiaconsult, 2003). Between the lakes Marsjöarna, depths of 57 m have been found from an earlier seismic investigation (Hilldén, 1984).

2.2 Hydrogeology

The hydraulic conductivity for samples from the boreholes has been calculated from grain size analysis curves. These are shown in the file *Borholes* and summarized in appendix 10.

During the raw water source investigation for Borås (Scandiaconsult, 2003), three test pumpings were performed and one-year measurements in observation wells installed in the boreholes described above. The location of observation well filters has not been found but, it is stated that all pipes were driven to solid bottom, except from three which was driven to a depth of ten meter. Also, lake levels were measured. The one-year measurements, which goes from September 1999 to December 2000, are found in appendix 15.

The location of the wells used in the test pumpings, B1 and B2, are shown in appendix 7. B1 have a filter placed in a depth between 18 to 28 m and B2 a filter at depth 11-17 m. The material surrounding B1 is mainly medium sand to gravely sand with some thin layers of silt. B2 is surrounded by gravely sand with finer material above.

The first test pumping was made 20th September to 4th October 2000. Approximately 11,6 l/s were pumped from well B1. The drawdown at pump stop in the pumping well was approximately 1,5 m. Groundwater heads recovered after approximately 10 days after pump stop.

The second test pumping was performed 15th may to 30th may 2001. Approximately 16,7 l/s were pumped from well B2. A time-drawdown curve is shown in appendix 12 for the well and the observation wells for this pumping. Groundwater heads recovered after approximately 12 days after pump stop. Changes in the water quality was observed during this test pumping. Documentation on these details has however not been found.

A third longer test pumping was made 17th December to 2001 to 8th April 2002 in well B1. Approximately 20 l/s were extracted. During this pumping, precipitation was measured locally. Measured heads, level in Lilla Kleven and precipitation is shown in appendix 14. Drawdown vs time is shown in appendix 13. Changes in the water quality was not observed during this test pumping.

The analysis of the pumpings were made as an open aquifer with delayed water table response with Neumans method, and recovery with Theis & Jacob with correction for an open aquifer. In table the result of the analysis is summarized. For more detail on the analysis and its result, the reader is referred to the attached documents *Analysis _testpumps_1-3*. Unanalyzed observations during test pumpings are also attached in *Observations_testpump_1-3*.

Table 1. Summary of the analysis of the test pumpings. Reproduced from (Scandiaconsult, 2003).

Areas	**Transmissivity (m/s^2)**	**Hydraulic conductivity (m/s)**	**Storage coefficient (open)**
West of the road R12-R14	$1,0\text{-}1,7 \times 10^{-2}$	$4,0\text{-}7,0 \times 10^{-4}$	0,06-0,20
East of the road R5-R7	$1,0\text{-}1,7 \times 10^{-2}$	$4,0\text{-}7,0 \times 10^{-4}$	0,06-0,20
North-east part, R11-R16	$2,0\text{-}2,5 \times 10^{-2}$	$1,0\text{-}1,2 \times 10^{-4}$	Analysis difficult

2.3 Surface water and hydrology

There are several streams and lakes in the area. The general flow pattern is shown in appendix 6. There are three incoming flows that meet in the eastern Marsjön. From north, a stream network coming into Fännelundasjön, continues south towards the eastern Marsjön. At SMHI wattenwebb the area of this watershed is reported to be 59,6 km^2. From east the river Viskan flows into the area. In the inlet to eastern Marsjön it has a catchment area of 201,1 km^2. From the south, the stream Rångedalaån flows into Marsjön. The area of its watershed is reported to be 47,3 km^2. The water flows out west from Marsjön, into Viskan. Additional to the major watercourses there are also several minor streams, going from the surrounding higher areas into the surface waters in the central parts. These can be identified in the map in appendix 6. Except from the lakes surrounding the central part of the aquifer, there is also a wetland called Toren, directly east of the church. Lake levels during one year in lakes surrounding the central part of the aquifer, measured by Scandiaconsult (2003) are reported in appendix 16 and in appendix 15 together with the observation wells.

The mean annual precipitation for the normal period (1961-1990) is around 1000 mm/year for the area. According to modelled data from hydrogeological model S-HYPE, SHMI, the evapotranspiration for the normal period, is approximately 400-500 mm/year (https://www.smhi.se/vadret/vadret-i-sverige/vattenbalans).

In table 2 the monthly precipitation for the years 1999 and 2000 at the climate station 73480, Rångedala A, is given. It is situated approximately 4 km south east of the central part of the aquifer.

SGU has approximated the catchment area for the aquifer, which is shown in appendix 1. They assume there is a recharge to the aquifer from direct precipitation on the aquifer and inflow from the surrounding till. They have roughly approximated the groundwater recharge from the primary catchment, (the area where the aquifer is in direct contact with the surface and the dominating part of the net precipitation reaches the aquifer) which has an area of 5,8 km^2 to be 100 l/s (Lång & Lindh, 2012).

