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Environmental Engineering
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ABSTRACT FOR THESIS

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Abstract

Many valuable ecosystems such as springs, wetlands, lakes and rivers depend on the presence of groundwater. These ecosystems, known as groundwater dependent ecosystems (GDEs), are biodiversity hotpots and provide important habitats for many endangered species. In recent decades, groundwater over-abstraction, contamination and climate change have put serious pressure on groundwater resources and groundwater-dependent ecosystems. This has shifted water management towards fully-integrated approach in which groundwater, surface water bodies and dependent ecosystems are treated as one management unit. The current EU legislation and the corresponding Finnish laws require assessment of the impacts of various land uses and groundwater abstraction to GDEs. The role of groundwater in GDEs is not, however, in many cases thoroughly understood. For this reason, groundwater-surface water (GW-SW) interactions and their dynamics need further investigation. Integrated groundwater-surface water modelling is a unique method to study connections between surface water and groundwater, and thus it is a potential tool for evaluation of various anthropogenic or climatic effects on GDEs.

The aim of this thesis was to examine the performance of fully-integrated physically-based GW-SW modelling to simulate groundwater dependent ecosystems in a case study of the Kälväsvaara esker aquifer located in Northern Finland. The target was to create a model of the geologically complex esker and its adjacent areas that captures all type of GDEs present in the area i.e. fens, kettle hole lakes, streams and springs without their prior definition to the model. The study investigated how the model should be scaled and what information is needed to replicate the studied GDEs. For this purpose, a simple model was built using the fully-integrated physically-based GW-SW code HydroGeoSphere. The model was run in steady-state and it was calibrated manually by the try-and-error method. The model did not include the forestry ditch systems and it assumed homogeneity within various zones of overland and porous domains. The effect of evapotranspiration was represented in a lumped manner through the term of effective rainfall. The model results were evaluated by comparing the simulation outputs with the field measurements and expected trends for the variables where data was not available.

The employed model reproduced relatively well the measured groundwater and lake levels as well as other spatially-distributed variables such as saturation, water depths and GW-SW exchange fluxes. Majority of lakes, wetlands and streams emerged during simulations in a natural way as a result of geological and topographical conditions. In contrast, small scale GDEs such as springs were not so well represented by the model, indicating that small-scale GDEs are more challenging to model in a physically-based manner without detailed information on the geology around these water bodies. The overall good consistency between simulations and observations demonstrated that the fully-integrated physically-based GW-SW modelling can be a viable method to simulate various boreal groundwater dependent ecosystems, making it feasible tool to study effects of anthropogenic actions, such as pumping or climate change, on GDEs. The spatial and temporal analysis of exchange fluxes under various scenarios could enhance our understanding about the dynamic behavior of GDEs, role of groundwater in these ecosystems and their sensitivity to deterioration under transient hydrological and climatic stresses.

Additional Information

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Tiivistelmä

Monet arvokkaat ekosysteemit, kuten lähteet, kosteikot, järvet ja joet riippuvat pohjaveden läsnäolosta. Nämä ekosysteemit, niin sanotut pohjavedestä riippuvaiset (PV) ekosysteemit, ovat luonnon monimuotoisuudeltaan rikkaita ja tarjoavat tärkeitä elinympäristöjä monille uhanalaisille lajeille. Viime vuosikymmeninä liiallinen pohjavedenotto, pohjaveden saastuminen ja ilmastonmuutos ovat aiheuttaneet vakavia paineita pohjavesivaroille sekä pohjavedestä riippuvaisille ekosysteemeille. Tämän seurauksena vesitalous on siirtynyt kohti täysin integroitua mallia, jossa pohjavesiä, pintavesiä ja PV-ekosysteemejä käsitellään yhtenä vesienhoitoalueena. Nykyinen EU-lainsäädäntö ja vastaavat Suomen lait edellyttävät eri maankäytön ja pohjavedenoton vaikutusten arviointia PV-ekosysteemeihin. Pohjaveden rooli PV-ekosysteemeissä on kuitenkin monesti tuntematon. Tästä syystä tarvitaan lisätutkimuksia pinta- ja pohjaveden vuorovaikutuksista ja niiden dynamiikasta. Täysin integroitu numeerinen pohjavesi-pintavesi virtausmallintaminen on ainutlaatuinen menetelmä tutkia pinta- ja pohjavesien yhteyksiä, ollen täten potentiaalinen työkalu arvioimaan ihmistoiminnan ja ilmaston vaikutusta PV-ekosysteemeihin.

Diplomityön tavoitteena oli tutkia integroidun numeerisen pohjavesi-pintavesi virtausmallinnuksen kykyä simuloida PV-ekosysteemiä Pohjois-Suomessa sijaitsevan Kälväsvaaran tapauksessa. Tarkemmin, työn tarkoituksena oli luoda malli geologisesti monimutkaiselle harjulaajentumalle ja sen lähialueille siten, että alueella esiintyvät erityyppiset PV-ekosysteemit kuten letot, suppalammet, purot ja lähteet muodostuvat malliin ilman niiden erillistä määrittelyä mallin rakentamisvaiheessa. Tutkimuksessa selvitettiin myös, miten mallia pitäisi mitoittaa ja mitä tietoja tarvitaan mallintamaan alueen PV-ekosysteemejä. Tätä varten rakennettiin yksinkertainen malli käyttäen täysin integroitua numeerista pohjavesi-pintavesi HydroGeoSphere-virtausmalliohjelmistoa. Malli ajettiin ajan suhteen muuttumattomassa tilassa (steady-state) ja se kalibroitiin manuaalisesti yritys-ja-erehdys menetelmällä. Malliin ei sisällytetty erikseen metsäojituksia ja lisäksi maanpinnallisten ja maanalaisten vyöhykkeiden oletettiin olevan homogeenisia. Kokonaishaihdunnan vaikutukset huomioitiin keskitetyllä tavalla tehokassadannan termiä käyttäen. Mallin tuloksia arvioitiin vertailemalla simulaatioita kenttämittausten, tai havaintojen puuttuessa, odotettujen trendien suhteen.

Rakennettu malli jäljensi suhteellisen hyvin pohjaveden ja järvien pintojen havainnot sekä muita alueellisesti jakautuneita muuttujia kuten maan suhteellista kosteutta, pintavesien syvyyttä ja pinta- ja pohjavesien välistä vuota. Suurin osa alueen järvistä, kosteikoista ja puroista muodostui simulaatioiden aikana luonnollisella tavalla geologisten ja topografisten olosuhteiden seurauksena. Sen sijaan pienen mittakaavan PV-ekosysteemit kuten lähteet eivät olleet yhtä hyvin edustettuna mallin tuloksissa. Tämä viittaa siihen, että pienimuotoiset PV-ekosysteemit ovat haastavampia mallintaa fysikaalispohjaisella tavalla ilman yksityiskohtaista tietoa vesistöjä ympäröivästä geologiasta. Kaiken kaikkiaan hyvä yhtäpitävyys simulaatiotulosten ja havaintojen välillä osoittaa, että täysin integroitu pinta- ja pohjavesi mallinnus on soveltuva tapa simuloida eri PV-ekosysteemejä. Täten se on toteuttamiskelpoinen työkalu arvioimaan ihmistoiminnan kuten vedenoton tai ilmastonmuutoksen vaikutusta PV-ekosysteemeihin. Alueellinen ja ajallinen pinta- ja pohjavesien välinen analyysi erilaisissa skenaarioissa voisi lisätä tietoutta PV-ekosysteemien dynaamisesta käyttäytymisestä, pohjaveden roolista niissä ja niiden mahdollisesta heikentymisestä ajan suhteen muuttuvien hydrologisten- ja ilmastollisten rasitusten alla.

Muita tietoja

PREFACE

The purpose of this thesis was to examine how various groundwater-dependent ecosystems, such as fens, kettle lakes, streams and springs can be simulated by integrated groundwater-surface water modelling approach. The investigation was carried in a case study of the Kälväsvaara esker aquifer. The study was conducted at University of Oulu, Water Resources and Environmental Engineering Research Group during autumn 2015. The financial support was provided by the University of Oulu and Maa- ja Vesitekniikan tuki ry.

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To Uula and Tupsu.

Thank you all,

Oulu, 25.11.2015

Anna Jaros

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SYMBOLS AND ABBREVIATIONS

3-D	Three-dimensional
asl	Above sea water level
DEM	Digital elevation model
d_0	Depth of the surface flow
ELY-centre	Centre for Economic Development, Transport and the Environment
EU	European Union
GDE	Groundwater dependent ecosystem
GW-SW	Groundwater - surface water
HGS	HydroGeoSphere
h_0	Elevation of water surface
$\mathrm{h_d}$	Rill storage
$\mathrm{h_o}$	Obstruction storage
$\mathrm{h_s}$	Combined height of depression storage and obstruction storage
$\mathbf{K}$	Hydraulic conductivity tensor of porous medium
K_{0x}, K_{0y}	Surface conductances in x- and y-directions
K_{XY}	Horizontal saturated hydraulic conductivity of porous medium
K_Z	Vertical saturated hydraulic conductivity of porous medium
k_r	Relative hydraulic conductivity
L	Primary dimension of length
l_{exch}	Coupling length
l_p	Pore-connectivity parameter of the Brooks and Corey saturation-pressure functions
$MARE$	Mean absolute residual error
$MaxE$	Maximum residual error
MRE	Mean residual error
n_x, n_y	Manning roughness coefficients in x- and y- directions
Q	Source/sinks to porous domain from the outside of the simulation domain
Q^+	Rate of all water entering the domain through sources
Q^-	Rate of all water leaving the domain through sinks
Q_0	Volumetric flow rate per unit area from external source/sinks to surface domain
R^2	Goodness-of-fit
$RMSE$	Root mean squared residual error

S_s	Specific storage coefficient of porous medium
$\mathbf{q}$	Darcy's fluid flux
S_e	Effective saturation
S_w	Degree of water saturation
S_{wr}	Residual water saturation
s	Maximum slope
T	Primary dimension of time
t	time
w_m	Volumetric fraction of the total porosity occupied by the porous medium
z	Elevation head

α	Empirical parameter α of the van Genuchten equation or inverse of air entry pressure of the Brooks and Corey saturation-pressure functions
β	Empirical parameter β of the van Genuchten equation or pore-size distribution index of the Brooks and Corey saturation-pressure functions
Γ_0	Fluid exchange between surface and subsurface systems
Γ_{ex}	Volumetric exchange rate between subsurface and other domain types
ΔS	Rate of change in the model's storage
ϵ_P	Percentage fluid balance error
θ_s	Saturated water content
ν	Ancillary variable of the van Genuchten equation
ϕ_0	Porosity of surface flow domain
ψ	Pressure head

1 INTRODUCTION

Groundwater is an important global source of freshwater. It provides water for drinking, agriculture and industry and accounts for approximately 50% of total world's potable water (Zektser and Lorne 2004). But groundwater does not only support water for human welfare but it is also a vital component of natural environment. Many valuable ecosystems, such as springs, wetlands, lakes, rivers and lagoons rely on the presence of groundwater. These ecosystems are often refereed as groundwater dependent ecosystems (GDEs). In such ecosystems groundwater creates unique conditions for fauna and flora and thus, favours local biodiversity (Boulton 2005; Kløve et al. 2011a; Gibert et al. 2009). GDEs provide habitats for endangered species, including numerous water birds, endemic plants and invertebrates (Boulton 2005; Kløve et al. 2011a; Danielopol et al. 2003). Furthermore, GDEs support valuable ecosystem services, such as filtration of water (Boulton 2005; Danielopol et al. 2003), recreational use (Kløve et al. 2011b), mitigate effects of floods (Kløve et al. 2011b) and sustain low flow in rivers and contribute positively to fisheries, agriculture and forestry (Boulton 2005).

In recent decades, groundwater depletion due to over-abstraction (e.g., Wada et al. 2010), contamination (e.g., Gleick et al. 2014) and climate change (e.g., Treidel et al. 2011) have placed serious strain on groundwater resources and groundwater-dependent ecosystems. According to Boulton (2005), the most serious threats for GDEs are disruptions in hydrological connections between groundwater and GDEs, e.g., by removal of vegetation; sea water intrusion; pollution; and other changes in groundwater systems that exceeds natural variability, e.g., lowering of water table through over-extraction. The expected growing population, warming of climate and escalating demand for water will further intensify use of groundwater and exacerbate the threats to groundwater aquifers and GDEs. Increasing pressure on water resources and growing evidence of connections between groundwater and terrestrial ecosystems are shifting water management towards fully-integrated approach in which groundwater, surface water bodies and dependent ecosystems are treated as one management unit (e.g., Winter 1995). The GDEs protection is already addressed in the current water-related legislation of European Union (EU) in the EU Groundwater Directive (EUROPEAN COMMISION 2006) and EU Water Framework Directive (EUROPEAN COMMISION 2000) as well as in the nature conservation policies, such as EU Habitats directive (EUROPEAN COMMISION 1992) and EU Bird Directive (EUROPEAN COMMISION 2009). These EU directives are implemented into the Finnish national law. Water Resources Management Act (2004), Water Act (2011) and Nature Conservation Act (1996) guide protection of GDEs, require monitoring and classification of the status of groundwater resources and oblige the assessment of the impacts of various land uses and groundwater abstraction to GDEs.

The present-day studies show, however, that the current understanding of the interactions of groundwater and surface waters is not sufficient to fully-protect GDEs and further studies are needed (Boulton 2005; Kløve et al. 2011a). The impacts of over-abstraction, pollution and climate change on GDEs can be studied quantitatively by analysing groundwater-surface water (GW-SW) interactions through mathematical models and field studies. While the contribution of groundwater to GDEs can be evaluated locally using field measurements, the integrated GW-SW modelling is a unique method to provide more complete picture of these interactions and their temporal variations. The main advantage of the integrated GW-SW modelling approach is its ability to represent adequately the key components of hydrological cycle and their relations starting from the precipitation input. This method allows a realistic representation of complex problems that would be impossible to address with simplified approaches. However, long computation times, problems with calibration and estimation of parameters significantly decrease the usefulness of physically-based models. Further development is needed before integrated models can be applied widely in commercial cases.

The objective of this work was to examine the performance of the fully-integrated physically-based GW-SW modelling to simulate groundwater dependent ecosystems in a case study of Kälväsvaara esker aquifer located in Northern Finland. The Kälväsvaara aquifer is a complex esker aquifer with characteristics of a delta structure, surrounded by various types of GDEs, i.e., fens, kettle lakes, streams and springs. The main goal of this thesis was to build a steady-state model that captures the presence of all types of GDEs present in the vicinity of Kälväsvaara without their prior definition by applying artificial boundary conditions. Instead, the target was to create correct conceptualization of the study area that produces GDEs as part of the simulation. The modelling of Kälväsvaara groundwater area was performed using the HydroGeoSphere code (Aquanty 2015) that was successfully applied in earlier studies concerning GW-SW interactions (e.g., Ala-aho et al. 2015b; Smerdon et al. 2007; Thompson et al. 2015; Levison et al. 2014). In this thesis the special focus was put on how model should be scaled and what information is needed to replicate both small-scale GDEs, such as springs, and large-scale GDEs, i.e., wetlands, lakes and streams.

2 TOWARDS INTEGRATED MODELLING

2.1 Purpose of groundwater modelling

Models increase our understanding about the surrounding world and controlling phenomena. They are valuable tools to make predictions and solve practical problems. The applicability of models to solve groundwater issues was understood long before the modern numerical methods were developed. The first mathematical models were applied in studying groundwater flow at the end of the 19th century by solving flow equations using analytical methods (Wang and Anderson 1995, p. 2). During last century groundwater models underwent a massive transition from sand tank and analog models to robust computer-based models.

Hydrogeology was a pioneer in geoscientific numerical modelling by believing that a properly designed and built mathematical model can be used as a base for feature predictions (Domenico and Schwartz 1998, p. 142). This tenant has established a clear direction for research over last 60 years and led to development of standard procedures for commercial applications (Domenico and Schwartz 1998, p. 142). Undoubtedly, one of the primary reasons in the interest of representing groundwater flow and to study groundwater aquifers through various types of models is that our ability to quantify involved process and their feedbacks is limited due to their complexity. Thus, modelling is a natural way of studying groundwater phenomena. It allows us to improve our understanding on processes that are not visible to our eyes and consequently difficult to characterize. It gives us also an ability to predict the system response to various external factors, such as water abstraction or contamination. On other hand, it is important to note that our perception of complexity exceeds our current ability to represent it in a form of mathematical equations and thus, models are simpler forms of reality (Beven 2009, p. 6). Despite the uncertainty related to simplifying assumptions, numerical groundwater modelling is a standard method to study and manage groundwater resources. It is a powerful tool to address various common groundwater related problems, such as groundwater contamination and impacts of water abstraction. Furthermore, groundwater modelling can be applied to simulate numerous more specific issues, such as impacts of climate change on subsurface water resources (e.g., von Gunten et al. 2014; Goderniaux et al. 2009), impact of deep building foundations on groundwater flow patterns (Ding et al. 2008) or salt water intrusion (Huyakorn et al. 1987).

2.2 Short overview of groundwater flow modelling approaches

Groundwater flow can be studied by various types of models. These models can be divided into three major classes from which the most popular methods are physical sand tank models and mathematical models. In the past the subsurface flow phenomena were also studied commonly by **analog models** that utilized the analogy between subsurface water flow (Darcy's law) and flow of electricity (Ohm's law) (Wang and Anderson 1995, p. 2). Analog models mimicked the aquifer properties through circuits built of capacitors and resistors (Wang and Anderson 1995, p. 2). This method was popular in 1950s prior to development of high-speed computers (Wang and Anderson 1995, p. 2).

A **sand tank model** is a physical model that represent subsurface flow domain through a tank filled with porous medium (Wang and Anderson 1995, p. 2). In this method subsurface flow is simulated by inducing water flow through tank (Wang and Anderson 1995, p. 2). The main disadvantage of this approach is problem with scaling down field conditions to tank size (Wang and Anderson 1995, p. 2). Beside this limitation, method is still used in some scientific applications since it provides valuable information for numerical model calibration, can be helpful in evaluating engineering solutions and allows to examine accurately flow and solute transport variables, thus has a potential to add to our current understanding of subsurface processes. Such applications include for instance studies of salt intrusion to coastal aquifers and possible countermeasures (Crestani et al. 2015) or research on solute transport in the capillary fringe (Persson et al. 2015).

In 1960s the increase in computer computing power led to developments in **mathematical models**. Implementation of numerical techniques made possible to simulate heterogeneous and anisotropic systems and thus, facilitated creation of more realistic representation of factual aquifers (Wang and Anderson 1995, p. 3). Since then, numerical models have been become the most commonly used tool to study groundwater flow. Already in the 1970s, more than 250 models were available to simulate various groundwater problems (Bachmat et al. 1978). Similarly, nowadays a wide variety of groundwater models exists. The models differ in terms of processes included, simulation basis (e.g., physically based, conceptual, empirical, stochastic), spatial representation (e.g., lumped, distributed), temporal representation (e.g., steady state, single event, transient) and method of solution (e.g., analytical, numerical, 0-dimensional) (Dingman 2008, p. 28).

