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INTEGRATED MANAGEMENT
OF GROUNDWATER AND
DEPENDENT ECOSYSTEMS
IN A FINNISH ESKER

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU, FACULTY OF TECHNOLOGY;
WATER RESOURCES AND ENVIRONMENTAL ENGINEERING RESEARCH GROUP;
VALUE DOCTORAL PROGRAMME



ACTA UNIVERSITATIS OULUENSIS
C Technica 491

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**INTEGRATED MANAGEMENT OF
GROUNDWATER AND DEPENDENT
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Academic dissertation to be presented with the assent of
the Doctoral Training Committee of Technology and
Natural Sciences of the University of Oulu for public
defence in the OP-Pohjola auditorium (L6), Linnanmaa, on
6 June 2014, at 12 noon

UNIVERSITY OF OULU, OULU 2014

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Acta Univ. Oul. C 491, 2014

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ISBN 978-952-62-0477-2 (Paperback)
ISBN 978-952-62-0478-9 (PDF)

ISSN 0355-3213 (Printed)
ISSN 1796-2226 (Online)

Cover Design
Raimo Ahonen

JUVENES PRINT
TAMPERE 2014

Rossi, Pekka M., Integrated management of groundwater and dependent ecosystems in a Finnish esker.

University of Oulu Graduate School; University of Oulu, Faculty of Technology; Water Resources and Environmental Engineering Research group; VALUE Doctoral Programme
Acta Univ. Oul. C 491, 2014

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Abstract

Groundwater, a key part of the hydrological cycle, is under increasing pressure from different land uses and changing climate. However, less attention has been paid to integrated groundwater management than surface waters. This thesis combined hydrological and socio-economic research for the case study of the Rokua esker aquifer in order to update current concepts of groundwater management. The Rokua area contains groundwater-dependent lakes and a periodic water level decline has raised concerns about the future of these lakes. Peatland drainage in the vicinity of the aquifer has been accused of changing the aquifer conditions.

Groundwater discharge from the esker aquifer to drained peatland was studied to identify relevant hydrological processes for groundwater-surface water interactions. The results revealed a connection between the aquifer and the peatland whereby groundwater can enter the ditches through seepage or preferential flow.

Modeling was used to determine critical factors in the management of the esker aquifer-peatland system. The results showed that climate and land use can affect esker groundwater, while peatland drainage in the vicinity can have similar impacts to groundwater abstraction and drought. Peatland restoration by filling in drainage ditches could possibly restore the aquifer groundwater levels. However, for the Rokua aquifer, which will possibly experience less severe dry periods in the future, extensive drainage restoration is currently too major, uncertain, and expensive a measure relative to the expected benefits.

Multi-criteria decision analysis was used to identify ways of facilitating stakeholder involvement and learning in groundwater management. The results obtained with this participatory process confirmed that it can foster learning on complicated groundwater issues and collaboration in a process encompassing disputes and diverse interests. The decision analysis process led to the initiation of dialogue on more integrated management, where the preferences of all stakeholders were discussed and taken into account.

Overall, this thesis shows how different aspects of aquifer management, such as land use, climate, ecological and economic values, and stakeholder preferences, can all be taken into account using a combined method which reduces the mistrust between opposing interests through research and information, resulting in more robust future planning.

Keywords: aquifer discharge area, drainage, groundwater management, groundwater modelling, multi-criteria decision analysis, peat, preferential flow, uncertainty

Rossi, Pekka M., Pohjavesien ja pohjavedestä riippuvien ekosysteemien kokonaisvaltainen hallinta.

Oulun yliopiston tutkijakoulu; Oulun yliopisto, Teknillinen tiedekunta; Vesi- ja ympäristötekniikan tutkimusryhmä; VALUE tohtoriohjelma

Acta Univ. Oul. C 491, 2014

Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Pohjaveteen, hydrologisen kierron avainosaan, kohdistuu kasvavia paineita eri maankäytön muodoista ja ilmastomuutoksesta. Pohjaveden hallintaan ei kuitenkaan ole kiinnitetty tarvittavaa huomiota. Tässä väitöstyössä yhdistettiin hydrologista ja sosioekonomista tutkimusta Rokuan harjualueella pohjaveden hallintakonseptin päivittämiseksi. Rokuan alueella on useita pohjavedestä riippuvaisia järviä, joiden vedenpinta on kausittain laskenut voimakkaasti. Pintojen lasku on kasvattanut paikallisten huolta järvien tilasta. Harjua ympäröivät metsäojitetut turvemaat, ja ojituksia on syytetty pohjaveden tilan ja sitä kautta myös järvien tilan heikkenemisestä.