Table 2 Precipitation per month in mm, at year 1999 and 2000 at Rångedala A climate station.

	1999	**2000**
Jan	134,5	126,4
Feb	59	116,3
Mar	74,4	60,9
Apr	105,3	98,3
May	56,7	74,5
Jun	118,5	85,8
Jul	67,6	72,4
Aug	109,2	57,4
Sep	133,8	45,7
Okt	89,5	177,2
Nov	44,4	123,7
Dec	204,8	134,9
SUM	1197,7	1173,5

3 The groundwater model

The imaginary scenario that should be investigated with the model is to assist a small town/village to decide if the aquifer can be used as a raw water source with average pumping of 50 l/s. In the wetland Toren, a unique biotope has been found that is sensitive to groundwater level changes. There is also a concern that extraction could cause infiltration from a lake with water of low quality. The decision makers are therefore interested to know what the consequences could be for these two issues. To aid solving this problem a model will be set up and used to run a future scenario of pumping 50 l/s equally divided between two wells, located at B1 and some meters north of it. The aim is more specifically to investigate: 1) the induced infiltration from the lake Lilla Kleven and 2) the draw down at the location of R19.

The numerical ground water models, built on the conceptual models, will be set up in GMS/MODFLOW. The models should be calibrated in steady state conditions. Data available for calibration is heads and levels measured during one year, see appendix 15. It is your choice how the data should be used and which calibration target should be met.

The models will be calibrated inverse stochastic, i.e. produce sets of parameters that fulfill the calibration criteria and then run the future scenario with these parameters sets. This will give the possibility to also investigate uncertainties within each model, originating from parameter uncertainties. Parameters that have the possibility to be varied in the software, the so called calibration parameters, are hydraulic conductivity (horizontal and vertical, or anisotropy) and recharge. It is your decision which parameters that should be set as calibration parameters. Parameters fields for the chosen calibration parameters will be created from pilot points.

3.1 The conceptual model

The conceptual model that you will set up should include all assumptions needed to set up and run a numerical model. If you think any computational processing of data should be done as input to the numerical model, please state so. GIS data available are digital elevation map (2x2m), soil depth (10x10m) and bedrock surface (50x50m) (which do not correspond perfectly well to borehole depths), hydrologic features such as lakes and streams. Please state if any of these or others that you know about should be used. Let me know if other information than the one in this document is needed, if you want any data in another format and if something needs to be clarified. Some iterative dialogue process is most likely going to be needed when I set up the numerical model, e.g. if adjustments must be done to the conceptual model be able to calibrate the model. Please also fill in the questionnaire in the following section. When the modeling work is finished, you will also be asked to answer some additional questions.

The following points should be included in the conceptual model. Text can be written for each of the points here or in a separate document. Some geological maps follow that can be used to draw on. Cross sections or other drawings can be sketched on blank paper.

1. The geographic extent and types of boundary conditions. You can use the following maps for drawing boundaries in plane. For other boundaries, explain in text and/or draw cross sections.

2. Sources and sinks and if you have any specific wish of mechanisms that you want to be reflected for these (or specific MODFLOW packages). Description of the groundwater flow system (flow into, out of and within the aquifer). You can use the following maps to draw on and explain in text.

3. Geological/hydrogeological units/stratification. Draw in plane and/or necessary cross sections and explain in text.

4. Grid size, orientation of grid and eventual locations for refinement (only structured rectangular grid will be used).

5. Parameters. Which should be set as calibration parameters and which should be varied (see restrictions in the section 3 above). Please include head and stages for specified head or general head boundaries/features. List them and their values.

Fixed parameters	Value

Calibration parameters	Mean	Min	Max

6. Pilot point locations/density for calibration parameters. Can be drawn on the following maps and/or described in text.

7. Variograms for interpolation between pilot points and relation between pilot points (can be discussed, maybe some result from model runs is needed first)

8. Calibration data. Which data and locations should be included (no need to state exact numbers but explain how the data available should be used). What should the calibration target be, expressed as total error (sum of square weighted residuals).

D Questionnaire

Following is a questionnaire that will be used in addition to the modelling result in the investigation of uncertainties. Mainly, questions comes from a checklist developed by Risbey et al. (2001) for quality assistance in environmental modelling with adjustment to adapt to this study. The key output variables for the model that are referred to in some of the following question, are drawdown at some different locations in the Varnum area and induced infiltration from the lake Lilla Kleven as result of drinking water extraction in wells close to this lake. The (imaginary) aim of the model is provide decision support in implementation of such extraction.

1. **What role should models in general play in setting policy on this issue?**

   (a) None

   (b) Heuristic or weak guide

   (c) A general guide

   (d) Policies directly keyed to specific model results.