In conventional water resource modelling, the surface and groundwater domains were considered separately (Condon and Maxwell 2013). However, growing evidence of connection between groundwater and surface water and existence of so called groundwater dependent ecosystems created an interest in the integrated management approaches and **integrated groundwater modelling**. The target has become to create a model that integrate both surface and groundwater domains and capture all most important physical processes of hydrological cycle. The first time this idea was outlined in the blueprint article of Freeze and Harlan (1969). The study investigated the feasibility of development of a physically-based model for the complete hydrologic cycle. The authors proposed to couple solutions of Richard's equation (Richards 1931) for subsurface domain and Saint Venant equations for overland flow and they defined the branches of hydrology that need still development of physically-based mathematical derivations (Freeze and Harlan 1969). The first trials to build fully integrated models emerged already in the 1970s, however, it took almost thirty years before the models were capable to replicate observations with acceptable accuracy. Beside deficits in physical understanding of such process as evapotranspiration, non-steady flow in natural channels and the role of vegetation (Freeze and Harlan 1969), the blueprint had to wait for advances in numerical and computational technologies (Maxwell et al. 2014). Meanwhile, the MODFLOW model was developed that is the most widely-used physically-based model nowadays.

The **MODFLOW** (McDonald and Harbaugh 1988) is a transient three-dimensional block-centred finite-difference groundwater model, developed by the U.S. Geological Survey primary to simulate only groundwater domain. The first version of software was published already in 1984 (McDonald and Harbaugh 1988) and since then model has become widely used around the world. Nowadays, MODFLOW is treated as a standard in modelling groundwater-related issues. The greatest advantage of the software is its modular structure that allows high flexibility (Harbaugh 2005) as the modules provide easy tools to adjust the model in a manner that it can be utilized for a particular application (US Geological Survey 2015). Another feature that undoubtedly increased the model use was a graphical user interface (GUI). GUIs were first provided by third-party commercial software (e.g., GMS, Visual Modflow, Leapfrog Hydro), however in recent years some free-ware GUI were developed; for instance ModelMuse by U.S. Geological Survey (Winston 2009). At the moment, simultaneous variants of the MODFLOW model are available that differ in respect of refinement capabilities, solver techniques, grid structure and other features. These recently developed versions indicate a general trend towards physically-based modelling. For instance, MODFLOW-OWHM (One-Water Hydrologic Flow Model) – the newest variant of MODFLOW models was developed to address conjunctive-use of water and it aims to represent in a complete way all major processes of hydrologic circle (Hanson et al. 2014). This version of software fully couples the flow in subsurface and overland domain and allows to simulate the effects of various water uses, e.g., irrigation, urban areas and natural vegetation (Hanson et al. 2014).

It is worth to note that the trend towards including surface and subsurface components of hydrologic cycle within one model is not only visible in hydrogeology but can be also observed in surface-water hydrology. The flow groundwater components are often included in surface water models. This is the case of the Finnish national **Watershed Simulation and Forecasting System (WSFS)** (Vehviläinen and Huttunen 2001). The WSFS is a real-time monitoring and forecasting system developed by Finnish Environment Institute (SYKE) nearly 40 years ago (Finnish Environmental Institute 2013). The WSFS is mainly used for flood forecasting and real-time monitoring of Finnish lakes and rivers, nutrient load simulations and climate change research (Finnish Environmental Institute 2013). The system is based on a **semi-distribute conceptual hydrologic model** and it uses daily rainfall, temperature and potential evaporation data to derive various hydrological variables, e.g., soil moisture, groundwater storage, runoff, discharge, lake level, ice depth (Finnish Environmental Institute 2013). The general structure of the WSFS is presented in Figure 1. In the model, the groundwater term is represented by a lower storage component, i.e., the amount of water stored above the imaginary base elevation (0-level) (Huttunen et al. 2008). The groundwater levels are derived by transforming the state of groundwater storage to the corresponding depth and summing the value up to the minimum record groundwater elevation and a calibration parameter indicating the difference between the 0-level and the actual minimum observed groundwater level (Huttunen et al. 2008). The effective porosity used in the transformation is calibration parameter (Huttunen et al. 2008). Despite its highly simplistic structure, the WSFS provides the relatively good agreement with observed groundwater levels even though the groundwater monitoring is not the main objective of the WSFS. The Watershed Simulation and Forecasting System is not, however, applicable to studying GW-SW interactions at the moment as it disregards feedbacks between soil storage components and surface water bodies.

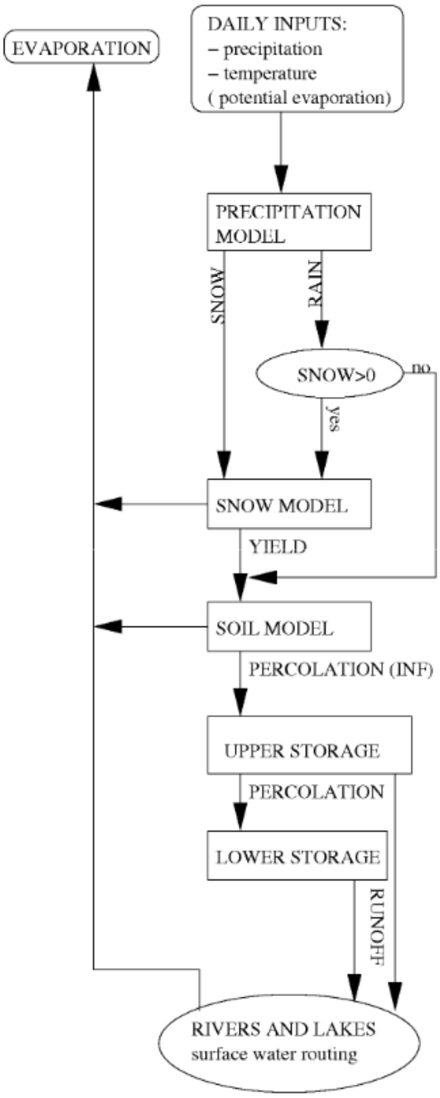

Figure 1. The flow chart of the WSFS system (Picture: Vehviläinen and Huttunen 2001).

2.3 Modelling GW-SW interactions

Today, GW-SW interactions can be addressed by two various types of physically-based modelling approaches: coupled models and integrated models. Both of these methods aim to integrate various processes of hydrologic cycle into one model. The main difference between these two types of modelling approaches is how the models solve surface and subsurface equations (Condon and Maxwell 2013).

Coupled models

Coupled models, such as MODFLOW-OWHM, solve surface domain equations and porous media domain separately (Condon and Maxwell 2013). This means that the model variables have to be sent back and forth between systems (Condon and Maxwell 2013). This way of linking subsurface and overland domains is not natural, however, it allows to simulate GW-SW interactions without decreasing computational speed of the model. In order to solve the equations, some assumptions must be done about the state of each system (Condon and Maxwell 2013). This in turn leads to errors or forces to introduce new simplifying assumptions about the connections between systems (Condon and Maxwell 2013). This kind of inaccuracies and errors can be avoided by solving iteratively systems until the solution converges but at expense of computational speed (Condon and Maxwell 2013). The important implication of coupled approach is that these models are unable to solve time varying feedbacks between model components (Condon and Maxwell 2013) . Other popular coupled models are SWATMOD, MODHMS and MIKE-SHE (Condon and Maxwell 2013).

Integrated models

The second approach to link overland and porous domains within one model is defined as an integrated modelling. Fully-integrated models were originally designed to implement the blueprint of Freeze and Harlan (1969). These models utilize the Richard's equation (Richards 1931) to solve variably saturated flow for the subsurface domain and Saint Venant equations for overland flow and derive all important components of hydrological cycle from precipitation. In this approach a system of subsurface and surface equations is solved simultaneously (Figure 2) (Condon and Maxwell 2013). To all appearances this small mathematical difference has important implications as it allows to model feedbacks between surface and

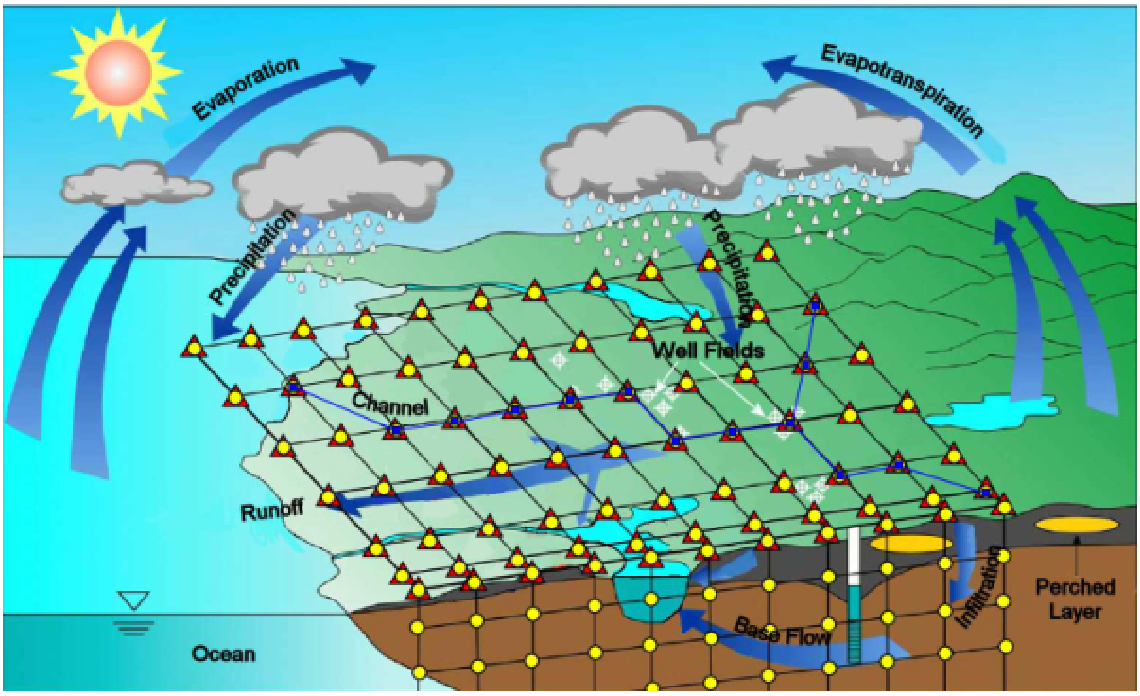

Figure 2. The concept of integrated numerical modelling of hydrologic system. The surface and subsurface are discredited and solved simultaneously. (Picture: Aquanty 2015)

subsurface domains (Condon and Maxwell 2013). Furthermore, in integrated models rivers, streams, lakes etc. are not defined separately but they emerge during simulations as result of geological and topographical conditions. Integrated solution also guarantees conservation of mass (Condon and Maxwell 2013).

Today, numerous integrated codes are available for example CATHY (Camporese et al. 2010), HydroGeoSphere (Aquanty 2015), OGS (Kolditz et al. 2012), ParFlow (Maxwell et al. 2009) and PAWS (Shen and Phanikumar 2010). The software differs in respect of several features, from which the most pronounced dissimilarities are related to (Maxwell et al. 2014):

- formulation of governing equations in respect of dimensionality (1-D, 2-D or 3-D representations)
- coupling strategy (first-order exchange, pressure continuity, boundary condition switching)
- numerical approaches (asynchronous linking, sequential iteration, globally implicit)
- supported grid structures (structured vs. unstructured)
- coupling with other models

This wide variety of approaches implemented can rise a question which integrated model is the most accurate or for what applications each of the models performs best. There is no straightforward answer to this problem as any analytical solutions are known for coupled subsurface-surface problems (Maxwell et al. 2014). Thus, there are not any invariable standards with which the models can be verified. For this reason, model performance is usually evaluated by running few models on the same problems and comparing the results (Maxwell et al. 2014).

2.4 Possible applications, benefits and drawbacks of fully-integrated physically-based models

The fully-integrated physically-based models have been applied to address broad range of scientific questions and practical problems of various scales. The conducted simulations studied such issues as: agricultural sustainability, atmosphere-subsurface water and energy fluxes, climate change impacts, cumulative watershed effects, dam removal, groundwater recharge , groundwater-lake interactions, island scale erosion, new-old water and residence times, pore-water pressure development and slope instability, radionuclide contamination/vulnerability, runoff generation, sediment transport, solute transport, stream-aquifer exchange and wetland-estuary exchange (Ebel et al. 2009; Maxwell et al. 2014).

Definitely, the main benefits of fully-integrated physically-based is their ability to simulate feedbacks between surface and subsurface domains and to solve complex problems. On the other hand, the complexity of these codes was widely criticized, by e.g., Beven (2002). One of the main arguments against integrated modelling approaches is that these models are based on Darcian theory (Beven 2002). According to Beven (2002), Darcy's law is not applicable to large scales due to arising non-linearities, heterogeneous soil properties and effects of preferential flow. Another reasons for criticism are long run times, problems with estimation of model parameters and high requirements for data (Brunner and Simmons 2012). On the other hand, simplified models may be unable to simulate complex problems (Brunner and Simmons 2012). Furthermore, Ghasemizade et al. (2015) demonstrated that model performance can improve with increasing complexity for short-time scale, e.g., daily time discretization, whereas an excessive complexity of model can be the reason of increasing uncertainty over annual scales.

From practical point of view, the main drawbacks limiting integrated models applicability are long computational times, slowness of calibration and lack of visualization and post-processing capabilities. Undoubtedly, more development is required before these kind of models can be broadly used in practical applications at commercial scale. However, there has been major advances towards enhancing usability of these models. For instance, von Gunten et al. (2014) presented a new time-effective method for model calibration that could be possibly automatized and Hwang et al. (2014) implemented a flexible parallel computing framework for the HydroGeoSphere model. First, real-time applications also emerged. Lapin et al. (2014) developed a real-time monitoring system for groundwater abstraction optimization close to rivers. The wireless network of sensors was combined with a cloud-based platform to run physically-based model and automatically calibrate it by implementing Ensemble Kalman Filters (Lapin et al. 2014).

2.5 Future prospectives

Langevin and Panday (2012) pointed out that the future groundwater modelling approaches will largely depend on the problems with which we will be forced to deal. Two emerging themes of issues: "climate change and its impacts on water resources" and "energy industry and groundwater" will require interdisciplinary work to fully address their complexity (Langevin and Panday 2012). Definitely, fully-integrated physically-based models provide us tools to address these questions in a physically sound manner. The complexity employed should, however, depend on the available data and type of the problem. Therefore, the importance of simpler models, such as WSGS and MODFLOW, should not be ignored as they are time effective and accurate tools for solving less complex problems.

3 GROUNDWATER-DEPENDENT ECOSYSTEMS

3.1 Short overview of GDEs

Groundwater-dependent ecosystems are ecosystems found in the crossing point of groundwater and surface water bodies, e.g., springs, lakes, but also subterranean systems rich in stygobion taxa can be understood as one (Gibert et al. 2009). Their current composition, ecological function and structure are shaped by presence of groundwater (Kløve et al. 2011a). In such ecosystems groundwater creates unique conditions for flora and fauna by providing water, nutrients, buoyancy and by stabilizing water temperature (Kløve et al. 2011a). In addition, groundwater boosts biodiversity locally and favours highly specialized species (Gibert et al. 2009). However, the exact role of groundwater in such ecosystems is not yet fully understood (Boulton 2005; Kløve et al. 2011a;b). The contribution of groundwater to various ecosystems depends on hydrogeological and climatic settings and can be continuous or transient in time, e.g., seasonal or episodic input of groundwater (Kløve et al. 2011a).

Broadly recognized types of GDEs include following ecosystems (Kløve et al. 2011a):

- rivers and lakes that rely on groundwater, including aquatic, hyporheic and riparian habitats;
- wetlands and peatlands sustained by groundwater;
- springs;
- lagoons, estuaries and other near-shore marine ecosystems that depend on presence of groundwater;
- groundwater aquifers and caves.

In addition, terrestrial ecosystem which are seasonally or occasionally dependent on groundwater can be incorporated to this classification (Boulton 2005), such as wet forests in Niepolomice (Kløve et al. 2011a).

Recently, the subject of GDEs was raised frequently in many scientific publications (reviewed among others in Boulton 2005; Kløve et al. 2011a;b; 2014; Gibert et al. 2009; Griebler et al. 2014; Griebler and Avramov 2015). The interest in this topic is driven by increasing awareness of the importance of GDEs. Groundwater dependent ecosystems provide directly and indirectly numerous valuable ecosystem services. The most important of those is filtration of water (Boulton 2005; Danielopol et al. 2003). Groundwater is purified not only through physical, chemical processes but as well as through biological processes in which the subsurface stygofauna and bacteria play a key role (Hancock et al. 2005). Kløve et al. (2011b) specified other ecosystem services, including biodiversity; infiltration and recharge enhancement; water storage; flood mitigation and flow regulation; erosion reduction and other positive impacts on river bed stabilisation; and cultural services, e.g., recreational values. Kløve et al. (2011b) also emphasizes that the services and functions of GDEs depends on the type of GDE. For instance, aquifers and cave ecosystem impact nutrient balances, whereas wetlands and lakes are important habitats for bird populations (Kløve et al. 2011b).

As groundwater and surface waters are closely connected in nearly all landscapes, the change in the state of one of the domains can have severe impact on the other domain (Winter 1999). This, in turn, may affect the services provided by GDEs (Kløve et al. 2011b). The capacity of GDEs to provide their services is associated with timing and availability of groundwater, however the response of each ecosystem to stress conditions is usually unknown, as various ecosystems show different non-linear dynamics to water availability (Boulton 2005). The main threats to groundwater and GDEs recognized by Boulton (2005) are:

- changes in groundwater systems that exceeds natural variability, e.g., lowering of water tables through over-extraction;
- disruptions in hydrological connections between groundwater and GDEs, e.g., siltation of the bed sediments can damage GW-SW interactions in hyporheic zone and affect both the surface and subsurface ecosystems;
- contamination by chemicals and salt intrusions;
- changes in groundwater quality.

According to Wada et al. (2010), the depletion of groundwater resources has already occurred at global scale. Growing population, climate change are expected to amplify demand for water that can further increase the threats to groundwater aquifers and GDEs. Kløve et al. (2014) gives an overview on the predicted impacts of climate change on groundwater and GDEs. According to recent studies, global warming may affect the timing and magnitude of recharge and groundwater formation (Kløve et al. 2014). The exact impacts on groundwater resources is, however, difficult to estimate as they do not only result from changes in precipitation and temperature, but can be also amplified or counteracted by impacts of urbanisation, other land use changes and increasing water consumption (Kløve et al. 2014). The future climatic conditions are also uncertain as the climatic models provide scenarios at large scales (Kløve et al. 2014). Nevertheless, it is expected that warming climate affects GDEs through alternations of GW-SW interactions and changes in thermal regime of water (Kløve et al. 2014). The exact impact will, however, depend on a type of ecosystem and already existing stresses (Kløve et al. 2014).