Työn ensimmäisessä osassa tutkittiin pohjaveden hydrologisia purkautumisprosesseja harjun pohjavesiesiintymästä ojitetulle suoalueelle. Tulokset osoittivat hydraulisen yhteyden akviferin ja turvemaan välillä: pohjavesi pääsi purkautumaan metsäoijiin joko suotautumalla tai turpeen kaksoishuokoisuusrakenteiden kautta.

Seuraavassa vaiheessa työtä pohjavesimallinnusta käytettiin määrittämään kriittisiä pohjaveden tilaan vaikuttavia tekijöitä pohjavesi-turvemaa-systeemissä. Mallinnustulosten perusteella niin ilmasto kuin maankäyttökin vaikuttavat kumpikin suoraan pohjaveden pinnankorkeuden tilaan. Turvemaiden ojituksilla pohjavesialueella voi olla samoja vaikutuksia pohjaveden pinnankorkeuden tasoihin kuin pohjaveden otolla tai kuivilla kausilla. Turvemaiden ennallistaminen ojia täyttämällä voi osittain palauttaa vedenpinnan tasoja pohjavesialueella. Rokuan harjualueen tapauksessa suuren mittakaavan oja-alueiden ennallistaminen todettiin kuitenkin liian epävarmaksi ja kalliiksi toimenpiteeksi hyötyihin nähden, varsinkin jos kuivien kausien vaikutus suurilla harjualueilla heikkenee tulevaisuudessa sademäärien kasvun myötä.

Työn kolmannessa osassa käytettiin monitavoitearviointia eri sidosryhmien osallistamiseen ja oppimiseen pohjavesien hallinnassa. Osallistavasta prosessista saadut tulokset vahvistivat, että menetelmää voidaan käyttää oppimisen edesauttamiseen vaikeissa pohjavesiasioissa sekä yhteistyön muodostamiseen ristiriitaisessa ja monimutkaisessa tapauksessa. Monitavoitearvioinnin prosessi johti keskustelun avaukseen yhtenäisemmän suunnittelun puolesta, joka ottaa huomioon eri sidosryhmien näkökulmat ja tuo ne osaksi keskustelua.

Tämä väitöstyö osoitti miten eri pohjavesialueen hallintaan tarvittavat näkökulmat, kuten maankäyttö, ilmasto, ekologiset ja ekonomiset arvot, sekä sidosryhmien mielipiteet voidaan kaikki ottaa huomioon yhdistämällä eri metodeja. Näin tutkimuksella ja informoinnilla vähennetään epäluottamusta eri intressitahojen välillä ja luodaan pohja vakaammalle pohjavesialueiden tulevaisuuden suunnittelulle.

Asiasanat: epävarmuusanalyysi, kaksoishuokoisuus, mallinnus, monitavoitearviointi, ojitus, pohjavesien hallinta, pohjavesien purkautumisalue, turve

To aunt Leena Matinheikki

Acknowledgements

This study was financed by the doctoral programme VALUE, EU Seventh framework programme GENESIS (contract number 226536) and the Academy of Finland project AQVI (project number 128377). Support was also provided by Maa- ja vesiteknikan tuki r.y., Thule doctoral programme, Finnish Foundation for Technology (TES), Sven Hall Foundation, Tauno Tönning Research Foundation and Olvi Foundation. My highest gratitude and acknowledgements for the financial support of my thesis go for all the above.

I give my most sincere recognitions to my main supervisor, Prof. Bjørn Kløve. This work has been the once-in-a-lifetime learning experience for me. The amount of information I have received on groundwater and hydrology is beyond humbling. Thank you for the possibility to work on interesting subjects and thank you for the advices either when I was a student, diploma thesis worker or doing my PhD work. I also give my gratitude to my second supervisor Timo P. Karjalainen from Thule institute. Thank you for teaching a guy with a more technical background to see from a broader perspective. I also would like to thank my pre-examiners Prof. Marie Larocque and Dr. Helen K. French for valuable comments. I'd also like to thank Dr. Mary McAfee for language check of my thesis.