Answers: Modeller A: c Modeller B: c Modeller C: c

2. **How do you judge the strength in the input data (quality in the data used to construct the conceptual and numerical model, parametrize it and calibrate it)? Is any input data lacking?**

Modeller A: Quite weak since the modelling is steady state for one specific date. I would have preferred continuous measurements over 1-2 years and a long time pump-test (one month) as calibration data. Now I am not sure if all observation wells are in the same geologic unit (the esker). If this is the case, I would also prefer more observation wells in other units to better understand the interactions in the system. Would also like continuous measurements in the lakes and flow measurements in the streams.

Modeller B: Strength of the data is moderate. There are drillings and detailed information on stratigraphy in the central aquifer area, but much less info in the outer parts. There are also results from test-pumping performed earlier, as well as results from earlier geophysical investigations. The quality of the data is considered to be accurate.
Information on sediments and their permeability is lacking, which makes some of the model parametrization (e.g. conductance between surface water bodies and the aquifer) highly uncertain. Also, detailed information on groundwater recharge is lacking.
Information on groundwater quality is sparse and information regarding the impact on water quality from extensive pumping is lacking.
Since drillings in the area are fairly sparse and concentrated to the central parts of the area, there is very limited hard data on geological and hydraulic boundaries. Boundary conditions therefore to a large extent have to be based on interpretation of imprecise geological information.
Water level measurements are only available for rather short times.

Modeller C: In general, the spatial coverage of observation wells is high. Unfortunately, most of them are located in a small area in the center of the model, leaving other part of the model domain blank. Parametrizing and calibrating a highly dynamic system by using annual average values certainly decreases the significance of the numerical model.
Information on the connection between the major lakes and the groundwater body would be an essential upgrade for the construction of a valid conceptual model.

3. **Which parameters and input variables (all numerical values used to describe the system, not only calibration parameters) included in your model do you find most uncertain?**

Modeller A: Recharge and conductance of lakes and streams.

Modeller B: Hydraulic conductivity (transmissivity) and conductance

Modeller C: The hydraulic heads, both in spatial and temporal distribution (cf. question 2). The application of a single vertical hydraulic conductivity for such a complex and dynamic setting (especially for pumping test analysis) also causes uncertainty problems (high range in hydraulic conductivity).

4. **Which parameters and input variables (all numerical values used to describe the system, not only calibration parameters) included in your model do you think are most sensitive, in aspect of result of the key output variables?**

Modeller A: Hydraulic conductivity and recharge.

Modeller B: The main uncertain parameters in order of importance:

i. Hydraulic conductivity of aquifer materials (transmissivity) due to uncertain geological stratification and compositions (grain size distribution) of aquifer materials
ii. Permeability on sediments in lakes and streams, i.e. conductance.
iii. Groundwater recharge
iv. Geological boundary conditions (locations)
v. Water level observations (for calibration)

Modeller C: Certainly the conductance of the head dependent BC (especially of Lilla Kleven) and to lesser extent the hydraulic conductivity.

5. **Which of the assumptions you made to construct the conceptual model do you find most uncertain?**

Modeller A: The stratigraphy of the esker, now embedded layers with fine graded sediments are not included. Also the assumptions on hydraulic contact between lakes and the esker.

Modeller B: See above –boundary conditions and geologic stratification.

Modeller C: The hydraulic connection between the lakes and the aquifer is a basic assumption of my conceptual model.

6. **Which assumptions in the conceptual model do you think have most implications on the result (for the key output)?**

Modeller A: I think this question needs to be answered together with the modeller. But I would assume the stratigraphy of the esker, if fine layers are embedded or not.

Modeller B: Boundary conditions and geologic stratification.

Modeller C: The hydraulic connection between Lilla Kleven and the aquifer (head dependent BC).

7. **Are there other plausible alternative conceptual models for representing the system? Describe them.**

Modeller A: Yes, different embedment of fine graded sediments and how they are connected. Also assumptions regarding how lakes and streams are connected to the hydrogeological system.

Modeller B: One alternative model (however, less likely) would be a smaller aquifer area (hydraulic barriers closer to the investigated area) and perfect hydraulic connection between lakes and streams and the aquifer.
Another alternative would be to have a more detailed geological stratification of the aquifer, based on a geological interpretation taking into full account the very complex formation of the delta deposit and subsequent ice-margin lake sediment deposition.

Modeller C: A large aquifer system based on the extension of the unconsolidated rock. The whole model domain is bounded by no-flow BC and the recharge from the surrounding till is considered by the ordinary recharge package (additional to direct recharge).
→Parameter uncertainty in most parts of the model would be high due to missing observation values.

8. **How do you expect results (for the key output variables) to vary when using different conceptual models?**

   (a) Trivially

   (b) Moderately

   (c) Radically

Answers: Modeller A: b Modeller B: c* Modeller C: c
* Taking into account the alternative conceptual model described above

9. **How was the location of boundaries and types of boundary conditions defined? Describe the reasons for made choices.**

Modeller A: First a greater model was defined from the area's watershed. Then this model was calibrated and the calibrated levels was used to define constant head levels at the end of a smaller model.