The increasing awareness of interconnection between surface and subsurface water and their importance to provide clean water and sustain biodiversity have given rise to the fully-integrated water management concept that recognizes surface water and groundwater resources simultaneously. The trend towards fully-integrated water resource management is already visible in the EU legislation. The EU Groundwater Directive (EUROPEAN COMMISION 2006) and EU Water Framework Directive (EUROPEAN COMMISION 2000) recognize GDEs and obligate to protect and monitor status of GDEs. Many groundwater dependent ecosystem are also protected due to their high ecological values as habitats under EU Habitats directive (EUROPEAN COMMISION 1992) and EU Bird Directive (EUROPEAN COMMISION 2009). The provisions of these directives are incorporated into the Finnish Nature Conservation Act Nature Conservation Act (1996) and water-related legislation: Water Resources Management Act (2004) and Water Act (2011). Water Resources Management Act (2004) establishes a base for integrated water management in Finland. The legislation enacts formation of water districts that consist of one or more river basins, coasts and groundwater aquifers (Water Resources Management Act 2004). Water Resources Management Act (2004) also requires monitoring and classification of the status of groundwater resources. In addition, Finish law enforces assessment of the impacts of various land uses and groundwater abstractions to GDEs in Water Act (2011). Nature Conservation Act (1996) obligates the protection of many valuable GDEs due to their high ecological importance, including oligotrophic lakes, Fennoscandian natural rivers, Fennoscandian springs and springfens, Alkaline fens and Aapa mires.

The most commonly occurring GDEs in Finland are streams, rivers, groundwater-dependent lakes, fens and springs. These ecosystems are commonly situated in the discharge zones of eskers aquifers (Kløve et al. 2011b). Eskers are depositional glacial landforms of sand and gravel commonly found in the areas covered by last deglaciation period, i.e., Europe and North America (Airaksinen 1978, p. 25). As glaciers retreated, meltwater in form of rivers and streams deposited sandy and gravel sediments under or within ice sheets, often in a stratified manner (Airaksinen 1978, p. 25). Eskers are commonly used for water supply in the the Fenno-Scandia region (Kløve et al. 2011b) and are often connected hydraulically to lakes, wetlands, rivers and streams located in vicinity of the aquifer (Kløve et al. 2011a). A typical esker landscape includes also springs that occur either on slopes of the esker formation or in lowland areas, in locations were groundwater discharges directly in a point discharge form. Many peatlands around eskers were drained for forestry and peat harvesting purposes in the 1950s–1980s (Kløve et al. 2011a). The effects of these drainage systems are still visible today; ditches induce water discharge at esker boundaries and lower groundwater levels (Rossi et al. 2012). It is estimated that even more than 90 % of springs in South Finland were affected negatively by ditching (Kløve et al. 2011a). In contrast, springs in the the northern parts of country remain in pristine condition (Kløve et al. 2011a). In addition, the ditching attributed most likely to declining of levels of groundwater dependent lakes, e.g., in the Rokua esker area (Rossi et al. 2012)

3.2 Groundwater - surface water interactions in GDEs

Winter (1999) recognized that the interactions between surface waters and groundwater occur in nearly all landscapes of various scales. Subsurface waters interacts with relatively small-scale surface water bodies, e.g., streams, lakes and wetlands as well as with large river valleys and sea coasts (Winter 1999). The exchange fluxes between surface waters and groundwater are governed by climate and physiography, i.e., topographic and geologic conditions (Winter 1999). A particular effect on the magnitude and direction of these fluxes has a relative position of surface water body and groundwater flow system, together with geology of porous domain, and direct transpiration from groundwater (Winter 1999). The exchange fluxes can be directed towards surface water bodies (i.e., positive flux), from surface water bodies (i.e., negative flux) or they can intertwine within one surface-water body. GDEs are systems that have positive groundwater flux for the whole ecosystem or its parts.

3.2.1 Rivers and streams

Streams and rivers are open flowing water bodies. The majority of streams and rivers gain water during their way towards outlets, although they can also lose water due to permeable bed, evapotranspiration and excessive use of water. In terms of GW-SW interactions, if water table exceeds the elevation of stream or river surface, groundwater recharges stream/river and consequently the stream gains water, i.e., gaining stream (Winter et al. 1998). On the contrary, if water table is lower that elevation of stream/river water surface, the stream/river loose water, i.e., loosing stream (Winter et al. 1998). In reality, rivers and streams are rarely solely gaining or loosing water throughout the whole length, but they consist of reaches interchangeably loosing water and reaches gaining water (Winter et al. 1998). The surface water and groundwater exchange occurs in hyporheic zone (Dingman 2008, p. 344). In connected systems, the exchange through hyporheic zone occurs continuously; water is moved back and forth between subsurface and surface domains (Bencala et al. 2011). In general, the water lost upstream is restored to the river downstream, and vice versa the water gained upstream is lost downstream (Bencala et al. 2011). Although, water volumes involved these exchanges are in most cases insignificant, the process enhances surface water and groundwater quality (Bencala et al. 2011). The resulting conditions from GW-SW exchange are important to surface water flora and fauna, e.g., spawning (Dingman 2008, p. 344).

The direction and magnitude of GW-SW interactions in the streams are related to meandering and to changes in slope, such as pool and riffle system (Winter et al. 1998). The spatial distribution of gaining and loosing reaches can change over short time frames in response to precipitation event or snowmelt (Winter et al. 1998). Moreover, the spatial distribution of seepage and hydraulic conductivity can be highly dynamic as a result of variable stream bed morphology (Hatch et al. 2010). The dynamics of GW-SW dynamics can be significantly altered by anthropogenic actions, such as water pumping and irrigation, various land use and river regulation (Kløve et al. 2011a)

3.2.2 Lakes and wetlands

The GW-SW interactions in wetlands and lakes are similar to those in streams. Analogically, wetlands and lakes can gain or recharge groundwater throughout their entire beds (Winter et al. 1998). However, the most common situation is the one in which these water bodies receive groundwater through parts of their beds and lose water in other parts (Winter et al. 1998). In terms of GW-SW interactions, two main types of wetlands can be distinguished: fens and bogs. Wetlands which mainly gain water are refereed as fens, and the one which loose water are bogs (Winter et al. 1998).

The role of GW in wetlands depends on climatic and hydrogeological conditions. In fens, groundwater provides stable temperature, minerals and oxygen that support unique wetland fauna (Heikkilä et al. 2011). In contrast, the exact role of groundwater in lake ecosystems is not in many cases known and it perhaps depends on climate, hydrologic and geologic conditions and nutrient status of a lake (Kløve et al. 2011a). The groundwater influx can have positive impact on the water quality of deep lakes and enhance various processes in the lakes sediments (Kløve et al. 2011a). In northern ecosystems, groundwater influx can be also crucial for survival of aquatic fauna by providing oxygen to the water (Kløve et al. 2011a).

A main distinction between groundwater interactions in lakes and wetlands is the ease with each water moves at interface of such bodies (Winter et al. 1998). In lakes, the discharge occurs predominantly in littoral zone, i.e., in zone close to the shore (Dingman 2008, p. 349). Wave movement removes fine-sediments from shore and allows relatively not constrained interactions between surface water and groundwater (Winter et al. 1998). However, it is worth to keep in mind that the exact flow paths and thus, the interaction spots depends on the hydraulic properties of lake bed (Dingman 2008, p. 349). In contrast, the GW-SW interactions in wetlands are usually much slower as the movement of water is constrained by low hydraulic permeability of wetland organic sediments (Winter et al. 1998). In wetlands the water exchange between surface and subsurface domains is affected by the presence of roots (Winter et al. 1998), occurrence of preferential flow (Lowry et al. 2009) and in case of peatlands, spatial and vertical distribution in the peat hydraulic properties (Ronkanen and Kløve 2005). According to (Winter et al. 1998), rooted vegetation increases soil hydraulic conductivity and enhances the water exchange between the wetlands sediments and surface water through water uptake. The characteristic features of peat-dominated wetlands are highly variable conductivity of peat (Ronkanen and Kløve 2005, e.g.,) and presence of soil pipes that can result in point discharge of groundwater in a form of springs (Lowry et al. 2009).

The spatial distribution of the seepage zones within lakes and wetlands mainly depends, however, on the state and extend of the GW-SW connection (Brunner et al. 2009). In transitional lake and wetland system, the centre of surface water body often remains connected to groundwater table while edges are disconnected what results in high spatial variations in seepage (Brunner et al. 2009). In general, lakes and wetlands show higher sensitivity to changes in groundwater table and risk to disconnection (Brunner et al. 2009).

3.2.3 Springs

Springs are small scale GDEs that are directly connected to groundwater flow paths, predominantly situated in discharge zones of aquifers. The location of springs usually coincidences with abrupt changes in hydraulic properties or with fractured rock/karst aquifer formations (Kløve et al. 2011a). However, springs can be also found in depressions of homogeneous medium, i.e., depression springs (Kløve et al. 2011a) or at spots of abrupt changes in slope at mineral soil/peat interface (Lowry et al. 2009). The magnitude of spring discharge depends among others on the aquifer type, climate and catchment size and can vary between 0.1 L^1s^{-1} up to 100 m^3s^{-1} (Kløve et al. 2011a).

Springs are commonly classified into high-flow springs with flow rate exceeding 0.028 m^3s^{-1} and low flow springs (Levison et al. 2014). High-flow springs, such as karst springs provide enough water for anthropogenic use, e.g., potable water, thermal baths and have been in focus of broad scientific research (Levison et al. 2014). In contrast, less attention have been given to low-flow springs as they cannot provide enough water for anthropogenic uses (Levison et al. 2014). The position and behaviour of springs is controlled by various hydrogeological parameters, yet the effect of these is not fully understand especially in wetland environments (Lowry et al. 2009). Valuable tools to study spring formation mechanism are near surface geophysics, e.g., ground penetrating radar combined with classical hydrologic tools (Lowry et al. 2009), whereas integrated modelling can improve our understanding about spring dynamics (Levison et al. 2014).

3.3 Integrated modelling of GDEs

3.3.1 Rivers and streams

Rivers and streams were perhaps the most commonly modelled systems by integrated modelling approach. Rivers and streams were cornerstones of numerous simulations addressing wide range of hydrologic process and scales. The GW-SW interactions on catchment scale were investigated by, e.g., Jones et al. (2008) and Li et al. (2008) in terms of rainfall-runoff responses. Sciuto and Diekkrüger (2010) studied how soil heterogeneity and spatial discretization of model domain affect water fluxes. Goderniaux et al. (2009) and von Gunten et al. (2015) simulated groundwater responses to climate change, whereas (Bolger et al. 2011) modelled the past GW-SW interactions of pre-development hydrologic regime in California, USA. Condon and Maxwell (2013) focused on the optimization integrated GW-SW water allocation to enhance management decisions and von Gunten et al. (2014) proposed a new calibration approach using a river watershed to test the method. Small-scale hydrologic process related to streams and rivers were simulated by e.g., Park et al. (2011); Brunner et al. (2009); Frei et al. (2010); Frei and Fleckenstein (2014). Park et al. (2011) addressed the problem of ”an old water paradox”, i.e., the significant contribution of groundwater to stream flow generation during a precipitation event, whereas Brunner et al. (2009) analysed spatial and temporal GW-SW interactions between rivers, lakes and groundwater during transition from connected to disconnected regimes.

3.3.2 Lakes

In contrast to rivers and streams, lakes were modelled only in few studies (e.g., Smerdon et al. 2007; Ala-aho et al. 2015b). Lake-groundwater interactions were first simulated by Smerdon et al. (2007) for a lake located in Northern Alberta, Canada. The study area (1800 m × 1800 m × 30 m section of outwash landscape) was represented by 8 zones characterized by various hydraulic properties (Smerdon et al. 2007). The model was first calibrated by comparing steady-state results to hydraulic heads of lakes, then the obtained steady-state results were used as an input for transient model (Smerdon et al. 2007). The simulated lake levels, water table configuration and seepage fluxes matched well measured values (Smerdon et al. 2007). The authors concluded that the GW-SW interactions were controlled mainly by hydraulic properties of outwash, presence of peatland on outlets of the lake and evapotranspiration (Smerdon et al. 2007). In addition, the results suggested that hydraulic conductivity and specific storage of peatland should be transient in time to represent thawing of peat during spring periods (Smerdon et al. 2007). Similar study was conducted by Ala-aho et al. (2015b). Ala-aho et al. (2015b) simulated transient groundwater-lake interactions in a large-scale model of an esker aquifer. The results of simulations were compared with results of the stable isotope analysis and airborne thermal imaging (Ala-aho et al. 2015b).

3.3.3 Wetlands

It seems that until now, wetlands were not the main focus of modelling. As far as the author has found, the only study that considered wetland in the centre of interest was the research conducted by Thompson et al. (2015). The main target of simulations was to evaluate key landscape features affecting complex GW-SW interactions in a pond-peatland complex of Northern Alberta, Canada and the feasibility of peatland landscape reclamation (Thompson et al. 2015). The study revealed that peatland ecosystem does not necessary requires additional input of water for survival, but rather peatland store water within its structure and provide water to other ecosystems (Thompson et al. 2015). Furthermore, the simulations indicate that this kind of systems are especially sensitive to duration and timing of snowmelt, evapotranspiration fluxes, hydraulic conductivity of underlying medium, presence of ponds and removal of peat cover (Thompson et al. 2015).

In addition, wetlands were included into few other studies (e.g., Smerdon et al. 2007; Ala-aho et al. 2015b) to provide a geologic setup for transient flow simulations of lake and esker systems. Bolger et al. (2011) used concept of wetland in simulations of the pre-development hydrologic conditions in the San Joaquin Valley, California, USA. Wetlands, defined by Bolger et al. (2011) as areas flooded by surface water, were compared to historical extent of wetlands in the region (Bolger et al. 2011). Groundwater levels with surface water distribution (including wetlands) were employed to evaluate model performance (Bolger et al. 2011). In addition, Frei et al. (2010) and Frei and Fleckenstein (2014) studied the effects of wetland micro-topography (hollows and hummock structure) on surface runoff generation. Although in these studies wetland topography served rather as experiment surface, the simulations identified important mechanisms responsible for surface flow generation and GW-SW exchange in wetlands (Frei et al. 2010; Frei and Fleckenstein 2014).

3.3.4 Springs

Springs are another example of GDEs that have received relatively little attention by modellers. Spring flow systems were modelled for example by Kordilla et al. (2012) and Levison et al. (2014). The study of Kordilla et al. (2012) focused on modelling karst systems using a double continuum approach and assessing the relative importance of various parameters on the flow dynamics of karst springs. In contrast, Levison et al. (2014) modelled low-flow bedrock springs of Covey Hill, Canada. The author investigated the performance of HGS to simulate the dynamics of intermittent headwater springs to supply spring discharge data for ecohydrological research on endangered salamander species (Levison et al. 2014). The model domain (4500 m long and 100 m wide) represented a part the Covey Hill slope and was discretised to 1m × 1m cells to capture the dynamics of small-scale low-flow springs (Levison et al. 2014). In study, it was assumed that groundwater flows only through bedrock fractures represented by discrete slanted and vertical fractures of a given apertures and spacing (Levison et al. 2014). According to the author current knowledge, springs associated with esker aquifers have not been modelled using integrated physically-based models.

4 HYDROGEOSPHERE MODEL

4.1 About Software

The HydroGeoSphere, subsequently refereed as HGS, is a fully-integrated physically-based GW-SW partial differential equation model. The model was developed by R. Therrien as a part of his doctoral work under the supervision of E. A. Sudicky and it was inspired as other integrated physically based models by the blueprint paper of Freeze and Harlan (1969) (Brunner and Simmons 2012). HGS derives all key components of hydrologic cycle from precipitation, i.e., overland and stream flow, evaporation, infiltration, recharge and subsurface discharge (Aquanty 2015). The software utilizes fully-implicit coupling approach to solve the model equations simultaneously by the control volume finite element method (Aquanty 2015). Thus, the model is capable to include feedbacks between various hydrologic processes and allows to simulate small and large scale systems in a physically-based manner (Aquanty 2015). A wide range of flow boundary conditions for subsurface and surface flow can be applied, including among others: free-drainage, interception, evapotranspiration, pore water freezing and thawing. Non-linear equations are solved using Newton-Raphson linearization techniques or Picard approach for weakly non-linear problems (Aquanty 2015). The matrix of discretised model domain is solved efficiently by parallelized iterative solver (Aquanty 2015). In addition, the software provides an adaptive time stepping option to speed up computation times (Aquanty 2015).

The performance of the model was verified in numerous verification examples. The software was successfully applied to a wide range of hydrological problems, including variably-saturated flow modelling of small-scale study sites (e.g., Frei and Fleckenstein 2014; Park et al. 2011; Smerdon et al. 2007) and large-scale watershed modelling (e.g, Ala-aho et al. 2015b; Li et al. 2008; Jones et al. 2008). The model was applied for solving both simple (e.g., steady-state saturated flow) and complex (e.g., heat and solute integrated flow) problems, such as the disconnection between surface water and groundwater, flow in fractured rock hydrology, contaminant transport, river bank storage processes, geothermal energy, dual permeability systems and reclamation of oil sands (adopted from Brunner and Simmons 2012). In addition, the model was successfully employed to study climate change effects on groundwater resources by Goderniaux et al. (e.g., 2009) and von Gunten et al. (2015)

The following sections describe shortly the model's governing equations and principles. Unless otherwise noted, this theory part is based on software manual

(Aquanty 2015). The full description of model implementation can be found in the HGS manual Aquanty (2015).

4.2 Governing processes and equations

4.2.1 Subsurface flow

The HGS has ability to simulate subsurface media flow in both saturated and unsaturated conditions. Three-dimensional transient flow in porous medium is modelled through the modified form of Richards' equation:

$$\nabla \cdot (w_m \mathbf{q}) + \sum \Gamma_{ex} \pm Q = w_m \frac{\partial}{\partial t}(\theta_s S_w) \tag{1}$$

where w_m represents the dimensionless volumetric fraction of the total porosity occupied by the porous medium ($w_m = 1$ for single medium continuum). Γ_{ex} is the volumetric exchange rate [$\mathrm{L}^3\mathrm{L}^{-3}\mathrm{T}^{-1}$] between subsurface and other domain types (e.g. surface domain, wells, tile drains, discrete fractures and dual continuum). Q represents source/sinks [$\mathrm{L}^3\mathrm{L}^{-3}\mathrm{T}^{-1}$] to porous domain from the domain outside the simulation. θ_s (dimensionless) indicates saturated water content, S_w degree of water saturation (dimensionless) and t indicates time [T].

The fluid flux $\mathbf{q}$ [LT^{-1}] is given by Darcy's equation:

$$\mathbf{q} = \mathbf{K} \cdot k_r \nabla(\psi + z) \tag{2}$$

where $\mathbf{K}$ is hydraulic conductivity tensor [LT^{-1}]
k_r is the relative hydraulic conductivity (dimensionless)
ψ is the pressure head [L]
z is the elevation head [L]

The right-hand of side of equation (1) represents the changes in the fluid mass storage in terms of water saturation. Assuming constant bulk compressibility of the medium for saturated conditions and insignificance of compressibility effects on storage for unsaturated conditions, the storage term can be approximated as (Cooley 1971; Neuman 1973):

$$\frac{\partial}{\partial t}(\theta_s S_w) \approx S_w S_s \frac{\partial \psi}{\partial t} + \theta_s \frac{\partial S_w}{\partial t} \tag{3}$$

where S_s indicates the specific storage coefficient of porous medium (L^{-1})

The solution of the equation (1) requires definition of the relations between pressure head ψ, saturation S_w and relative permeability k_r. These relations are defined in HGS by Brooks and Corey (1964) and Van Genuchten (1980) functions as well as can be handled by providing experimental data (Aquanty 2015).