My big hand goes to all you people in Water Resources and Environmental Engineering Research Group. Coffee break and lunch discussions have been the essence of this work! Especially thank you for Pertti of all the great cooperation, the interesting dialogue on research issues and on the other important subjects e.g. the random gig chosen for the weekend. I would like to acknowledge all the people who have helped me in the field, planning with the articles or other part of the thesis research: Riku, Elina, Tuomo R., Paavo, Tuomo P., Virve, Anna-Kaisa, Jarkko, Mikko for the geophysics, Helena, Aarne, Kalle, Manuel, Hong, Hannu, Tapio S and Tero. John Doherty I especially would like to thank for making me understand modeling so much more.

Thank you to the Centre for Economic Development, Transport and the Environment for all the collaboration with Rokua studies, Geological Survey of Finland for the collaboration on geological research, both Metsäkeskus and Metsähallitus helping on forestry issues, Humanpolis Oy for the cooperation and the high interest on our studies and Turveruukki on expertise on Petäikönsuo area.

Thank you for all the people of Rokua area for the cooperation. This work could have not been done without your commitment and interest on groundwater. You've brought this study a long way ahead. Thank you all the people in VALUE doctoral programme from the fruitful meetings around Finland. Thank you to all the people in GENESIS for the great international collaboration! Thank you for all my friends for keeping the extra-curricular time so much more interesting, all the way through the studies. And a Big Thank You goes for my family, Liisa, Helge and Maija for everything and especially for helping me to find the right road on my studies and career.

Travel, discuss and change your thoughts with people around you as much as you can. You'll never stop learning. Punk, over and out:

Change of ideas, change of ideas,

What we need now is a change of ideas.

Greg Graffin - Change of Ideas, 1989

List of symbols and abbreviations

C	Concentration
Ca	Calcium
Con	Conductance
DAI	Decision analysis interviews
DEM	Digital elevation model
E.C.	Electrical conductivity
ET ₀	Reference evaporation
FAO	Food and Agriculture Organization of the United Nations
FMI	Finnish Meteorological Institute
GCM	Global climate model
GPR	Ground penetrating radar
gw	Groundwater
k _{peat}	Hydraulic conductivity of a peat
l	Model cell length
LIDAR	Light detection and ranging
MAVT	Multi-attribute value theory
MCDA	Multi-criteria decision analysis
MCA	Multi-criteria analysis
NSMC	Null-space Monte Carlo
P	Precipitation
Q	Discharge
SDM	Structured decision making
SiO ₂	Silicon dioxide
SRES A1B	Special Report on Emissions Scenarios A1B
SWE	Snow water equivalent
SYKE	Finnish Environmental Institute
b	Thickness of a peat below a ditch
w	Width of a ditch

List of original publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Rossi PM, Ala-aho P, Ronkanen A-K & Kløve B (2012) Groundwater-surface water interaction between an esker aquifer and a drained fen. *Journal of Hydrology* 432–433 (2012): 52–60.
- II Rossi PM, Ala-aho P, Doherty J & Kløve B (2014) Impact of peatland drainage and restoration on esker groundwater resources: modeling future scenarios for management. *Hydrogeology Journal*. DOI 10.1007/s10040-014-1127-z.
- III Karjalainen TP, Rossi PM, Ala-aho P, Eskelinen R, Reinikainen K, Kløve B, Pulido-Velazquez M & Yang H (2013) A decision analysis framework for stakeholder involvement and learning in groundwater management. *Hydrology and Earth System Sciences* 17: 5141–5153.

The author's contribution to publications I-III:

- I Designed the study with Pertti Ala-aho and Bjørn Kløve, conducted the field work with Pertti Ala-aho. Analyzed the results and wrote the paper with co-authors.
- II Designed the study and conducted the field work with Pertti Ala-aho, analyzed the study results with the co-authors. John Doherty and Bjørn Kløve critically commented on all versions of the manuscript.
- III Designed the study with Timo P. Karjalainen and Kalle Reinikainen. Conducted the decision analysis interviews and meetings with Timo P. Karjalainen and Pertti Ala-aho. Wrote the paper with the co-authors.

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1 Introduction

Water resources management is recognizably a challenging task worldwide. River catchment management, restoration of eutrophic lakes, and agricultural irrigation in arid regions are just a few examples of areas where expertise in hydrology, ecology, economics, and many other fields is needed to build coherent plans for the future.