Modeller B: Boundaries were defined from geological interpretation of the area, based on available geological information (drillings, maps), knowledge of the geological history and information of surface water bodies (lakes and streams) of the area. Recharge conditions were defined based on general information on precipitation and evapotranspiration in combination with the hydrogeological conceptual understanding (unconfined aquifer) of the area.

Modeller C: Till/bedrock: Aquitard, only considered as additional recharge (recharge package) -> no-flow BC
Clay-silt: Aquiclude -> no-flow BC
Thin soil cover: no-flow BC (most likely it would cause numerical instability, minor influence on model results (water budget): small areas, not close to the pumping well)
Lakes: const. head BC (based on the assumption of hydraulic connection to the aquifer; general flow pattern on a larger scale)
Lilla Kleven: head dependent BC (based on the assumption of hydraulic connection to the aquifer; const. head boundary would cause to "abstraction" of the pumped water mostly from the lake)

10. **Would other types and location of boundaries be possible? If so, what would the implications for the result be (for key outputs)?**

(a) Trivial

(b) Moderate

(c) Radical

Answers: Modeller A: b* Modeller B: c** Modeller C: b-c
* This depends on how much water that is coming from the constant head levels in the water balance. If this amount is small, then maybe other boundaries would not affect the result to a large extent ** Taking into account the alternative conceptual model described above

11. **How was geological/hydrogeological units/stratification defined? Describe the reasons for made choices?**

Modeller A: See comment regarding simplification of esker with embedded layers. The geology was simplified to enable numerical modelling with stochastic PEST, which is numerically demanding.

Modeller B: Based on drillings and geological interpretation based on drillings, maps and knowledge of the geological history (formation processes) of the area.

Modeller C: The definition of only one layer representing the unconsolidated rock was chosen after discussing the issue with the executing person. The original idea was definition of three different units:

- gravel (Gr)/grusig sand (grSa)

- sand (mSa/fSa)
- siltig sand (siSa)/silt (Si)

According to the grain size analysis the hydraulic conductivity differs in several magnitudes between those units. Without any information about the screen location for the pumping well/observation well such differentiation is not feasible (calibration of values).

12. **Would other geological/hydrogeological units/stratification be possible? If so, what would the implications for the result be (for key outputs)?**

    (a) Trivial

    (b) Moderate

    (c) Radical

Answers: Modeller A: b* Modeller B: c** Modeller C: b
* see comment above regarding different layers ** See point 7 above. A more complex stratification model would result in larger variations in hydraulic conductivity (both in vertical and horizontal directions) resulting in substantially different hydraulic responses to groundwater abstractions in the area. The same is expected for a conceptual model with hydraulic boundaries located at different positions.

13. **How vulnerable do you think the model is to "hack and crack"? (Do you think it is possible to produce an arbitrary chosen output by tweaking the system?) If you were asked to change the main result of the model for this problem by a factor of 2 (doubled drawdown/doubled flow from the lake – possible to give separate answers for them), how much would you need to "tweak" the most sensitive parameter values or input variables.**

    (a) Barely-well inside range of expert opinion

    (b) Moderately-moving to tails of expert distributions

    (c) Radically-outside expert distributions

Answers: Modeller A: a Modeller B: b Modeller C: a

If you were asked to change the main result of the model for this problem by a factor of 10, how much would you need to "tweak" the most sensitive parameter values or input variables.

    (a) Barely-well inside range of expert opinion

    (b) Moderately-moving to tails of expert distributions

    (c) Radically-outside expert distributions

Answers: Modeller A: a/c* Modeller B: c Modeller C: b
* Depends if the gw is small or large in the initial case. Going from 1dm to 1m, then a. Going from 1 to 10 m, then c

14. **What is the level of accuracy required for model results to be useful in the policy process?**

    (a) Order of magnitude

(b) A factor of 2

(c) Better than 10 %

Answers: Modeller A: b Modeller B: b* Modeller C: c
*In my view model results must be handled using a probabilistic approach or using safety margins. I assume that the main result of interest is the potential abstraction of the well(s) placed in the aquifer.

15. **For this particular problem, model results can be used:**

(a) With high confidence

(b) With confidence

(c) With caution

(d) With extreme caution

Answers: Modeller A: Somewhere between b-c but have to look at the answers first. Modeller B: b Modeller C: c

What were the most important factors that led you to choose this ranking?

Modeller A -

Modeller B If the model is based on a sound conceptual understanding (from good and relevant geological and hydrogeological judgement and interpretation of available information) and carefully validated against measurements, model results should be possible to use with confidence. This must be based on an understanding that the model is not a true and full representation of the reality, but a realistic and useful approximation.

Modeller C The application of annual mean values for a highly dynamic system and the high degree of simplification applied on the numerical model.