The Brooks and Corey saturation-pressure functions are given by the following equations:

$$\begin{aligned} &S_w = S_{wr} + (1 - S_{wr})\,|\alpha\psi|^{-\beta} && \text{for } \phi < -1/\alpha \\ &S_w = 1 && \text{for } \phi \geq -1/\alpha \end{aligned} \tag{4}$$

with the relative permeability:

$$k_r = S_e^{(2/\beta + l_p + 2)} \tag{5}$$

where α indicates inverse of air entry pressure [L^{-1}], β is pore-size distribution index (dimensionless) and l_p is pore-connectivity parameter (dimensionless). S_{wr} represents residual water saturation (dimensionless) and S_e is effective saturation defined as:

$$S_e = (S_w - S_{wr})/(1 - S_{wr}). \tag{6}$$

The saturation-pressure relation proposed by Van Genuchten (1980) is given by the equations:

$$\begin{aligned} &S_w = S_{wr} + (1 - S_{wr})\left[1 + |\alpha\psi|^{\beta}\right]^{-\nu} && \text{for } \phi < 0 \\ &S_w = 1 && \text{for } \phi \geq 0 \end{aligned} \tag{7}$$

and the relative permeability:

$$k_r = S_e^{(l_p)}\left[1 - \left(1 - S_e^{1/\nu}\right)^{\nu}\right]^2 \tag{8}$$

where α and β are experimentally defined parameters and ν is defined as:

$$\nu = 1 - \frac{1}{\beta},\ \beta > 1. \tag{9}$$

4.2.2 Surface flow

In HGS, the surface flow is solved using the 2-D diffusion-wave Saint Venant approximation:

$$\frac{\partial \phi_0 h_0}{\partial t} - \frac{\partial}{\partial x}(d_0 K_{0x}\frac{\partial h_0}{\partial x}) - \frac{\partial}{\partial y}(d_0 K_{0y}\frac{\partial h_0}{\partial y}) + d_0\Gamma_0 \pm Q_0 = 0 \tag{10}$$

where d_0 is the depth of the flow [L] and h_0 represents elevation of water surface [L] and K_{0x} and K_{0y} are surface conductances in x- and y-directions [LT^{-1}]. ϕ_0 indicates porosity of surface flow domain, Γ_0 is fluid exchange between surface and subsurface systems [LT^{-1}] and Q_0 represents volumetric flow rate per unit area from source/sinks [LT^{-1}].

The conductance terms K_{0x} and K_{0y} are defined using Manning equation, Chezy equation or Darcy-Weishbach relation, i.e., commonly used empirical formula that describe averaged velocity of one-dimensional steady open-channel flow (Dingman 2008, p. 426-427). Using Manning equation, the conductances K_{0x} and K_{0y} are given by (Aquanty 2015):

$$K_{0x} = \frac{d_0^{2/3}}{n_x} \frac{1}{[\partial h_0 / \partial s]^{1/2}} \tag{11}$$

and:

$$K_{0y} = \frac{d_0^{2/3}}{n_y} \frac{1}{[\partial h_0 / \partial s]^{1/2}} \tag{12}$$

where s inicates maximum slope [L] and n_x and n_y are Manning roughness coefficients [L$^{-1/3}$ T] in x- and y- directions.

The implemented Saint Venant approximation neglects the inertial effects of surface flow, i.e., water ability to resist the changes in flow speed and direction. Furthermore, the Saint Venant equation (10) assumes depth-averaged flow velocities, vertical distribution of hydrostatic pressure, mild slopes and dominance of bottom shear. The usage of the equation also requires the assumption of validity of Manning equation, Chezy equation or Darcy-Weishbach relation. (Aquanty 2015)

Surface topography is a governing factor of surface and groundwater flow at small and large scales. Through numerical simulations Frei et al. (2010) showed that surface micro-topography has adverse effect on surface flow generation in wetlands and can cause distinct shifts in surface and subsurface flow dominance. The surface flow activation occurs after the small-scale depressions are partly filled with water, however, the process is highly non-linear and hysteric (Frei et al. 2010). In HGS the effects of micro-topography are accounted by the parameters of rill storage (depression storage) and obstruction storage. The rill storage $\mathrm{h_d}$ denotes a minimum storage that must be filled before any surface flow can occur and represents the effects of local depressions in surface. The obstruction storage $\mathrm{h_o}$ accounts for the storage exclusion caused by the presence of vegetation and urban features e.g. buildings and has impacts on horizontal flow through increase of friction and additional energy dissipation. In the HGS, the disturbance of depressions and obstructions is represented by porosity ϕ_0 of surface flow domain that changes according a parabolic function from zero at land elevation L.S. to unity at combined height of depression storage and obstruction storage $\mathrm{h_s}$. The graphical representation of this concept is shown in Figure 3.

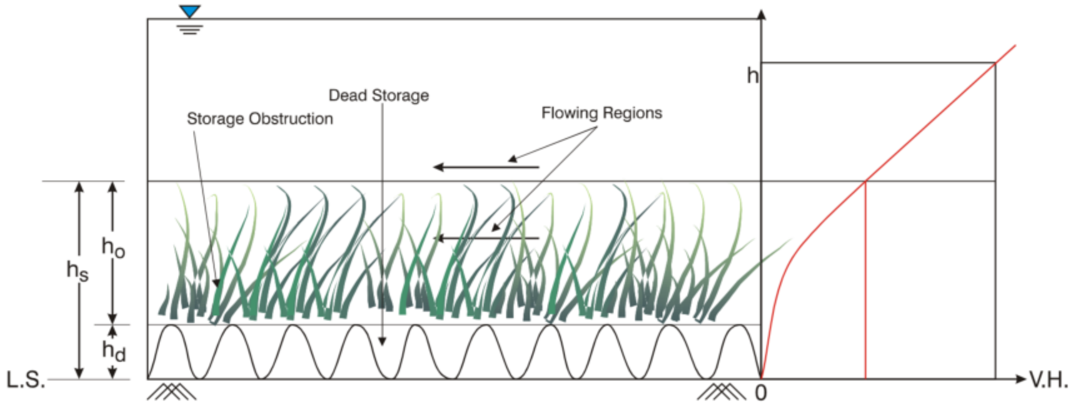

Figure 3. Conceptual model for depression storage and obstruction storage exclusion. L.S. represents surface elevation, i.e., the elevation of top of underlying subsurface node. $\mathrm{h_d}$ and $\mathrm{h_o}$ are respectively rill storage and obstruction storage. $\mathrm{h_s} = \mathrm{h_d} + \mathrm{h_o}$ denotes the combined height of depression storage and obstruction storage over which porosity of surface flow domain ϕ_0 is unity. Volumetric height V.H. represents a height from land surface containing the same volume of water as $\mathrm{h_s}$ without rills and obstructions. (Picture: Aquanty 2015)

4.2.3 Flow coupling

Two various approaches can be used to couple the surface to the subsurface: common node approach (Therrien and Sudicky 1996) and dual node approach. The first method assumes the continuity of hydraulic head between surface domain and porous medium. The approach is based on superposition leading to immediate equilibrium between both systems, and thus it does not result explicit exchange term.

The dual node approach utilizes the conductance concept in which two domains are separated by a physical interface (Kollet and Maxwell 2006). In HGS model, it is assumed that this interface is a possibly thin layer of porous material. The fluid exchange rate $d_0\Gamma_0$ between the surface and subsurface systems is defined by the Darcy flux relation and depends on difference between hydraulic heads of two domains:

$$d_0\Gamma_0 = \frac{k_r \mathbf{K_Z}}{l_{exch}}(h - h_0) \tag{13}$$

where $\mathbf{K_Z}$ indicates saturated hydraulic conductivity of porous medium. Coupling length l_{exch} is a numerical parameter that quantifies exchange between the surface and subsurface continua. According to studies of Ebel et al. (2009), the choice of coupling length parameter does not affect results in respect of hydrographs and GW-SW interactions if the coupling value is lower than a given threshold value. The k_r represents relative permeability for exchange flux that is equal to the retaliative permeability of porous medium when water flows from subsurface to surface. In case of flow from surface to subsurface, k_r is related by water depth d and the obstruction height H_s:

$$k_r = \begin{cases} \left({}^{d_0}/_{H_s}\right)^{2(1-{d_o}/{H_s})} & \text{when } d_0 < H_s \\ 1 & \text{when } d_0 < H_s \end{cases} \tag{14}$$

In addition, HGS allows to define the water exchange between other domains in a flexible way. The software numerous provide options for flow coupling between porous medium and other domains, such as discrete fractures, second continuum, wells, tile drains, surface and channels.

5 KÄLVÄSVAARA STUDY CASE

5.1 Site description

Kälväsvaara is an esker aquifer located in Northern Finland, approximately 90 km from the city of Oulu (Figure 4). The aquifer was formed during last deglaciation period and it is a part of a long esker ridge stretching from the gulf of Bothnia inland up to Suomusalmi, Eastern Finland. The esker belongs the Viinivara groundwater area together with other eskers located in the vicinity: Kokkomaa esker, Viinivaara esker, Pitääminmaa esker, Sarvivaara esker and Vaananharju esker. According to Köppen's climate classification, the area belongs to "temperate coniferous-mixed forest zone with cold, wet winters" (Kersalo and Pirinen 2009, p. 11) with annual average temperature 1.5 °C (Kersalo and Pirinen 2009, p. 125). The precipitation

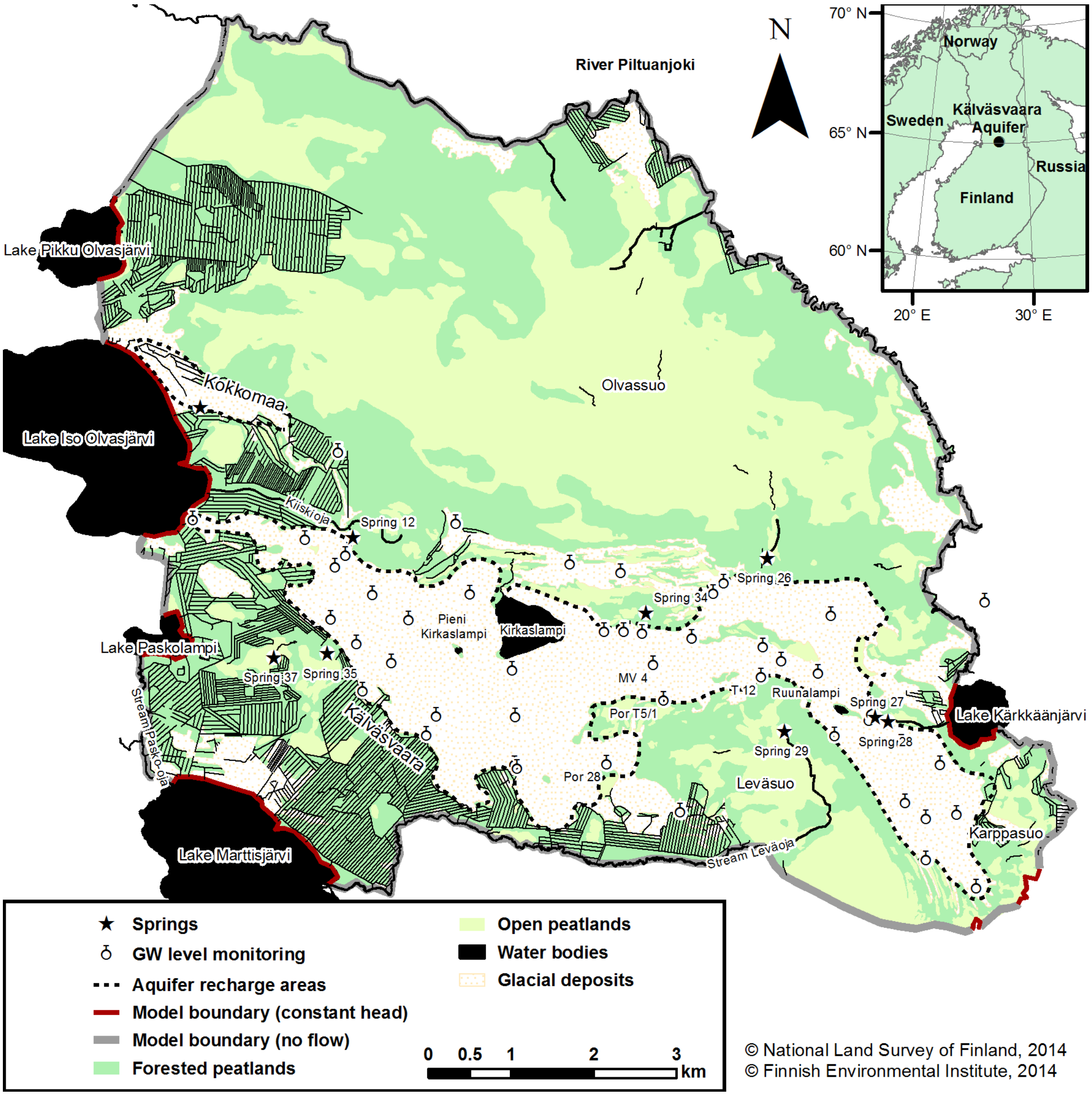

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Figure 4. The study site of the Kälväsvaara esker aquifer, Northern Finland.

in the area amounts 600-650 mm (Kersalo and Pirinen 2009, p. 11) and potential evapotranspiration is around 300 mm (Vakkilainen 1986, p. 79).

Kälväsvaara is a complex unconfined esker aquifer with characteristics of delta structure in its central part whereas the north-western part of the formation resembles a typical esker (Natura Borealis Oy 1995). The aquifer recharge area is estimated to 14.47 km^2, whereas the groundwater protection area covers 25.49 km^2 (Finnish Environmental Institute 2014). The aquifer rises up to 50 m above the surrounding peatland landscape up to 180 m asl at its highest (National Land Survey of Finland 2014b) and it is covered to a large extent by Scots pine. The esker is anticline type as it mainly discharges water to adjacent wetlands (Maa ja Vesi Oy 1993). The area has typical, for esker formation, a rolling terrain with numerous ”kettle holes” (Natura Borealis Oy 1995), i.e., depressions in the esker surface created during last deglaciation period as blocks of ice deposited together with sand and gravel material melted in later periods (Mälkki 1999, p. 69-71). Most of the kettle holes are dry, but few small lakes and ponds intersperse the esker from which the most significant are Iso Kirkaslampi lake and Pieni Kirkaslampi and Ruunalampi ponds.

Kälväsvaara was originally formed under the water as at that time the sea water level was around 200 m higher than nowadays (Natura Borealis Oy 1995). When the sea water level later dropped, the vast areas of the hill top showed up simultaneously (Natura Borealis Oy 1995). Waves and pack-ice created large descending dune formations around the crest of the esker, whereas the top of the hill preserved its initial rolling form (Natura Borealis Oy 1995). As the sea water level were descending further, wave and wind action further sculpted the esker structure transporting sand along esker towards east and forming characteristic for the formation wide form (Natura Borealis Oy 1995). Majority of the dune gaps underwent paludification and today they are part of extensive peatland landscape surrounding Kälväsvaara (Natura Borealis Oy 1995).

The peatlands around the esker are mainly in a natural state, albeit a part of the landscape was ditched for the forestry purposes, e.g., areas situated west and south from the esker. Nevertheless, the peatlands surrounding Kälväsvaara esker aquifer have high environmental value. Olvassuo located north from the aquifer is an example of a natural state Aapa peatland and provides important habitat for rare and endangered species including among others: Saxifraga hirculus, European otter, brown bear, lynx and numerous birds, e.g., boreal owl, northern hawl-owl and red-throated loon (Heikkilä et al. 2011). The value of this mire ecosystem was noticed already in 1960s when the protection of area has been proposed for the first time (Heikkilä et al. 2011). Today, the major part of the esker area with its adjacent peatlands are included in the Olvassuo NATURA 2000. Furthermore, the natural-state wetlands are protected under Finnish natural conservation programs and the streams and rivers around Olvassuo belong to the Kiiminki river catchment that is also protected as a NATURA 2000 site. Recently, the ecological values of the area were improved by restoring the old ditch system in the south part of the Olvassuo mire. The wetlands around Kälväsvaara play an important role in reindeer husbandry as natural grazing sites.

A major part of groundwater exfiltrates to adjacent wetlands by diffusive seepage mechanism (Natura Borealis Oy 1995; Maa ja Vesi Oy 1993). Nonetheless, many groundwater springs occur around esker (Figure 4) (Natura Borealis Oy 1995; Heikkilä et al. 2011), from which the most significant is Kiiskioja spring (spring no. 12). Various visible morphological features of the springs and their setup indicate that the mechanisms responsible for spring flow can differ considerably. Figure 5 illustrates two springs of the Kälväsvaara esker area that differs in terms of flow mechanisms and topographic setup.

Owning to the good quality of water and its close location to the city of Oulu, Kälväsvaara together with other eskers belonging to Viinivaara groundwater area were considered as a possible source water for the city of Oulu (Maa ja Vesi Oy 1993; Natura Borealis Oy 1995; Heikkilä et al. 2011; Rantala et al. 2014). The first plans to use Kälväsvaara groundwater originated already in 1980s (Maa ja Vesi Oy 1993). The initial plans presumed to use groundwater as a backup water source for the city during crisis situations. Later, the plans evolved and the solutions extracting larger amounts of water were favoured with a final proposal to use the Viinivaara groundwater area as a main source of water for Oulu. Concerns related to the project's environmental impact triggered a strong opposition of local residents (Kløve et al. 2011b). The main concerns were related that the large-scale pumping may decrease overall groundwater levels and surface levels of clear-water lakes and could affect groundwater-dependent rivers and streams (Kløve et al. 2011b). There were also fears that water extraction may led to destruction of the Olvassuo wetland, as rare Aapa peatland ecosystem can be highly sensitive to small changes in groundwater regime (Kløve et al. 2011b). After long processing in the legal system, the permit for water extraction was approved in 2011 (Kløve et al. 2011b). The ruling induced many appeals and in 2012 the Finnish Supreme Administrative Court rejected the permit (Rantala et al. 2014). The plans, however, have not be abandoned and in May 2015 the city of Oulu chose the Viinivaara groundwater area as a backup water source for the city (Rantala et al. 2014). The permit process is under way at the moment.

(a)

(b)

Figure 5. Springs at the Kälväsvaara esker area: a) the large pressurized spring of Kiiskioja (spring no. 12) b) moderate-size spring located in the west part of the Leväoja fen (spring no. 35). (Pictures: Jaros 2015)

5.2 Previous studies and data used in modelling

The Kälväsvaara esker aquifer has been studied thoroughly since 1984 when the idea of utilizing Kälväsvaara for the water supply of Oulu was first originated (Maa ja Vesi Oy 1993). Since then, numerous geologic, hydrologic and ecological surveys were conducted in this area . The measurements included among others: pumping tests, water level measurements, spring discharge measurements, water quality measurements, borehole drilling, soil analysis and geophysical measurements. These surveys were conducted by numerous organisations, including Oulun Vesi - the water supply company of Oulu, the Maa- ja Vesi Oy consult company (at present Pöyry), Centre for Economic Development, Transport and the Environment (ELY-centre) of North Ostrobothnia, Finnish Forest Research Institute (Metla) and the Departments of Geology and Geophysics of Oulu University.