Management of groundwater resources poses even more challenges. Groundwater reserves are usually not directly visible and their status is therefore a more abstract concept than the condition of a lake or the discharge volume of a river. However, groundwater is one of the main freshwater sources in the world. Globally, groundwater is currently facing increasing pressure from land use and water abstraction, and there is evidence of dramatic changes in aquifer water resources (Wada *et al.* 2010). As the groundwater is usually out of sight, public awareness of groundwater resources, groundwater-dependent ecosystems, and problems related to pollution and declining groundwater levels is surprisingly poor (Kløve *et al.* 2011b, Kløve *et al.* 2011c).

Demystification of groundwater through research started in the 19th century (e.g., Darcy 1856) and groundwater research is nowadays one of the cornerstones of hydrological cycle studies (Freeze & Cherry 1979). The management of groundwater evolved as problems of overexploitation, contamination, and ecosystem deterioration started to arise (e.g., depletion of aquifer resources or salinization of coastal aquifers). However, the legal status of groundwater can still be quite ambiguous, as in the United States (Narasimhan 2009), and therefore more information and research is needed. In the European Union (EU), the Water Framework Directive (European Commission 2000) defines groundwater as part of river basins. Member states are required to prepare plans for achieving good ecological status in all waters within the EU by 2015. This includes groundwater, generating a need for good groundwater management practices.

As is the case globally, groundwater is also an important water resource in Finland. It is the main source of potable water, with 580 000 m³ of groundwater and 120 000 m³ of artificial groundwater delivered daily by municipal waterworks to consumers (Britschgi *et al.* 2009). Artificial groundwater is produced by enhancing groundwater recharge through pumping surface water from a lake or a river to an aquifer for example using sprinklers or seepage wells. In 2012, there were 6040 classified groundwater areas in Finland, with an average size of 3.7 km². These groundwater areas consist of two different parts: a recharge

area, where rainwater seeps into water-bearing soil (usually sand or gravel), creating new groundwater, and a groundwater protection area surrounding the recharge area. The latter is a legally established zone to restrict or limit potentially harmful land use practices such as industry or agriculture near groundwater resources. The groundwater formations of Finland are mostly unconfined sand and gravel glaciofluvial esker formations or marginal deposits where glacier retreat has paused (Mälkki 1999, Katko *et al.* 2006).

Finnish groundwater management is directed by national water legislation (Water Resources Management Act 2004) and the European Union Groundwater Directive (European Commission 2006). The main objective of all relevant legislation is to ensure good quality and quantity of groundwater. A common threat to groundwater quality derives from soil contamination by e.g., oil spills, de-icing of roads with salt, chlorinated hydrocarbons, agricultural contaminants (pesticides, fertilizers) or heavy metals. Groundwater quantity becomes an issue for example when municipalities and cities are planning their potable water strategies. Extraction of groundwater from the aquifer for potable water lowers the groundwater level and can for example decrease the discharge from natural springs. Many of the large cities in Finland use only groundwater as potable water, e.g., Lahti, Joensuu, and Seinäjoki. Other cities such as Turku, Lappeenranta, and Pori use a combination of groundwater and artificial groundwater. Other Finnish cities, such as Oulu or Tampere, have also had plans for using groundwater as these cities currently rely solely on surface water. The recently established water safety plans of the EU have put even more pressure on the use of groundwater, as multiple sources of potable water are required for cities. In many previous groundwater abstraction cases the plans have been controversial, sparking opposition and litigation (e.g., the Virttaankangas case in Turku and the Viinivaara case in Oulu). The reasons for controversy in these cases can be diverse, but the fact that controversy can easily arise indicates the need for better governance of groundwater issues in Finland.

The increasing use of groundwater emphasizes the need to understand the exact role of groundwater and different land uses. Besides groundwater abstraction, one of the main land use management questions related to Finnish aquifers arises from the drainage of peatlands in groundwater discharge areas, e.g., for forestry purposes. The impacts of peatland drainage on groundwater bodies have not yet been studied. As the groundwater conditions in northern aquifers are also expected to alter with climate change (Okkonen & Kløve 2010, Hiscock *et al.* 2011), it is important for future management to understand and differentiate the

impacts deriving from climate change and those deriving from land use. As stated by Katko *et al.* (2006, p. 76) “*In addition to Integrated Water Resources Management, there should also be discussion about integrated aquifer management*”.