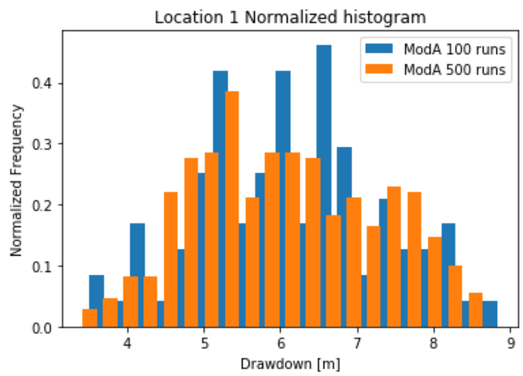
E Manual calibration model B

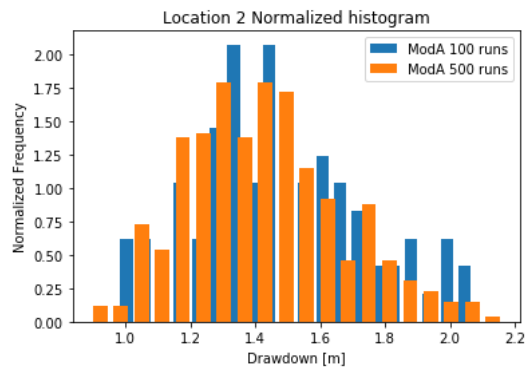
Computed drawdown in Model B in layer 3 with constant head boundary and head dependent boundary for Lilla Kleven, compared to test pump in B1 after 23 days.

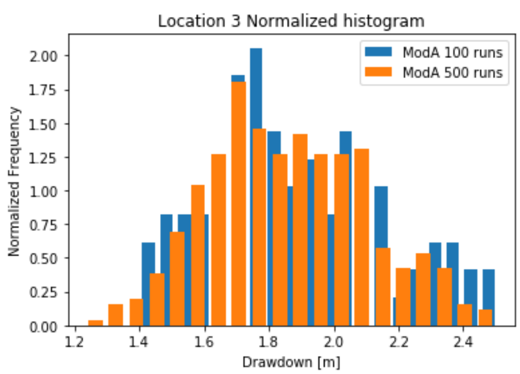
		Constant head BC all lakes	Head-depend BC Conductance = 10^-6 [1/m] Lilla Kleven (other lakes constant head)	Head-depend BC Conductance = 10^-7 [1/m] Lilla Kleven (other lakes constant head)	Head-depend BC Conductance = 10^-7 [1/m] all Lakes	Test pump, approximate values read from diagram
R12	Head [masl] vid Q=0	170,62	170,62	170,63	170,78	
	Head [masl] vid Q=20l/s	169,99	169,9	169,85	169,87	
	Drawdown [m]	0,63	0,72	0,78	0,91	0,82
R4	Head [masl] vid Q=0	170,62	170,64	170,64	170,78	
	Head [masl] vid Q=20l/s	170,21	170,08	170,01	170,02	
	Drawdown [m]	0,41	0,56	0,63	0,76	0,62
R13	Head [masl] vid Q=0	170,62	170,63	170,63	170,75	
	Head [masl] vid Q=20l/s	170,37	170,3	170,26	170,25	
	Drawdown [m]	0,25	0,33	0,37	0,5	0,48
R14	Head [masl] vid Q=0	170,62	170,63	170,64	170,79	
	Head [masl] vid Q=20l/s	170,34	170,28	170,21	170,23	
	Drawdown [m]	0,28	0,35	0,43	0,56	0,51
Flow from Lilla Kleven [l/s] during pumping Q=20l/s		8,90	3,8	0,7		

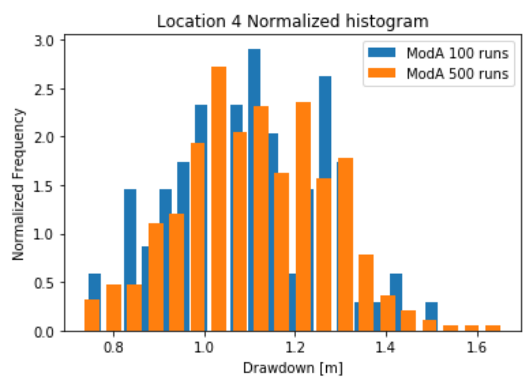
F 100 vs 500 realizations

	Mean 100 run [m]	Mean 500 run [m]	Std 100 run [m]	Std 500 run [m]
Location 1	6.11	6.10	1.18	1.19
Location 2	1.47	1.43	0.25	0.24
Location 3	1.88	1.86	0.27	0.24
Location 4	1.09	1.12	0.17	0.16