The majority of data used in this study was provided by ELY-centre. The data includes spring discharge measurements, groundwater level measurements, borehole data, Kirkaslampi lake bathymetry data and geophysical measurements of the adjacent peatlands. In addition, this thesis utilized information presented in the reports by Natura Borealis Oy (1995), Maa ja Vesi Oy (1993) and Heikkilä et al. (2011) to create conceptual model of the area. The bedrock definition used the results of seismic measurements published in Maa ja Vesi Oy (1993). Furthermore, Elevation Model (DEM) provided by National Land Survey of Finland (2014b) was used to accurately estimate surface elevations of the model domain. The monitoring sites at the Kälväsvaara study area are shown in Figure 4.

5.3 Geological model

The conceptual geological model of the study area was defined using the existing data collected from earlier studies (Figure 6). The geological structure of the aquifer has been examined by numerous surveys, including shallow and deep borehole drillings and seismic refraction/reflection measurements and GPR measurements. These surveys revealed that Kälväsvaara is geologically complex. The bedrock is covered by 17 m to 83 m of heterogeneous glacial sediments. Elevation of the bedrock surface ranges from 71 m asl up to 135 m asl. The seismic lines indicate that changes in the bedrock elevation can be abrupt and are characterized by high slopes.

The bedrock is overlain by intertwining layers of silt, sand, gravel, boulders and glacial till. In addition, fractured bedrock was found in two boreholes in the east part of the esker and other two in the west-south part. The changes in soil stratigraphy are considerable and thus, large-scale continuous stratigraphical units could not be defined. The previous geological surveys revealed that locally low permeability till soil and bedrock rises can block groundwater flow (Natura Borealis Oy 1995). Such groundwater flow disconnecting structures are located south-east from Iso Kirkaslampi and under Pieni Kirkaslampi pond (Natura Borealis Oy 1995).

Whereas the porous media of Kälväsvaara esker aquifer is heterogeneous, the geological setting of adjacent areas is relatively homogeneous. The bedrock around

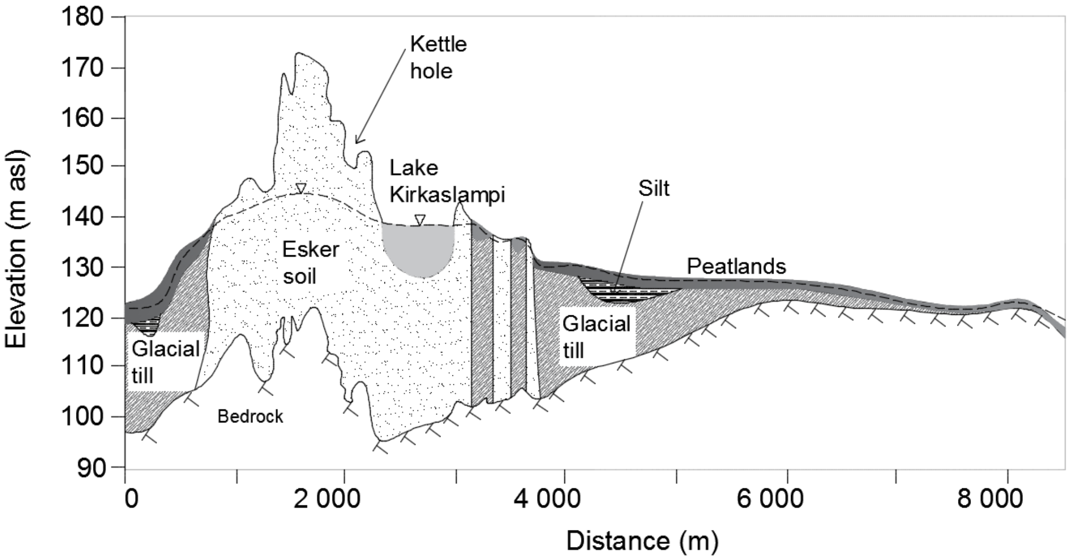


Figure 6. Conceptual geologic model of Kälväsvaara. Note that for clarity intertwining layers of silt, sand, gravel, boulders and glacial till are represented by esker soil.

the esker is predominantly covered by silt till and other types of moraine soils. The moraine layer is overlain by natural and modified peatlands with silt lenses in between. Total depth of overburden ranges from zero to over 15 m with an average depth around 7.5 m, whereas the depth of peat varies from 10 cm up to 5 m, with an average of 1.8 m. These overburden estimates are based on shallow borehole drillings and GPR measurements.

5.4 Application of HydroGeoSphere to the Kälväsvaara esker aquifer

The HGS model was employed to simulate surface and subsurface flow in the Kälväsvaara esker aquifer and its adjacent areas. The main objective of this work was to create a model that captures GW-SW interactions between Kälväsvaara and various GDE types present in the vicinity of the esker, i.e., fens, kettle hole lakes, streams and springs. This study also attempted to clarify how model should be scaled and what information is needed to model small-scale GDEs, such as springs. For simplification purposes simulations were run only in steady-state and the model was calibrated manually. The model results were evaluated by comparing the simulation output with expected trends and available field observations, including average groundwater and lake levels and discharge data of springs.

5.4.1 Model domain delineation

Model domain boundary

Most commonly the maximum extend of the model is constrained by the outer catchment boundary. In such cases, it is assumed that the boundaries of surface and subsurface catchment coincidence and all boundaries are no flow except for the catchment outlet. Water is allowed to freely leave the catchment by assigning critical depth boundary for the whole perimeter of the surface domain and no flow boundary for the subsurface. Since the Kälväsvaara esker and its adjacent areas cannot be comprised in any catchment without significantly increasing model domain, an alternative model domain delineation had to be applied. The aim was, however, to limit the study in a possibly "natural way" using topography and water bodies.

For this purpose, the model domain was decided to contain largest part of Olvassuo mire and was bounded by Piltuaanjoki river on the north and north-east and Leväoja stream on the south. The chain of lakes (Marttisjärvi, Paskolampi, Iso Olvasjärvi, Pieni Olvasjärvi) and linking streams constrained the model area on the west, whereas Kärkkäänjärvi lake and small water bodies of Karppasuo limited the area from the east. The south-east part of boundary between Karppasuo ponds and Leväoja stream was chosen arbitrary, however the boundary took the advantage of local depressions. The total area of the model domain amounted to 92.9 km^2.

Surface elevation

The surface elevation of the model domain was defined using 10 m $\times$ 10 m digital elevation model (DEM) provided by the National Land Survey of Finland (2014b). The DEM gives only the information about the water table elevation for water bodies. For this reason, the DEM must be transformed to represent accurately the actual land surface, i.e., depressions under lakes and streams. The elevation under Iso Kirkaslampi lake was adjusted according to the bathymetric data, whereas the surface elevation under other lakes and ponds was lowered by 6 m. This chosen value for lake depths represents the average lake depth in Finland. Similarly, the land surface under stream beds was lowered 0.5 m and smoothed manually. The DEM data was used to define a continuous downward gradient from upstream to downstream in order to increase speed of simulations and reduce ponding.

Bedrock elevation

The bottom of model domain is defined by bedrock surface elevation. The bedrock depth information was obtained by combining the results of some previous geologic surveys in form of point data set. The data combined included fully-penetrating borehole drillings, seismic refraction/reflection measurement lines, GPR lines and GPR auxiliary hand borehole drillings and bedrock outcrop information from basic map (National Land Survey of Finland 2014a). The bedrock depth information was then interpolated using ArcGIS topography method and subsequently subtracted from the DEM data to derive elevation. To sustain numerical stability interpolated bedrock was adjusted by increasing the depth of bedrock to 3 m in the areas where the depth was lower than this threshold, i.e., in small patch at the center of the Olvasssuo mire and on the south edge of Olvassuo.

5.4.2 The conceptual model and domain discretization

The conceptual model of the Kälväsvaara esker aquifer shown in Figure 6 was used as the basis of construction of the numerical model (Figure 7). The finite element grid for the model was generated using mesh generation software GRIDBUILDER. The two dimensional overland flow domain was discretised using 20935 triangular elements and 10700 nodes. In order to better capture GW-SW interactions the grid was refined around esker recharge boundaries, streams and lakes. The resulting distance between nodes varied in plan view from 14 m close to the features of interest up to 210 m in other areas, with an average segment length of 90 m.

The nodes of surface domain coincided with the top layer of the subsurface flow domain, which was discretised using triangular prismatic finite elements. The corrected surface elevation raster was used to assign nodal elevations for the nodes of the overland domain and the top layer of porous domain. The bottom nodes of the subsurface domain were given values of the adjusted bedrock raster. The porous media domain consisted of 117700 nodes and 209350 elements divided vertically into 10 layers. The bottoms of first 8 layers were located at 0.05, 0.1, 0.15, 0.25, 0.4, 0.65, 1.05 and 1.8 m depths below ground surface in order to represent better the flow in partially saturated medium. The bottom of the last layer (1.8 m depth) represents the average depth of peat layer of the area. In addition, the model included two layers with proportional thickness 34% and 66% of total remaining soil column depth to incorporate highly variable depth of the overburden.

The surface domain was divided into 3 zones representing distinct overland surfaces: sand (mineral) soils, peat and stream channels (Figure 7). The surfaces differed in respect of subscribed surface flow properties (Table 3). The parameters were mainly derived from the literature and their choice was predominantly based on the work of Ala-aho et al. (2015b) on Rokua esker aquifer, located 60 km from Kälväsvaara.

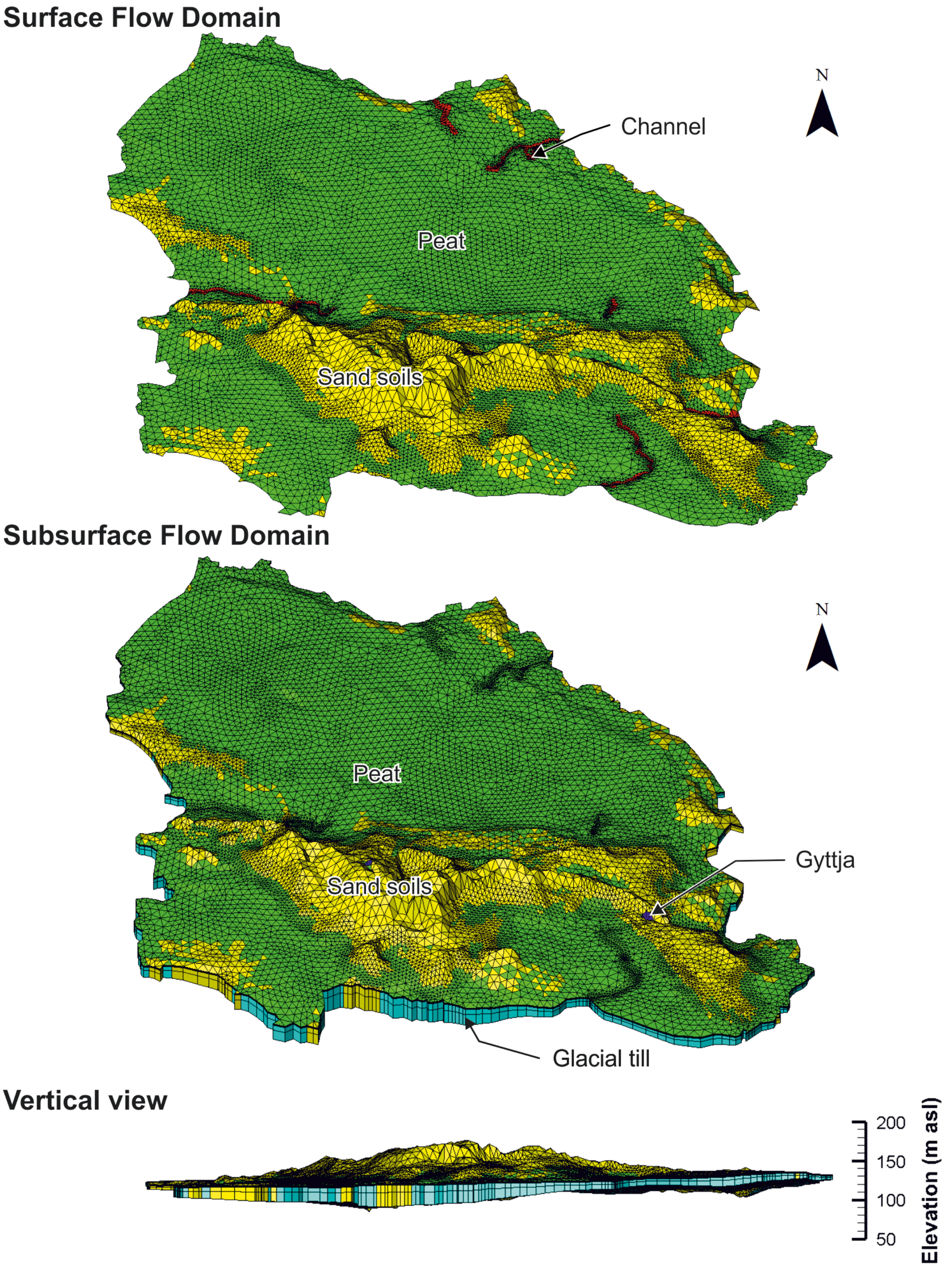


Figure 7. Conceptual model of Kälväsvaara of overland domain (upper diagram), subsurface domain (centre) and side view (bottom). Vertical exaggeration is 20:1

The channel zone properties were given to the elements adjacent to the streams, whereas the peat properties were assigned to spatial distribution of forested and open peatlands derived from the base map of National Land Survey of Finland (2014a). Other areas were represented by sand (mineral) soils.

The subsurface domain of the model consists of four media types: sand, peat, gyttja and glacial till as show in Figure 7. The zone hydraulic properties were derived mainly from literature and analogically to surface model domain, their choice followed the values by Ala-aho et al. (2015b), besides the hydraulic conductivities of the mineral soil and glacial till that were calibrated manually by trial-and-error method. The calibration procedure is discussed in more detail in section *5.4.5 Model calibration*. The peatlands surrounding Kälväsvaara are represented by assigning peat soil properties to spatial extend of peatlands within uniform depth of 1.8 m, i.e., the average peat depth. The soil under wetlands was assumed to consist of glacial till, whereas sand material occupies the whole column of subsurface domain in the places where no peatlands exists according to the base map.

Gyttja is an organic sediment covering lake bottoms consisting of highly decomposed peat (Pajunen 1995). Gyttja sediments originated from ancient peatlands located in the bottoms of kettle-holes. As later groundwater level rose, the wetlands were submerged and small lakes and ponds created (Pajunen 1995). The presence of gyttja layer can affect lake-groundwater interactions (e.g., Smerdon et al. 2007). For this reason, hydraulic properties of gyttja were assigned to elements located within the bottoms of two lakes of Kälväsvaara: Pieni Kirkaslampi and Ruunalampi. These small water bodies are located in the kettle holes and their adjacent environment indicate that there is high probability of organic sediments. The gyttja sediments extended vertically to the depth of 1.8 m under the lake bottoms and it was assumed that gyttja has the same hydraulic properties as peat, as proposed by Ala-aho et al. (2015b). In addition, peat layers were assumed to cover the small pond bottoms within fens.

5.4.3 Boundary conditions

The boundary conditions assigned to the subsurface domain of the model fell into two categories: prescribed head boundaries and no flow boundaries. Constant head boundary conditions were assigned to subsurface domain restricted by lakes. The prescribed head values were defined as the average lake levels calculated from the lake level data provided by ELY-centre with exception of two small water bodies located on the east boundary of the model, at Karppasuo peatland. These ponds were prescribed the steady head values equal to the land elevation as no water level observations were available and the DEM data did not indicate any constant values for the water levels.

Other segments of the model perimeter were modelled as no flow boundaries. These segments coincidence mainly with stream and river channels and thin thickness of overburden. A main rationale for assuming no flow conditions under the streams around water domain is based on the assumption that the bedrock surface follows the land elevations on the borders of the model. As these streams flow in local depressions groundwater flow through boundary is assumed to be insignificant and thus, the flow in subsurface domain occurs mainly along the border of the model. If groundwater table exceeds the land elevation, groundwater discharges to surface. The water was allowed freely to leave the surface domain by assigning the critical depth boundary conditions to the model surface domain. The critical depth boundary permits changes in discharge without any constraints and thus, prevent water accumulation. Finally, a no flow boundary conditions was also assigned to the bottom of the domain as the bedrock was assumed to be impermeable.

5.4.4 Other settings

The steady-state solution ignores all terms dealing with time. This means that many non-linear terms of equations are disregarded what can lead to inaccuracy in a complex model solution or even to false solutions. For this reason, it is recommended to use a time-marching approach for the steady-state solution in HGS. In practice, this means that the steady-state is obtained by running transient model with constant input conditions over a long period of time until the system reaches equilibrium. Therefore, the Kälväsvaara model was solved in the transient mode by a time-stepping approach. The steady-state of the system was accomplished by applying effective rainfall (315 mm/year) equal the average annual precipitation minus potential evapotranspiration over a period of 10 000 years of the model run. The value for mean annual precipitation (615 mm/year) was derived from the previous modelling study of the Viinivaara groundwater modelling conducted by Hakoniemi and Ikäheimo (2015). The potential evapotranspiration (300 mm/year) was taken from Vakkilainen (1986, p. 79), which is a typical value for Finland. In order to reduce simulation times, the model was run in the adaptive timestep mode, i.e., timestep values are modified automatically depending on the transient behaviour of the system (Aquanty 2015). In general, larger timesteps were allowed as the model converges.

Running model in a transient state requires use of initial conditions. An initial state for the first simulations was established by interpolating averaged water table levels from the groundwater monitoring points for the areas where measurements were available (Figure 4) and using 1 m lowered DEM surface for the rest of the model domain. The model complexity evolved with time and the results of subsequent simulations were used as initial conditions for following simulations. It was assumed that the results of previous simulations usually provided better estimation for the actual groundwater configuration. In that way, it was assured that starting point of a new simulation was possibly close to steady-state conditions and the simulation times were shorter.

The initial water depth applied equalled 10^{-4} m representing dry conditions. For simplification purposes, the model did not included the drainage system and disregarded soil heterogeneities within various zones. The subsurface and surface domains were coupled using dual node approach with a coupling length of 0.01 m.

5.4.5 Model calibration

The model calibration was conducted by so called manual calibration approach, i.e., the best set of parameters were searched by try-and-error method. As found by von Gunten et al. (2014) and Bonton et al. (2012) the outputs of integrated models are most sensitive to saturated hydraulic properties. For this reason, only hydraulic conductivities of esker soil material and glacial till underwent calibration process. Majority of other parameters were derived from literature and were mainly based on the parameter set proposed by Ala-aho et al. (2015b). The exceptions were rill storage and obstruction storage parameters for stream channels that were based on field observations.

The streams around Kälväsvaara flow mainly through peatlands and forest and are characterized by narrow but usually deep channels with dense vegetation on banks and bottoms (Figure 8). The vegetation increases friction and leads to additional energy dissipation. The effect of dense vegetation at the streams bottoms and banks was taken into account by adjusting the parameters of rill storage and obstruction storage. Consequently, these parameters are significantly higher than in the Rokua model by Ala-aho et al. (2015b).

The main calibration target was to match possibly well the observed groundwater and lake levels and the discharges of springs. The goodness of the calibration was assessed quantitatively using general statistical measures, such as maximum residual error, mean residual error, mean absolute residual error, mean squared error and goodness-of-fir R^2. The expressions of employed statistics are shown in Table 2. The best calibration set found in terms of these statistics is presented in Table 3. Additionally, Table 3 shows values for parameters derived form literature or estimated from field observations.