In order to provide a more scientific basis for better future management of groundwater resources, the GENESIS project was started in 2009. It is an EU-funded project involving researchers from 13 EU member states and four associated countries. The main aim of the project is to provide scientific data to update the EU Groundwater Directive with new scientific knowledge. For the purposes of the project, 15 case study sites were chosen throughout Europe. One of these sites is the Rokua esker aquifer in Northern Finland. At the Rokua site, the groundwater level and the water level in groundwater-dependent lakes have been an issue for concern in recent decades. Land use in the surrounding peatlands for forestry and peat harvesting has been cited as one of the reasons for the periodic declines in water levels. The work described in this thesis forms part of the GENESIS project and its aim was to examine how different research and management tools can be refined and combined to provide a more comprehensive structure for the future management of the Rokua aquifer area. The main focus of the work was the role of peatland forest drainage in groundwater areas. The starting assumption was that in order to devise an appropriate management strategy for the Rokua aquifer, there is a need for new information on the hydrology of the area, the possible impacts of land use and climate change, and the needs of different local stakeholders and livelihoods.

1.1 Modeling as a groundwater management tool

Groundwater models are one of the basic tools used in supporting groundwater management and assessing the impacts of different pressures affecting groundwater resources, as required in the EU Groundwater Directive. In Finland, groundwater modeling has been used in many groundwater abstraction plans for potable water, for example in planning artificial groundwater pumping in Turku (Artimo *et al.* 2003, Artimo *et al.* 2008). Modeling has also been used in other cases, for example to estimate climate change impacts on groundwater-surface water interactions in a cold climate (Okkonen & Kløve 2011) and to define groundwater flowpaths for contamination risk assessment (Backnäs *et al.* 2013).

When models are used as a basis for management decision making, understanding and analysis of model uncertainty is a key part of the modeling

chain. Uncertainties associated with groundwater models derive, for example, from uncertainties in geological structure (e.g., Bredehoeft 2005, Seifert *et al.* 2008), model structural simplification (Doherty & Welter 2010), non-uniqueness of model parameters (Binley & Beven 2003), inadequate measurement disposition and density, and noise associated with measurements comprising the calibration dataset (e.g., Moore & Doherty 2006). Analyses of the uncertainties associated with predictions made by environmental models have been variously based on Bayesian methods (e.g., Marin *et al.* 1989), generalized likelihood methods (Beven & Binley 1992), calibration-constrained subspace methodology (Tonkin & Doherty 2005), and other methods (see e.g., Refsgaard *et al.* 2012). These analyses provide the necessary understanding for decision making on management issues that might have high costs and/or high risks in the event of failure (e.g., Blazkova & Beven 2004, James *et al.* 2009). However, groundwater models are just one technical device for use in e.g. assessment of different land use impacts. Other management tools are equally necessary for discussion and participation processes involving the people affected by future decisions.

1.2 Participatory analyses supporting management

Due to the high degree of complexity and uncertainty in groundwater management, a combination of thorough analysis and informed deliberation is clearly useful and important for decision making. Generally, the need for interdisciplinary and participatory processes combining scientific and local knowledge in environmental research and planning is widely acknowledged in environmental, natural resource, and water governance (e.g., Renn 2006, Silva *et al.* 2010, Pahl-Wostl *et al.* 2010).

Multi-criteria decision analysis (MCDA) is a method which is increasingly being used for fusing available scientific and technical information with stakeholder knowledge and values in order to support decisions in many fields, including natural resources and environment management (Belton & Stewart 2002). There is a wide range of MCDA approaches and applications covering different fields of natural resource management and environmental planning (e.g., Kangas *et al.* 2001, Keefer *et al.* 2004, Huang *et al.* 2011). MCDA is increasingly being used to support stakeholder involvement in environmental and natural resource planning, and experiences from many participatory MCDA applications have been positive (e.g., Pykäläinen *et al.* 1999, Qureshi & Harrison 2001, Regan *et al.* 2007, Marttunen & Hämäläinen 2008). There is also a fairly rich body of

literature related to the use of multi-criteria analysis (MCA) or MCDA in participatory water resource management projects (e.g., Brown *et al.* 2001, Silva *et al.* 2010, Straton *et al.* 2011).

Multi-criteria methods have often been applied to the analysis of groundwater management, mostly in the form of multi-objective optimization (e.g., Willis & Liu 1984, Yang *et al.* 2001, Almasri & Kaluarachchi 2005). However, with a few exceptions (e.g., McPhee & Yeh 2004), decision analysis has been restricted to the assessment of trade-offs among the selected objectives and to the determination of non-dominant solutions. The approaches have not been interactive or participatory, mostly because they have omitted the explicit inference of the stakeholders' preferences.