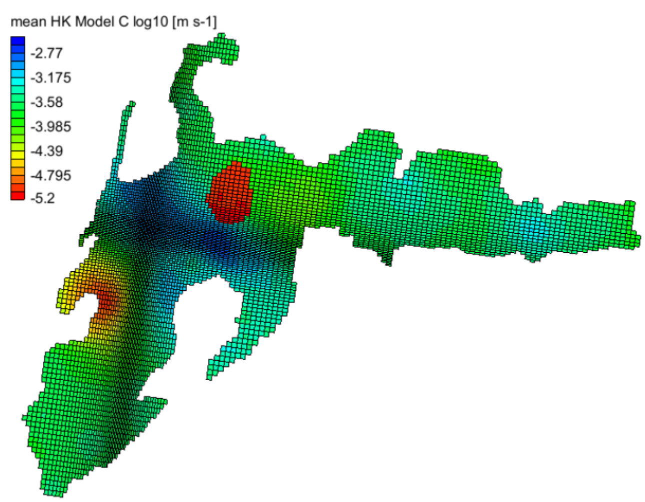


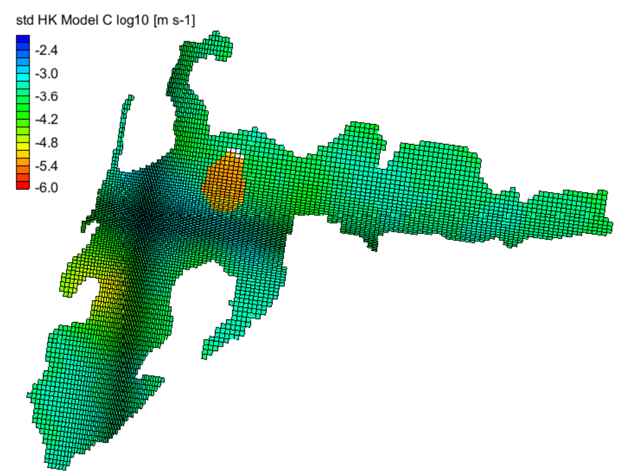


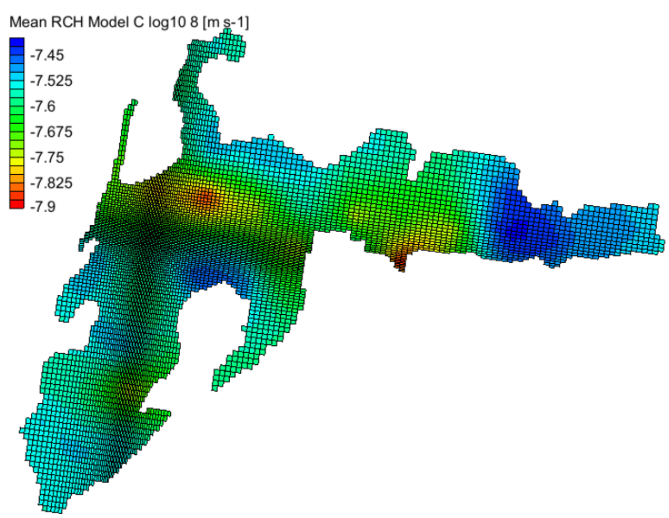


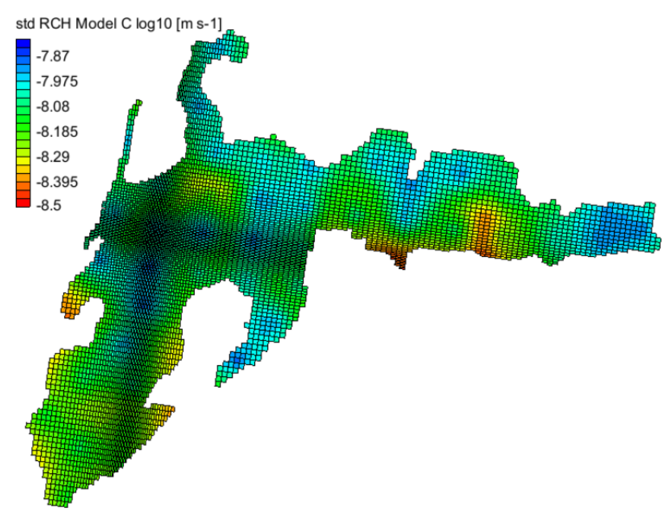


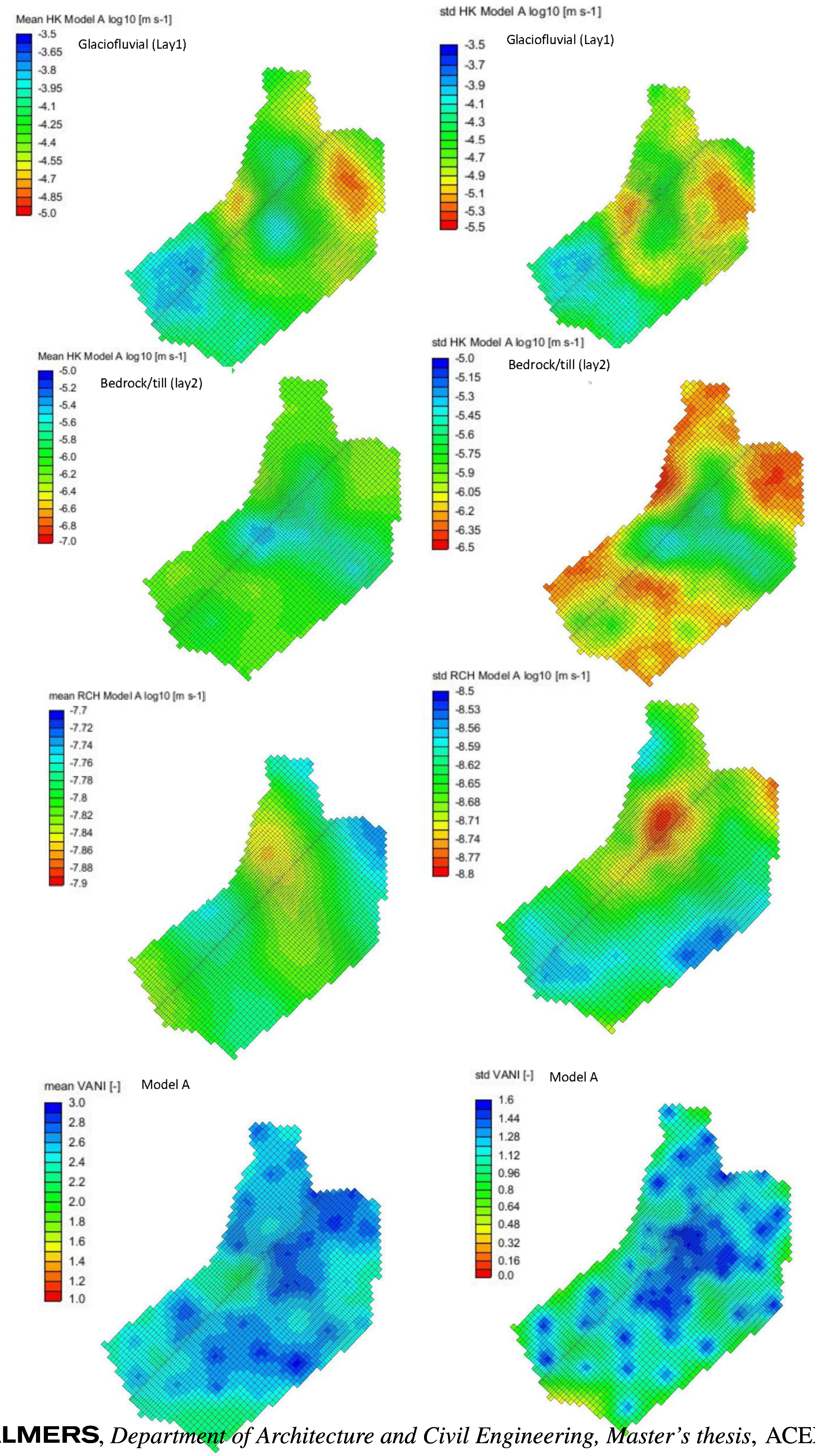
G Parameter fields in calibrated models

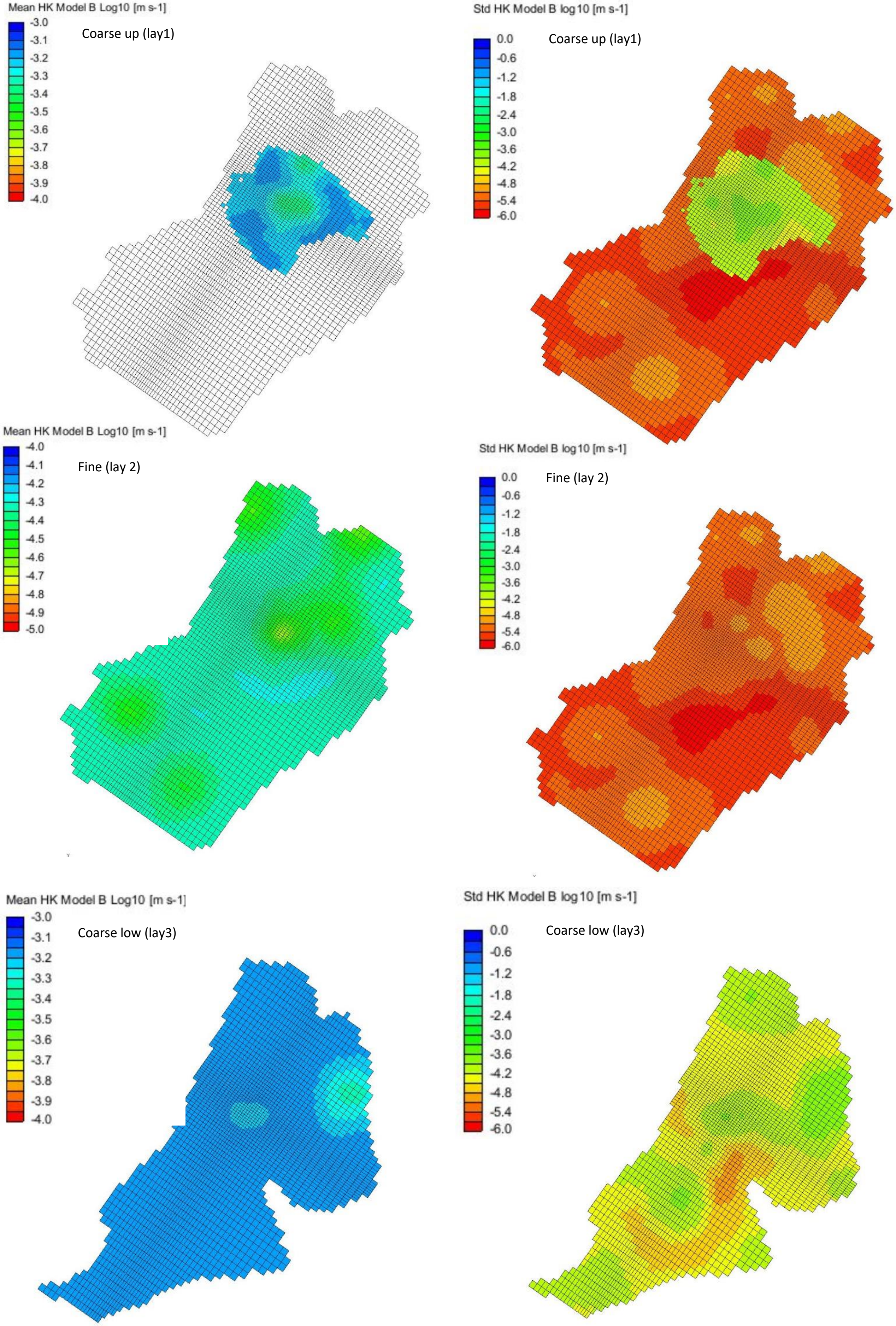









Mean HK Model A log10 [m s-1]
Glaciofluvial (Lay1)
-3.5 -3.65 -3.8 -3.95 -4.1 -4.25 -4.4 -4.55 -4.7 -4.85 -5.0
std HK Model A log10 [m s-1]
Glaciofluvial (Lay1)
-3.5 -3.7 -3.9 -4.1 -4.3 -4.5 -4.7 -4.9 -5.1 -5.3 -5.5
Mean HK Model A log10 [m s-1]