(a)

(b)

Figure 8. The small Heteoja stream passes through peatland and forest areas located in the east part of the Kälväsvaara study site. Narrow but reactively deep vegetated channel increases friction and affect flow velocities. (Pictures: Jaros 2015)

Table 2. Statistical measures used to evaluate the model's performance under various calibration sets.

Statistical measure	Mathematical expression
Maximum residual error	$MaxE = max\,\lvert C_i - O_i\rvert_{i=1}^{N}$
Mean residual error	$MRE = \frac{1}{N}\sum_{i=1}^{N}(C_i - O_i)$
Mean absolute residual error	$MARE = \frac{1}{N}\sum_{i=1}^{N}\lvert C_i - O_i\rvert$
Root mean squared residual error	$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(C_i - O_i)^2\right]^{0.5}$
Goodness-of-fit R^2	$R^2 = \frac{\left(\sum_{i=1}^{N}(C_i - \bar{C})(O_i - \bar{O})\right)^2}{\sum_{i=1}^{N}(C_i - \bar{C})^2\sum_{i=1}^{N}(O_i - \bar{O})^2}$

C indicates calculated data and O is observed data. $\bar{C}$ and $\bar{O}$ are respectively

$\bar{C}$ and $\bar{O}$ are respectively the means of the calculated and observed data.

Table 3. Used parameters that deviate from default values of the HGS software

Model domain	Parameter	Value		
Porous media		Sand soils	Peat	Glacial till
	Saturated K_Z (ms^{-1})	2×10^{-5} [1]	1×10^{-7} [2]	1×10^{-6} [1]
	Anisotropy ratio $K_Z : K_{XY}$	$1 : 10$ [1]	$1 : 1$ [3]	$1 : 1$
	Specific storage (m^{-1})	2×10^{-4} [4]	1×10^{-1} [3]	5.6×10^{-4} [5]
	Porosity	0.3425 [3]	0.86 [2]	0.21 [6]
	Residual saturation	0.044 [3]	0.058 [2]	0.003 [6]
	van Genuchten α	2.35 [3]	26.15 [2]	-
	van Genuchten β	2.38 [3]	1.39 [2]	-
	Air entry pressure (m)	-	-	0.3 [6]
	Brooks and Corey l_p	-	-	2 [6]
	Brooks and Corey β	-	-	0.31 [6]
Overland flow		Sand soils	Peat	Channel
	Manning's n ($\mathrm{m}^{-1/3}\mathrm{s}$)	0.6 [7]	0.6 [7]	0.004 [7]
	Rill storage (m)	0.1 [8]	0.1 [9]	0.1
	Obstruction height (m)	0.05 [3]	0.05 [3]	0.2
	Coupling length (m)	0.01 [3]	0.01 [3]	0.01 [3]

[1] calibration; [2] Päivinen (1973); [3] Ala-aho et al. (2015b); [4] Domenico (1972) in Ala-aho et al. (2015b); [5] Shaver (1998); [6] Jansson et al. (2005); [7] Jones et al. (2008); [8] Ala-aho et al. (2015a); [9] Frei and Fleckenstein (2014);

6 RESULTS AND DISCUSSION

6.1 Surface water levels and depths

Simulated surface water levels were evaluated at three lakes: Kirkaslampi, Pieni Kirkaslampi and Ruunalampi. As Figure 9 illustrates, the computed levels of Ruunalampi and Kirkaslampi lakes matched relatively well the corresponding field observations, albeit these values were slightly underestimated ($MRE = -0.71$ m). In contrast, the model was unable to reproduce the average water level of Pieni Kirkaslampi. The actual water level in the lake was around 6.6 m higher than the computed one. The discrepancy between the simulated and measured value is attributed to local heterogeneity of the esker soil. The previous geological surveys revealed that low permeability till soil overlays the kettle hole of the Pieni Kirkaslampi lake (Natura Borealis Oy 1995). In contrast, in the model the porous medium of the esker was represented as an uniform layer of a mineral (sand) soil through the whole aquifer depth beside in locations of gyttja layer. As a consequence, the model was unable to capture the effects of local heterogeneities of soil.

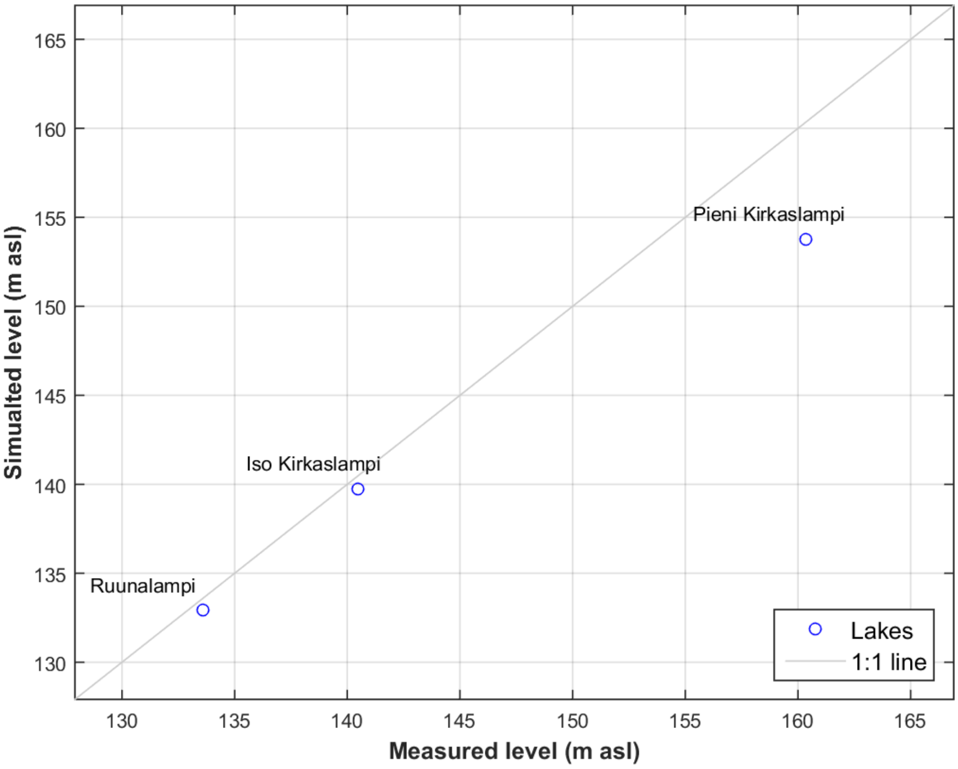


Figure 9. Comparison of simulated and observed water levels within lakes.

Figure 10 shows the spatial distribution of simulated surface water depths within the study area. For clarity, more detailed results for Pikku Kirkaslampi, Ruunalampi and two other small ponds are shown in Figure 11. The distribution of surface water depths was relatively well captured by the model. The depths of small lakes and ponds were consistent with assumed bathymetry in the majority of cases with an exception of the Pikku Kirkaslampi lake (discussed earlier). In peatlands, the areas of water accumulation are associated with depressions in the land surface. According to the air photos (National Land Survey of Finland 1996-2011), most of these water accumulation areas by the Kälväsvaara model are occupied by very wet wetlands or even small ponds located within the wetlands. One of the exceptions is an area located on the south border of the recharge zone, represented by a small patch with surface water depth of approximately 2 m. According to DEM data (National Land Survey of Finland 2014b), the ponded area by the Kälväsvaara model is situated in a depression leading to accumulation of water. The aerial photos (National Land Survey of Finland 1996-2011) do not, however, indicate presence of exceptionally wet peatland or pond in the area indicated by the model. While discrepancy could be explained by inaccuracy of the DEM data, it is more probable that the forestry

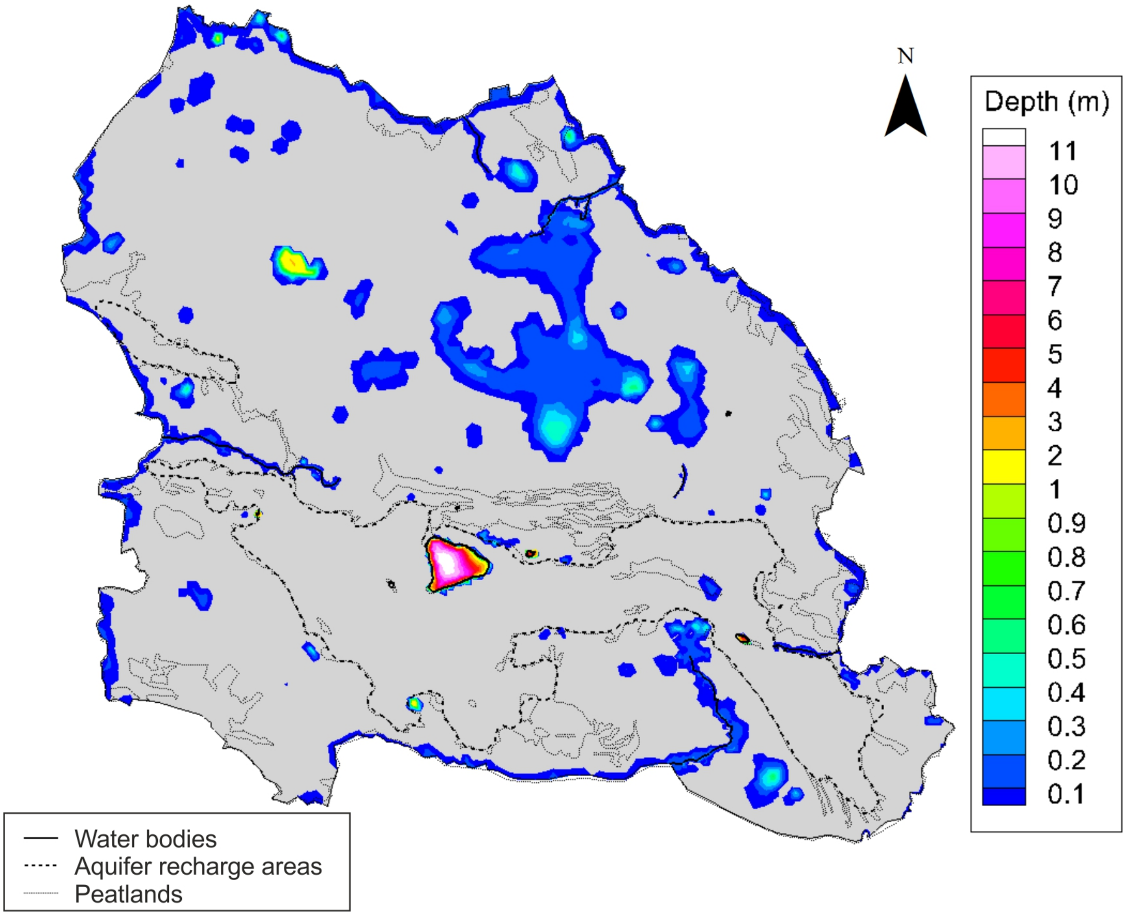
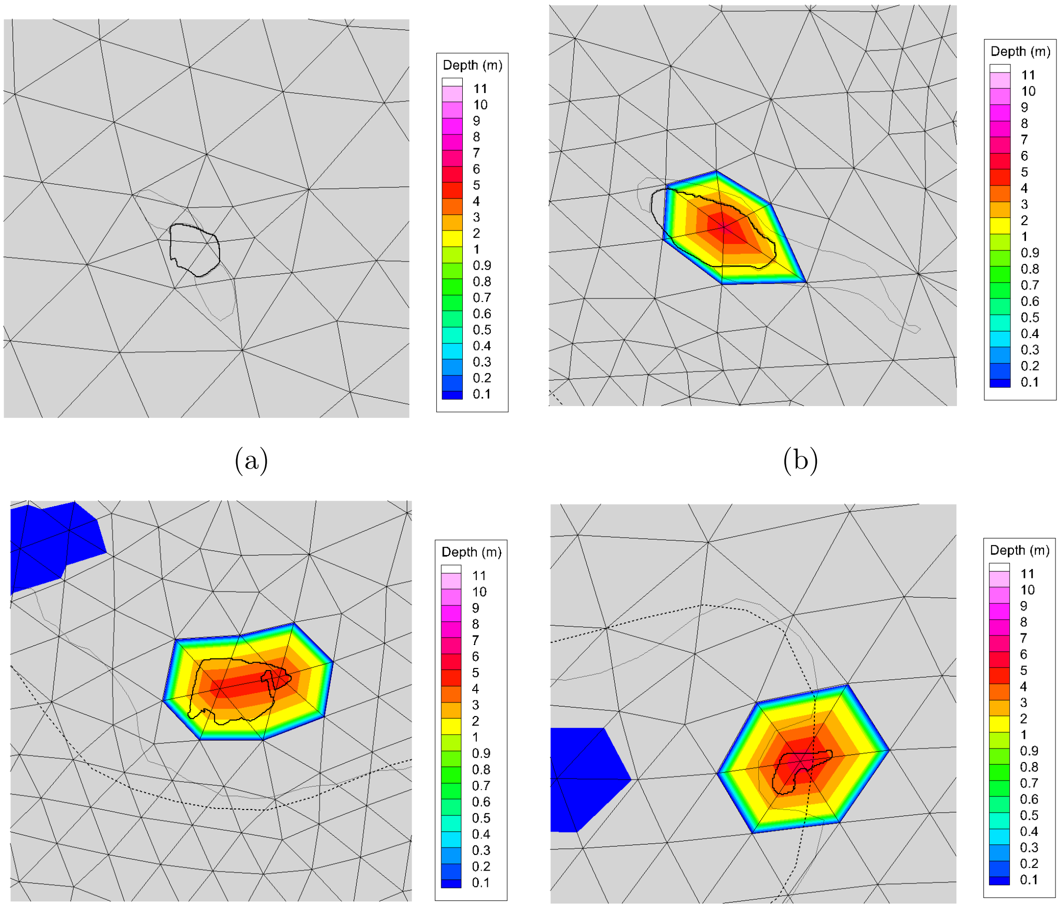


Figure 10. Surface water depths greater than 0.01m. Grey colour express water depth below this threshold.



(a) (b)

(c) (d)

Figure 11. Surface water depths within a) the Pikku Kirkaslampi lake, b) the Ruunalampi lake, c) the Leililampi pond, d) small pond located on the east boundary of the Kälväsvaara recharge area. Grey colour indicates cells with the surface water depth less than 0.01 m.

ditches located in the area efficiently drain water out of depression or the hydraulic conductivity values are locally higher than assigned ones.

On the other hand, some especially wet parts of the mire system were not reproduced by the model, e.g., north parts of the Leväsuo fen located west from the Leväoja spring (spring no. 29). Because DEM shows water surface elevation of water bodies and not the actual land elevation, some exceptionally wet wetlands were overlooked by the simulation. This implies also that the surface water depth within other areas are presumably under predicted. For this reason, it is reasonable to conclude that an accurate topographic representation of land surface is crucial to model explicitly surface water depths within wetlands. On the other hand, these results, though not perfect, indicate that the model successfully captured ”pondy” character of the peatlands adjacent to the esker. Such realistic and detailed representation of wetlands is an evidence that the surface water bodies are effectively reproduced as part of the simulations in the integrated GW-SW models. In contrast, such

”natural” formation of surface water bodies is not possible in traditional water resource modelling.

Finally, with respect to surface water depths, the attention should be paid to the occurrence of ponded water on the boundaries of the model area. The phenomena arises from the assigned boundary conditions and it is explained in detail in the subsection *6.4 Spatial patterns in GW-SW interactions.*

6.2 Groundwater table configuration

Simulated hydraulic heads were evaluated at 46 groundwater monitoring points (Figure 12). The computed values replicated relatively well the average groundwater levels measured at the monitoring sites. The relative error exceeded 5 % only in four piezometers. The interesting fact is that all of the observation sites with high relative error are located in the central part of the esker formation, south-east from the Kirkaslampi lake. The simulated water levels in Por T5/1 piezometer is largely underestimated, whereas the computed heads are over predicted in the rest of these four points. The large discrepancy between the average simulated value and mean of field observation at piezometer Por T5/1 is presumably caused by local heterogeneity. The area was reported to be a perched water table (Miettunen 2006). Excluding Por T5/1, the groundwater levels were weakly positively biased indicated by mean residual error equal to 0.11 m. The root mean square error amounted to 2.5 m and the mean absolute residual error was equal to 1.7 m. The goodness-of-fit $R^2 = 0.68$ demonstrates that the model works quite well but does not fully capture the variability in the groundwater levels within whole aquifer. It seems likely that the assumption of homogeneity of the esker soil reduce the goodness of the model. Water table configuration and depth to groundwater are shown in Figures 13 and 14. Note, that the highest values of water table elevation are most probably overpredicted as the simulations overestimated the groundwater levels for the piezometers Por 28, T 12 and MV 4 that are located within this high water table region.

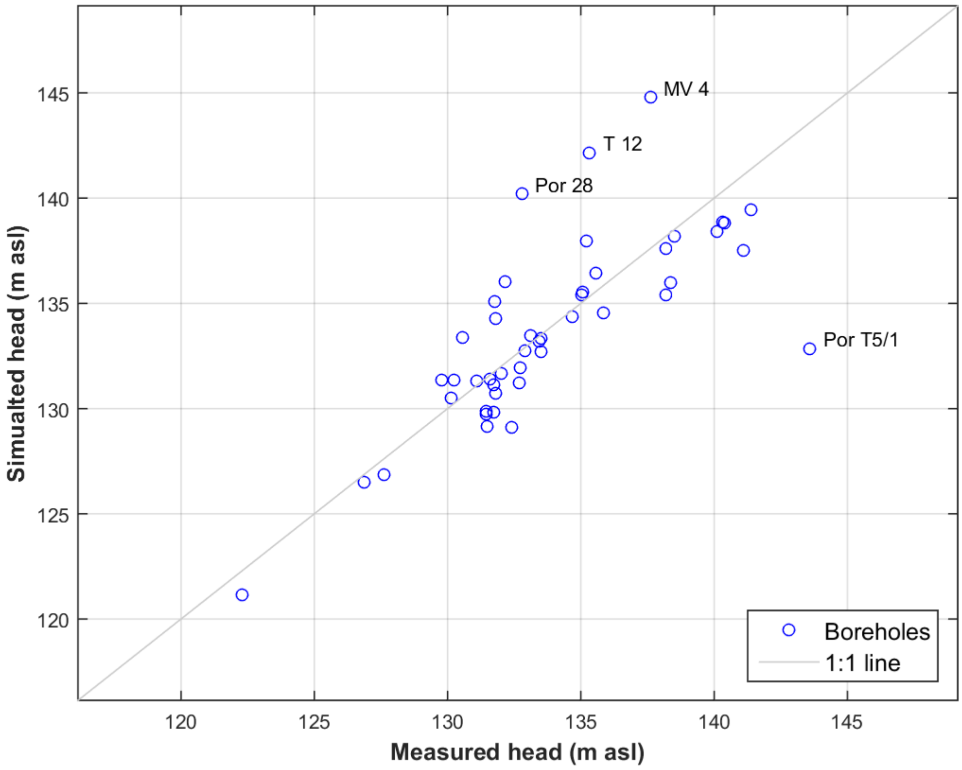


Figure 12. Steady-state simulated and measured hydraulic heads. The labelled points indicate monitoring well with relative error exceeding 5 %

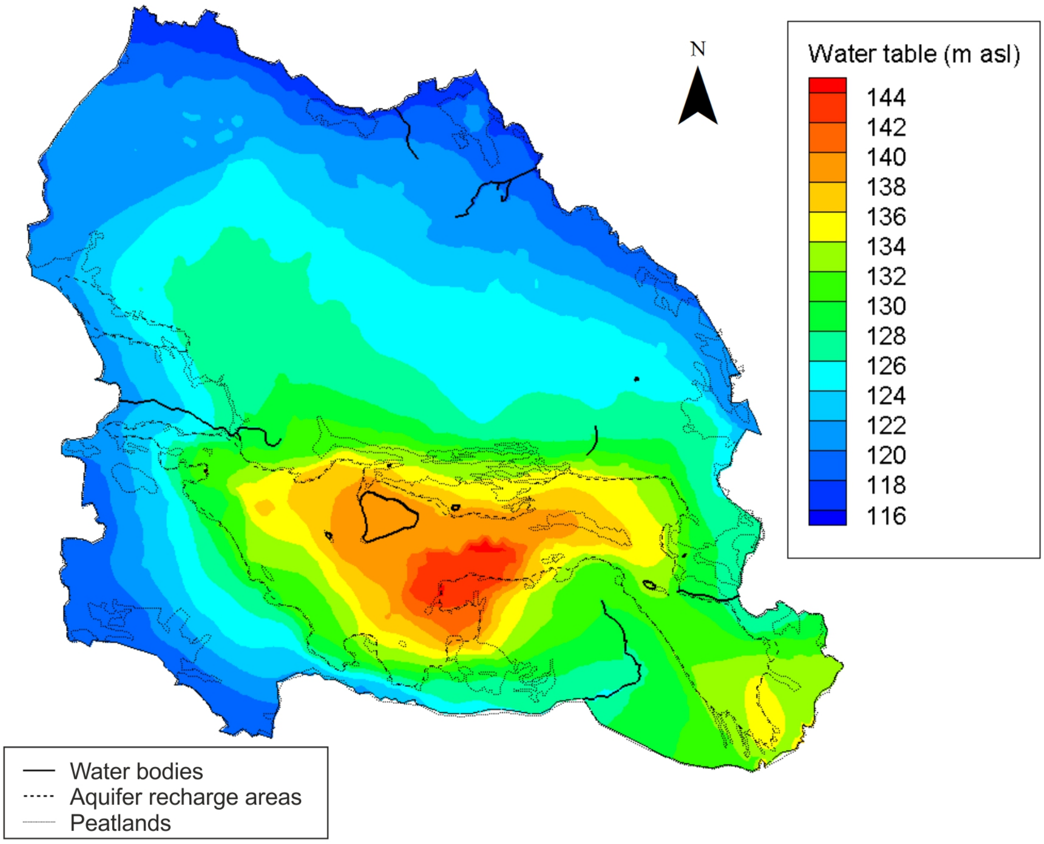


Figure 13. Water table configuration.

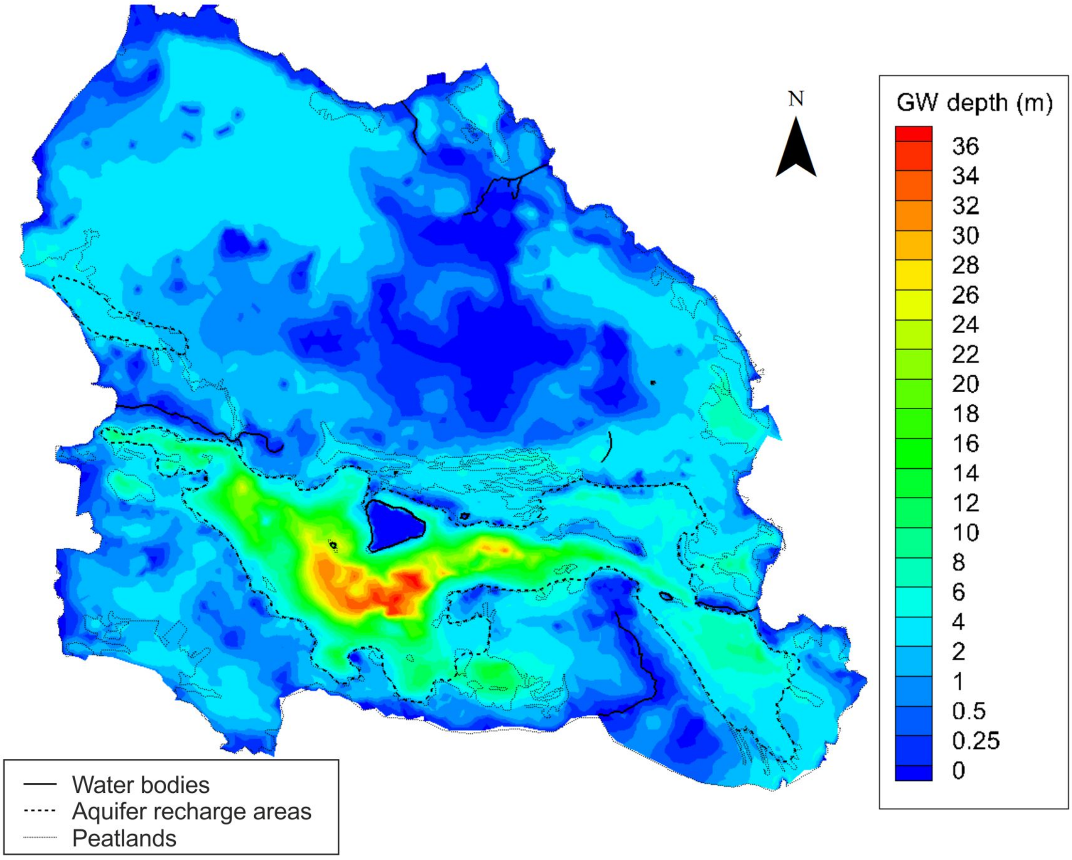


Figure 14. Depth to groundwater from ground surface.

6.3 Saturation levels

Figure 15 shows saturation levels at the ground surface of the modelled Kälväsvaara and Olvassuo area. The simulated saturation levels follow expected saturation distribution within the model domain. Fully saturated areas (> 0.99) represent regions occupied by surface waters, i.e., lakes, streams and ponded water on wetlands. Other areas of high saturation correspond to presence of peatlands. In contrast, low saturation values occur within higher situated areas of the Kälväsvaara study area. These low saturation zones are also related to assigned soil hydraulic properties. Sand soil allows incoming water to percolate down relatively fast. In contrast, low hydraulic permeability of peat slows down the flow of water from higher located areas and increases saturation levels in sand soils at the esker/peat interface.

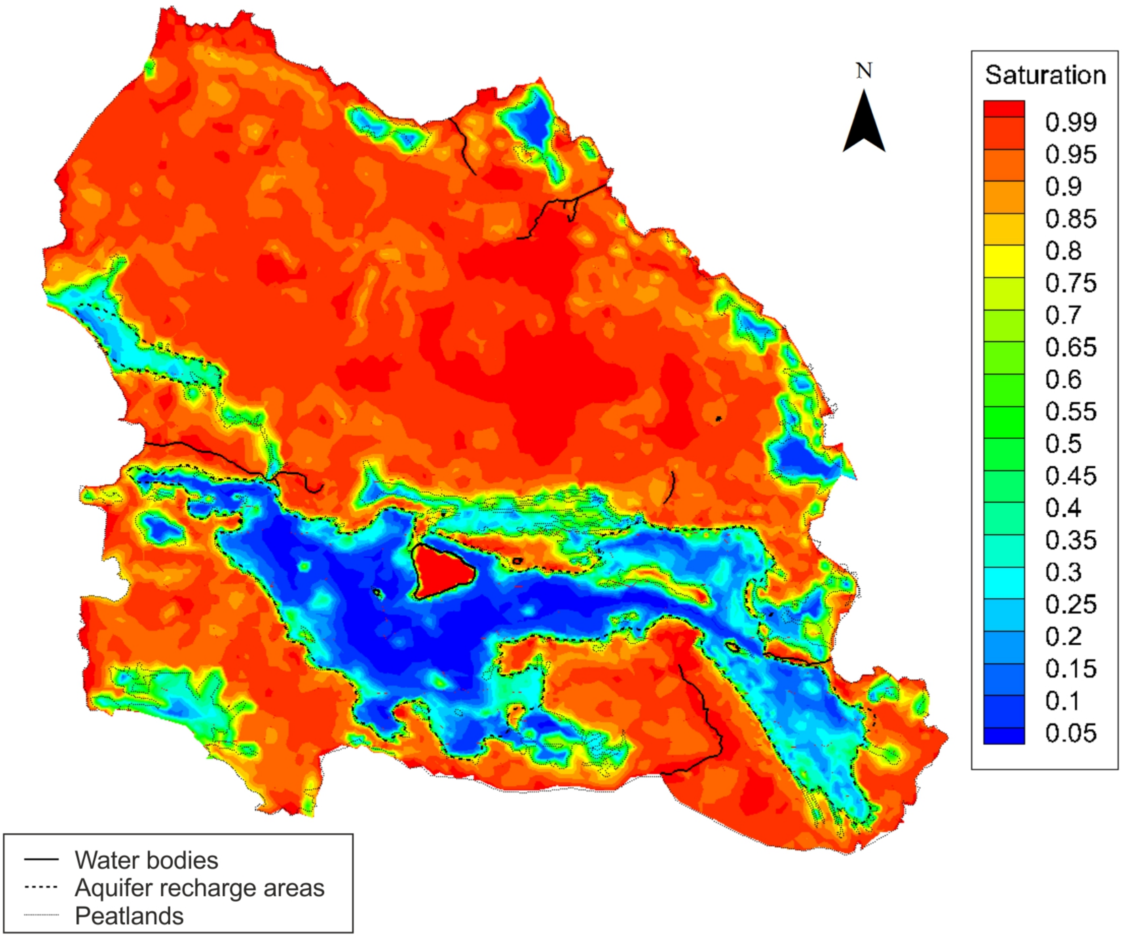


Figure 15. Degree of saturation at ground surface.

In addition, it is worth to note that the degree of saturation is dependent on evapotranspiration that is mainly controlled by vegetation type and soil water availability. Because evapotranspiration was represented in the model in a lumped manner through the term of effective rainfall, the model was not able to capture the subtle impact of evapotranspiration on spatial distribution of saturation levels and further, on groundwater levels. The effects of evapotranspiration on soil moisture should be studied further in more detail as the peatland vegetation can be highly sensitive to changes in spatial and temporal distribution of soil water content.

6.4 Spatial patterns in GW-SW interactions

The GW-SW interactions are expressed in terms of exchange fluxes (Figure 16). Positive fluxes indicate places where groundwater exfiltrates to land surface or surface waters, whereas negative values represent locations of water infiltration to porous media domain.

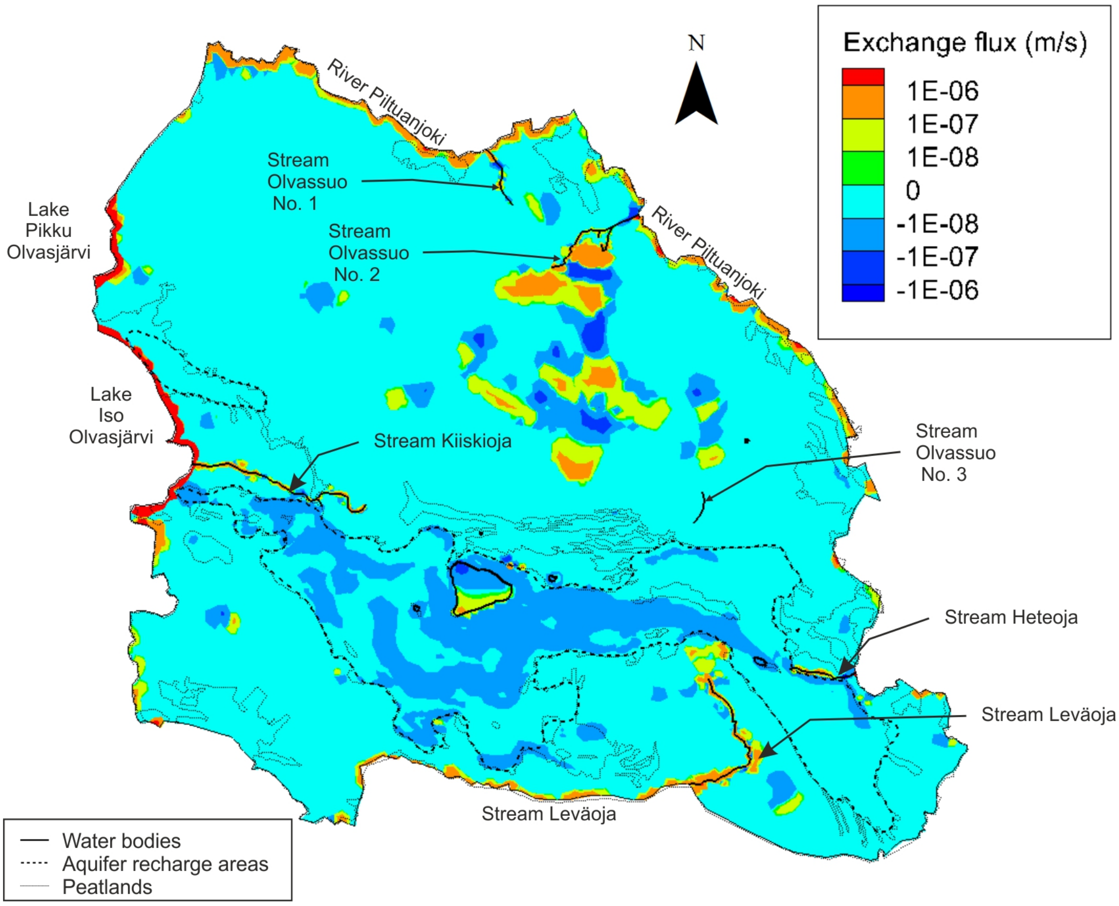


Figure 16. GW-SW interactions within the Kälväsvaara model domain.

Boundary conditions

As seen from Figure 16, strong seepage into the overland domain occurs on the model boundaries with highest fluxes along the Olvasjärvi and Pikku Olvasjärvi boundaries. The main reason for overestimated fluxes along the Olvasjärvi and Pikku Olvasjärvi lakes is the applied steady-head boundary condition. The heads applied as constant head boundaries exceeded the land elevation at the boundaries leading to flooding of the cells indicated by small water depths around the lakes (Figure 10). The used, in a way "incorrect", boundary delineation with respect of the applied steady-head boundary conditions enhance water exchange in the close vicinity of the boundary; it causes water to circulate in an artificial manner between the domain outside the simulation and areas located in the close vicinity of the boundary. This behaviour further result in a numerical instability indicated by a large percentage fluid balance error equal to 31 % that is defined as (Aquanty 2015):

$$\epsilon_P = \frac{|\pm Q - \Delta S|}{max(Q^+, |Q^-|)} \times 100\% \tag{15}$$

$\pm Q$ is the net rate at which fluid enters (Q^+) or leaves (Q^-) the model
ΔS is the rate of change in storage

Changing boundary conditions, e.g., by decreasing steady-head levels by 1 m, reduced the fluid balance error to 3.8 %. The effect of this alternation was mainly local. The new boundary conditions reduced the unrealistically high fluxes along the Olvasjärvi and Pikku Olvasjärvi boundaries and decreased the ponding but led only to minor decrease of groundwater levels within the aquifer. The resulting drop in groundwater levels was on average 0.02 m. This value is insignificantly small in comparison to the changes in the applied constant head conditions.

In contrast, the effect of the tested artificial conditions show that the proper choice of boundary conditions is important for the fluid balance within the model even though the effects on other variables can be minor. In order to avoid this problem, the model domain along the constant head boundaries could be delineated using DEM data in such manner that the minimum land elevation along boundary exceeds the average water levels. This boundary condition test also demonstrated that in the case of the Kälväsvaara model most of the model output was not very sensitive to changes in constant head boundary. On the other hand, such arbitrary change for steady-head boundaries induced unnatural gradient between lakes. Thus, it is highly probable that more natural lake water levels configuration with respect to each other would reduce further the mismatch between model's inputs and outputs. Another possible source of fluid balance error may be inaccuracies in the DEM data.

The relative small impact of the tested constant head boundaries on the groundwater levels as well as general good agreement between observed and simulated data indicate that the error induced by the assigned constant head boundaries is local and has no impact on the GW-SW fluxes interactions indicated by the model beside the small areas situated at the model borders. In addition, one should keep in mind that the positive fluxes along the Piluaanjoki river and Leväoja stream are anticipated as groundwater is expected to discharge to local streams and rivers.

Lakes

As shown in Figure 16, groundwater discharges to the south, higher located part of the Kirkaslampi lake and infiltrates to the local groundwater in the north part. This obtained seepage pattern is similar to the one presented by Smerdon et al. (e.g., 2007) for the lake located in Northern Alberta, Canada. In contrast, other lakes and ponds of the Kälväsvaara study site are characterized by negative exchange fluxes. This could suggests that these water bodies may act as local points of surface water accumulation and recharge the aquifer. However, the full picture of GW-

SW interactions within these small water bodies could remain unrecognised due not sufficient discretization with regard to the scale of these water bodies and the assumption of homogeneity of porous medium. As stated by Smerdon et al. (2007) and Ala-aho et al. (2015b) the lake-groundwater interactions are highly dynamic in space and time, thus is not inconceivable that the lake-groundwater interactions would change in a transient model. Thus, the dynamics of the lake-groundwater interactions within the Kälväsvaara could be inspected further in future studies.

Streams

The simulation results suggest that the both types of interactions (positive and negative fluxes) occur within almost all streams of the Kälväsvaara study site. As seen from Figure 16, most of the streams gain water over the majority of length, however, the loosing reaches also exists within each stream. An exception is a stream located in the south part of the Olvassuo fen (Stream Olvassuo no. 3). The model output suggest that there is no GW-SW interactions within stream what contradicts the field observations as according to the data provided by ELY-centre a small spring is located at the stream beginning.

Wetlands

Figure 16 shows that relatively strong GW-SW interactions occurs within Olvassuo. The wettest part of the fen is indicated by the model by intertwining patches of positive and negative exchange fluxes. This pattern seems to be physically realistic as this area of the Olvassuo was also noted to be strongly groundwater dependent by the earlier studies (Heikkilä et al. 2011). However, it is important to emphasize that in reality the magnitude and distribution of the GW-SW interactions can be influenced by preferential flow phenomena within the peat, as indicated by Lowry et al. (2009). Furthermore, the magnitude and pattern can be modified by depth of peat layer and spatial variations in hydraulic properties of peat. The hydraulic conductivity can vary horizontally and vertically in natural wetlands over a range of few magnitudes as indicated by e.g. Ronkanen and Kløve (2005). Because in the model peat was represented as a 1.8 m thick uniform layer with hydraulic conductivity ($K_{XY} = K_Z = 1 \times 10^{-7}\text{ms}^{-1}$) equal to a typical value for catotelm peat, the GW-SW interactions arising due to heterogeneity in the layer composition and thickness could not be captured by the model.