Bedrock/till (lay2)
-5.0 -5.2 -5.4 -5.6 -5.8 -6.0 -6.2 -6.4 -6.6 -6.8 -7.0
std HK Model A log10 [m s-1]
Bedrock/till (lay2)
-5.0 -5.15 -5.3 -5.45 -5.6 -5.75 -5.9 -6.05 -6.2 -6.35 -6.5
mean RCH Model A log10 [m s-1]
-7.7 -7.72 -7.74 -7.76 -7.78 -7.8 -7.82 -7.84 -7.86 -7.88 -7.9
std RCH Model A log10 [m s-1]
-8.5 -8.53 -8.56 -8.59 -8.62 -8.65 -8.68 -8.71 -8.74 -8.77 -8.8
mean VANI [-]
Model A
3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2 1.0
std VANI [-]
Model A
1.6 1.44 1.28 1.12 0.96 0.8 0.64 0.48 0.32 0.16 0.0


Mean HK Model B Log10 [m s-1]
-3.0 -3.1 -3.2 -3.3 -3.4 -3.5 -3.6 -3.7 -3.8 -3.9 -4.0
Coarse up (lay1)
Std HK Model B log10 [m s-1]
0.0 -0.6 -1.2 -1.8 -2.4 -3.0 -3.6 -4.2 -4.8 -5.4 -6.0
Coarse up (lay1)
Mean HK Model B Log10 [m s-1]
-4.0 -4.1 -4.2 -4.3 -4.4 -4.5 -4.6 -4.7 -4.8 -4.9 -5.0
Fine (lay 2)
Std HK Model B log10 [m s-1]
0.0 -0.6 -1.2 -1.8 -2.4 -3.0 -3.6 -4.2 -4.8 -5.4 -6.0
Fine (lay 2)
Mean HK Model B Log10 [m s-1]
-3.0 -3.1 -3.2 -3.3 -3.4 -3.5 -3.6 -3.7 -3.8 -3.9 -4.0
Coarse low (lay3)
Std HK Model B log10 [m s-1]
0.0 -0.6 -1.2 -1.8 -2.4 -3.0 -3.6 -4.2 -4.8 -5.4 -6.0
Coarse low (lay3)