The GW-SW interactions within other wetlands seems to have smaller spatial extend and magnitude. On the other hand, the GW-SW interactions in this area could be overlooked by the model as the model disregarded the presence of ditches in the west part of the model domain for simplification purposes. Ditches possibly induce point and seepage discharge in a similar way as observed in the Rokua area by Rossi et al. (2012). However, to confirm the hypotheses more field observation must be done in the Kälväsvaara area. It would be also plausible to evaluate if the more realistic representation of peatlands in terms of various properties for vegetation layer and decomposed layer as well as assigning variable depth for peat cover would change the spatial distribution and magnitude of GW-SW interaction with the fens of the Kälväsvaara area. More complex representation of wetlands area could show how sensitive the model is to the employed simplifying assumptions. On the other hand, the revealed GW-SW interactions could serve as a basis for studying the effects of anthropogenic actions, such as pumping, to these GDEs. It can be expected that the effects of such actions will have similar trends even if the actual fluxes somehow differ from the simulated. Definitely, such simulations can provide more information on locations of possibly affected areas that solely the information of groundwater level decrease.

6.5 Spring discharge comparison

Figure 17 presents simulated versus measured average spring discharges. The disagreement between computed values and field observation is large. The model managed to capture only flow in three out of seven springs. All of these three small-scale GDEs are situated on the east part of the esker. The discharges are in most cases underpredicted by the model. The exception is spring no. 29 where the discharge is largely overestimated. Positive exchange fluxes around springs no. 27, 28, and 29 (Figure 16) suggest that all of these springs are formed within the model through diffuse seepage mechanism. The model outcome can reflect that small-scale GDEs, such as springs cannot be modelled in a physically-based manner without detailed information about geology around these water bodies.

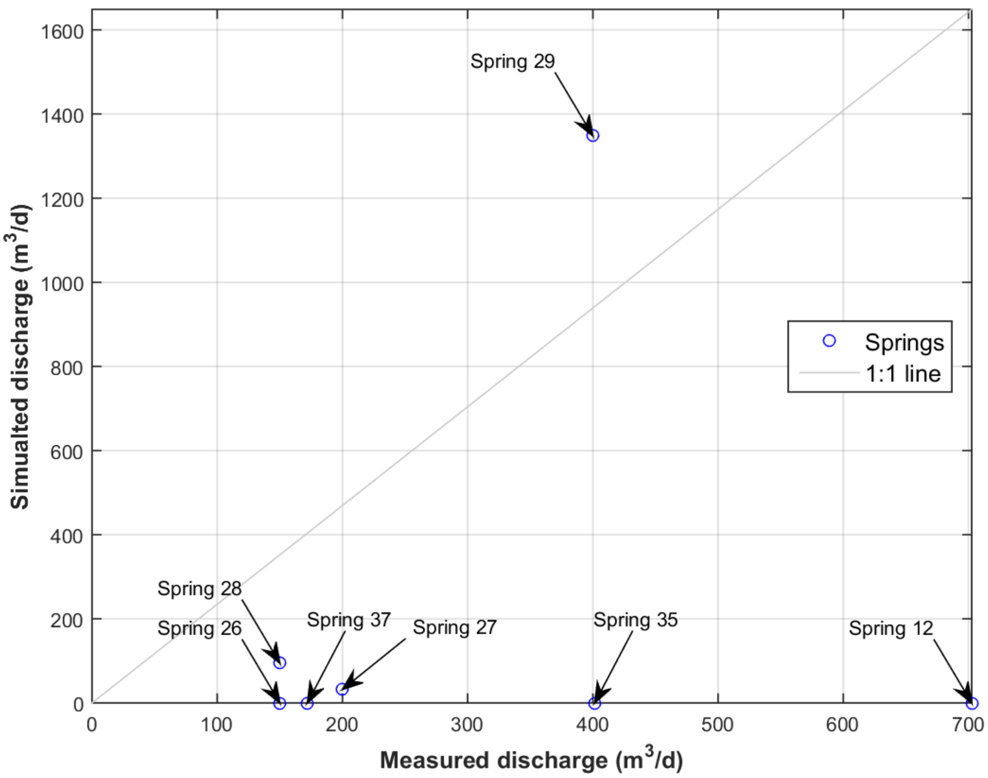


Figure 17. Simulated and measured spring discharges.

6.6 Flow in streams

The model performance was further assessed by investigating stream discharges along the Kiiskioja. For this purpose, the steady-state discharge was extracted along the stream approximately every 100 m, starting from the beginning of longer stream branch and ending at stream outlet (Figure 18). This further investigation was especially interesting as the model results wrongly show that the majority of water comes from the east longer branch of the stream, whereas in reality most of the water has its origin from spring no 12. As the long-term data of the stream discharge is not available, the computed discharges along stream cannot be evaluated precisely. Therefore, simulated values were compared to expected trends, the average discharge of spring no. 12 and one discharge measurement conducted during October 2015 approximately 500 m of stream outlet by the Water Resources and Environmental Engineering Research group, University of Oulu.

The model results show as expected that the discharge of Kiiskioja stream increases towards the stream outlet. The stream discharge at the confluence point is also the same magnitude as an average discharge of spring no. 12. Thus, it seems likely that the Kälväsvaara model wrongly directs water to east branch of the stream

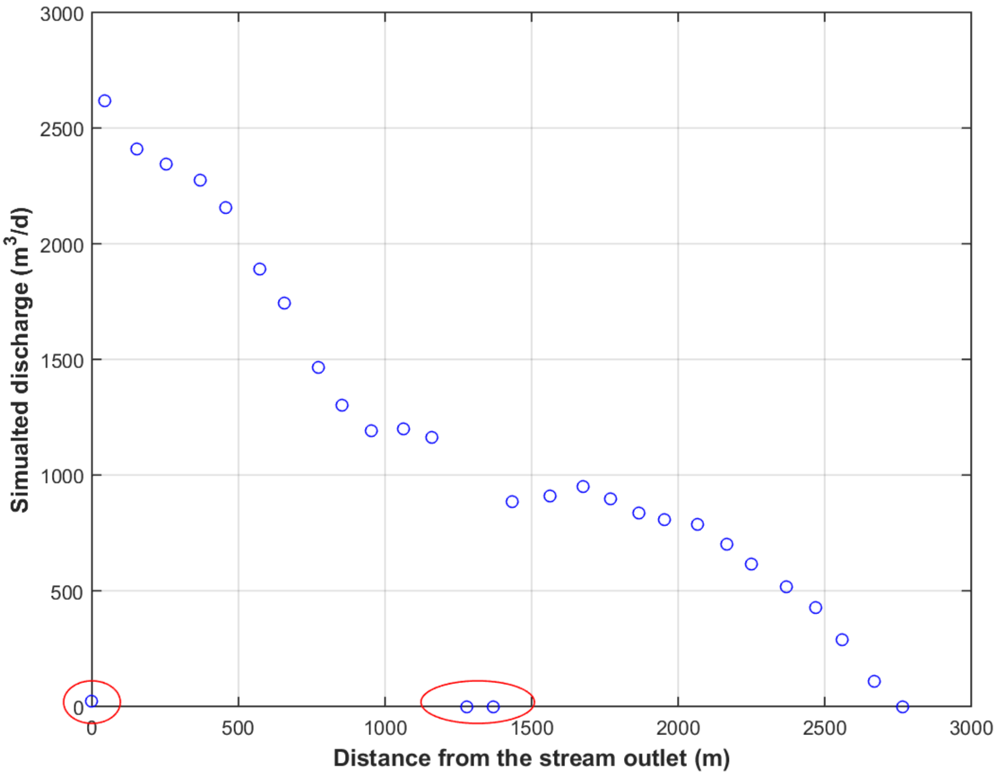


Figure 18. Simulated discharge along the right branch Kiiskioja stream. The inlet of the left branch of the stream fed by spring no. 12 is located approximately 1800 m fron the stream outlet. The numerical instabilities are shown in red circles.

instead to the west, spring branch. Furthermore, the results suggest that the model significantly underestimates the discharge in the lower part of the stream. The measured discharge during the autumn 2015 (4370 m^3d^{-1}) is twice as large as the computed value for the corresponding reach (2050 m^3d^{-1}). These values cannot be, however, compared confidently as any single field observation unlikely represents adequately the long-term average as well as the year 2015 was relatively wet in the Northern Finland.

The zero-values encircled by red lines in Figure 18 are apparent errors of the Kälväsvaara model. The zero discharge close to stream outlet is a numerical error caused by the improper boundary conditions, discussed in section *6.4 Spatial patterns in GW-SW interactions*. The cause of zero flows in the middle section of the stream is likely caused by unrealistic channel shape in this part of the stream characterized by very small gradients between the lowest point of the channel and the banks. This leads to conclusion that the discretization along stream was not sufficient. The correct representation of stream cross-sections would require elements with segments size around 0.5 m long. It is clear that this value is disproportionally small to the size of the model domain and would induce very long running times.

Thus, the degree of discretization must be a compromise between accuracy of modelled processes and computational times.

6.7 Uncertainty of the model and recommendations for future work

The applied steady-state model of the Kälväsvaara area was rather simple mainly due to limited availability of field data and time constrains. Despite its simplicity, the model relatively well mimicked average observed groundwater and lake levels. Other spatially-distributed model outputs, such as saturation, water depths, GW-SW interactions also seem to be physically realistic. On the other hand, it is important to emphasize that all employed simplifying assumptions can be potential sources of error. In the Kälväsvaara model case, such simplifications were related for example to assumptions of homogeneity within various zones, uniform peat depth for all wetlands and applying effective rainfall. The problem of uncertainty attributed by simplifying assumptions is a complex one. The issue is not only a concern of the employed model for the Kälväsvaara study site but it rather general problem of modelling itself as all models are simplified versions of reality.

Other general problems related to any environmental modelling are the issues of equifinality, non-identifiability and non-uniqueness. Theoretically, any environmental system of interest can be equally well described by numerous models. The behaviour of the system can be successfully reproduced by various model structures that differ in respect of implemented processes and specified zones, however yield acceptable consistence between simulations and observations. This concept is known as equifinality and it arises from our inability to decide between competing models under limited amount of information. Further, within the same structure multiple parameter sets can reproduce in acceptable manner the system behaviour. The problem arises from limited description of the system as well as errors in observations and model structure . The optimum parameter set cannot be found due to non-identifiability resulting from the lack of clear optimum or because of non-uniqueness caused by multiplied optima. In some cases, the problems of non-identifiability and non-uniqueness can be further intensified by model over-parametrisation, i.e., using to many parameters with respect to available calibration data. (Beven 2009, p. 13-14).

For above mentioned reasons, it must be recognized that the steady-state behaviour of Kälväsvaara can be reproduced by numerous models differing in terms of structure and parameter sets. It is probable that model consisting of one, four, five or ten subsurface zones could represent even better the observations. On the other hand, there is no certainty that any other model varying in terms of structure and parameter set would yield better consistence between simulations and observations until such a model is tested. Increasing complexity of model could also lead to model over-parametrisation given that calibration data was quite limited.

The majority of the Kälväsvaara model parameters were derived from literature. Parameter extrapolation from other sites can lead to incommensurabilty problem, i.e., the problem of scaling variables and parameters, discussed by, e.g., Beven (2009, p. 8). Due to incommensurabilty, the applied parameters in the Kälväsvaara model may not represent the variables at the model scale. For instance, the derived overland properties for peat and sand from Ala-aho et al. (2015b) may not define the same quantities in the Kälväsvaara model as these effective parameters may depend on model structure and scale. Each location has also its own characteristics. For instance, the glacial till specific storage from North Dakota, USA can differ from the specific storage within the Kälväsvaara study area. As the most parameters for the Kälväsvaara model were derived from literature, one should be conscious of uncertainty and errors related to use of these parameters. On the other hand, when no field measurements are available, deriving values from literature is a good starting point for a model construction. Later, the parameters can be adjusted as our knowledge about the system properties improves. The problem of incommensurabilty emphasize the importance of field measurements and the need of having sufficient filed data to create and calibrate reliably any model. Definitely, the Kälväsvaara model would benefit from additional laboratory and field measurement. Extra data on variability of soil hydraulic properties such as hydraulic conductivity, storativity, pressure-saturation-conductivity curves of the predominant soil types would provide valuable information for model parametrization.

The main limitation of the model is presumably its assumption of homogeneity within the identified porous media zones: sand, glacial till and peat. The largest mismatch between measured and simulated values resulted from local heterogeneities, e.g., in the Pieni Kirkaslampi lake and the Por T5/1 piezometer. The uniform parametrization within various subsurface zone presumably led also to some error in the simulated GW-SW interactions, similarly, as noted by Ala-aho et al. (2015b). Including local-scale heterogeneities and more realistic representation of wetlands would improve our understanding on the prevailing GW-SW interactions within peatlands. On the other hand, incorporation too much detail into model may lead to over-parametrization and challenges for calibration.

A second source of potential error is the uncertainty associated with applied boundary conditions. As discussed in subsection *6.4. Spatial patterns in GW-SW interactions*, improper boundary conditions with respect to model delineation may lead to numerical instability of the model. Even though, the arbitrary correction of the constant head values seemed not to have pronounced effects on the model output, inevitably inaccurate boundary conditions introduce errors into simulation especially to cells located in the vicinity of the model boundary. Further, no flow conditions along streams may build up internal pressure within the porous domain as discussed by Jones et al. (2008). This simplifying assumption seems also not to be fully physically realistic as the possibility of water exchange under the streams within adjacent areas cannot be excluded. These issues suggest that the boundary conditions assigned to model's subsurface domain should be further reflected.

In addition, some error can be related to the model symmetry representation induced by interpolation of bedrock data, discretization of model, assumed lake bathymetry and channel shape representation. The Kälväsvaara model results indicated that not sufficient discretization around streams can lead to numerical instability or at least unrealistic results. The uncertainty related to model symmetry could be decreased by finer discretization of model domain and by using more accurate raster data for surface and bedrock topography.

Finally, uncertainty is connected to the calibration data itself, i.e., spring discharge data, lake water levels and groundwater levels. All measurements, even if these were carefully made, are subjected to some uncertainty and errors. The analysis of the calibration data quality in more detail was, however, out of scope of this work.

Definitely, the presented sources of uncertainty and errors are not limited to the ones described above. On the other hand, the good agreement between field observations and the simulation results suggest that the model captures the essence of the overland and subsurface processes occurring within the study area. The understanding of the system could be improved by conducting sensitivity analysis which allows to quantify model response to changes in parameter values, boundary conditions and representation of model symmetry. The goodness-of-the-model could be further studied by running model in transient state using time-varying rainfall input. Adding dynamics to the system would provide more information about GW-SW interactions and their sensitivity to anthropogenic actions. The model would also benefit from a more systematic calibration methodology. The calibration of the model was carried out by try-and-error calibration method for identifying hydraulic conductivities of esker soil material and glacial till. Arguably, the employed manual calibration approach did not identified the model optima as the search for optimum parameter sets was limited by the relatively long computational times varying between one and three hours depending how far the initial conditions were from the steady-state solution. Thus, more-time efficient calibration methods, such as the grid coarsening calibration approach presented by von Gunten et al. (2014), would increase the confidence about the goodness of calibration. On the other hand, it is important to emphasize that modelling is an iterative process; it could continue endlessly as our knowledge and understating of the system improves. Thus, in modelling it is necessary to find a compromise between the employed complexity, accuracy of results and devoted time simultaneously meeting modelling objectives.

7 CONCLUSIONS

The fully-integrated physically-based GW-SW model HydroGeoSphere was applied to simulate groundwater dependent ecosystems, such as fens, kettle lakes, streams and springs around the Kälväsvaara esker aquifer. The model performance was evaluated by comparing the model outputs to available field measurements and to expected values and patterns for the variables with no data available.

The employed model structure was simple due to limited availability of field data and time. The model subsurface domain was separated into four homogeneous zones, from which three represent the predominant soil types of the Kälväsvaara study area: peat, sand soils and glacial till. Additionally, gyttja layer was assigned to the bottoms of the kettle hole lakes. The surface domain was divided into three zones representing distinct surfaces, such as peatlands, sand and stream channels. For further simplification, the model was run is steady-state and it was calibrated manually by the try-and-error method.

Despite simplification, the findings of the calibrated model are promising. The model mimicked well the measured groundwater and lake levels. Other spatially-distributed model outputs, such as saturation, water depths, GW-SW interactions also appear to be physically realistic. The model was capable to reproduce the presence of lakes, wetlands and streams without their prior definition by artificial boundary conditions. In addition, various GDEs could be identified by determining specific characteristic properties for each of these ecosystems. For instance, the wetlands were distinguished by high saturation levels at ground surface and presence of shallow ponded water over some areas; lakes were characterized by high surface water depths, whereas streams differed from adjacent cells by significantly higher surface water velocities and moderate surface water depths.

In contrast, small scale GDEs, such as springs were not so well represented by the model. A plausible explanation is that it may be difficult to model small-scale GDEs in a physically-based manner without detailed information on the geology around these water bodies. The fact that springs usually emerge in regions characterized by abrupt changes in hydraulic properties or coincidence with fractured rock/karst aquifer formations supports the hypothesis. It is, however, worth to note that including detailed geologic information would require locally significantly finer discretization of model domain what would increase computing times. Similarly, the main prerequisites to properly capture depression springs are very fine grid and accurate elevation data around these water bodies.

The overall realistic depiction of various GDEs indicates that the spatial discretization of the model domain was sufficient to meet the simulation objectives. The model results suggest, however, that the grid size was deficient in the vicinity of stream channels to fully represent stream flow within the the Kälväsvaara study area. The unrealistic channel shape caused by too coarse grid was deduced to be the main reason for the zero flows in the middle part of the Kiiskioja stream. The effect was, however, rather local as the overall discharge of Kiiskioja stream increased towards the stream outlet as expected. It is reasonable to conclude that the discretization around features of interest should be proportional to their size, e.g., width of a stream or areal extend of lake. Other uncertainties were related to simplifying assumption of homogeneity within the identified porous media zones, assigned boundary conditions, representation of model geometry, parameters derived from literature and used calibrated data. It was also recognized that conducting sensitivity analysis could improve our understanding of the model sensitivity to chosen parameters and together with more systematic than manual calibration approach could increase our confidence about the goodness of the calibration.

On the other hand, the overall good consistence between simulations and observations demonstrates that the Kälväsvaara model captures the essence of the overland and subsurface processes occurring within the study area and thus, the model could be also used as such. As modelling is an iterative process, it is necessary to find a trade-off between the model complexity, accuracy of results and devoted time simultaneously meeting modelling objectives. The employed model can be treated as a result of such compromise; it revealed accurately most of GDEs within the model domain, i.e., lakes, wetlands and streams and exhibited nicely GW-SW interactions within these GDEs. The obtained results could be a starting point for further investigation of the GW-SW dynamics within GDEs and the impact of pumping and other anthropogenic actions to these GDEs.

This study demonstrated that the fully-integrated physically-based GW-SW modelling is a viable method to simulate various groundwater dependent ecosystem in a physically based manner. Therefore, this approach could be a useful tool to study effects of anthropogenic actions, such as pumping or climate change, on GDEs. In contrast to traditional water resource modelling, the fully-integrated models provide valuable information on GW-SW interactions in a form of feedbacks between the overland and subsurface domains. The spatial and temporal analysis of exchange fluxes under various scenarios could serve as a basis for evaluation of possible impacts of the human induced changes on GDEs.

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