The use of MCDA in a participatory way is a challenging task requiring careful design and expertise related to the methodology and process (Sparrevik *et al.* 2011). Many problems have been identified, including the need for transparent and easily applied methods for engaging stakeholders and for developing a robust decision model that accounts for the time and resource constraints experienced by practitioners attempting real-life MCDA applications (Huang *et al.* 2011). It is said that successful deliberation as part of the decision analysis approach depends on learning, "*which in turn depends on the ability of those leading the process to create an environment that fosters dialogue, questioning, and self-reflection*" (Gregory *et al.* 2012, p. 246). This behavioral and learning viewpoint is important when applying any decision analysis framework. The process should be planned in such a way that all of the participants can fully understand the reasoning and results. However, practical applications of decision support methods are often too technically oriented and difficult to use, understand, or interpret (Kangas *et al.* 2008). The learning aspect has been mentioned in many papers on MCDA (e.g., Kangas *et al.* 2001), but not systematically studied in practice.

1.3 Outline and aims of this study

This thesis is divided into three sections, reflecting the content of the three papers on which it is based.

(I) The main objective of Paper I was to determine how groundwater discharges from an esker aquifer and interacts with a drained peatland (fen). In many cases drains are a boundary to groundwater systems and this interaction is therefore of general importance and required for groundwater modeling. Paper I studied how the peatland located in the Rokua esker discharge zone influences the

hydraulic pressure head in the sand aquifer. It also examined whether the contact between groundwater and peat depends on preferential flow (double porosity) channels being formed in the peat, how discharge patterns are spatially distributed, and how peatland drainage influences this distribution.

(II) A typical management question arises when peatlands in groundwater discharge areas have been drained by excavating open drainage channels to create more suitable conditions for forest growth. Therefore, groundwater modeling was used in Paper II as a tool to study management options for esker aquifers and related land uses. A MODFLOW model (McDonald & Harbaugh 1984) was built to simulate saturated groundwater flow and drainage in the surrounding discharge zone peatlands of the Rokua esker. PEST and its ancillary support software (Doherty 2013) were used for model calibration and uncertainty analysis. Modeling was conducted considering the underlying uncertainties of the model, measurement data quality and scarcity, geology, climate, and land use. The model was used a) to examine groundwater-surface water interactions between a drained peatland and an esker aquifer; and b) to study how peatland drainage and possible drainage restoration by blocking or filling of the ditches would be reflected in the aquifer. To date, peatland drainage restoration has been studied to show the effects on catchment discharge (Wilson *et al.* 2010) and water quality (e.g., Wallage *et al.* 2006, Wilson *et al.* 2011) but not on aquifer conditions. Paper II aimed to contribute to more integrated management of groundwater resources. It presents a suitable and pragmatic method for determining the impacts of different pressures and identifying future management strategies for esker aquifers.

(III) Paper III analyzed the potential of interactive multicriteria decision analysis – especially the decision analysis interview (DAI) approach (Marttunen & Hämäläinen 2008) – for facilitating stakeholder involvement and learning in groundwater management. It evaluated the results of an MCDA process conducted for the Rokua esker aquifer in Northern Finland. There were fears of disturbance of the system's water dynamics by human activity, leading to the loss of ecosystem goods and services, affecting recreation and other associated activities in the area. The MCDA started a process, in association with stakeholder groups, to find ecologically sustainable, economically feasible, and socially acceptable options for sustainable land use management of the Rokua esker area and to evaluate these alternatives systematically and transparently. The main objective of Paper III was to evaluate the usefulness of the MCDA process in sustainable land use and groundwater management in the Rokua case. The questions examined included: Did the process facilitate stakeholder involvement

and learning among the participants? What was the benefit of the interactive MCDA process for land use planning in the area? Was the process successful in enhancing the conditions for learning (meaningful participation and dialogue among participating stakeholders) and in fostering learning (especially a common understanding of the problem)?

During the PhD studies the author of this thesis has also contributed to papers by Kløve *et al.* (2011b), Koundouri *et al.* (2012), Ala-aho *et al.* (2013) and Bertrand *et al.* (2013). These papers further widened the Rokua esker aquifer case studies and the integrated groundwater management issues.

2 Hydrogeology of eskers and surrounding peatlands

Eskers are glacial sand and gravel deposits from the last deglaciation period. The eskers were formed as glacier meltwater flow transferred sediment in the direction of ice withdrawal. The meltwater ran either in sub-glacier tunnels or in ice crevasses near the edge of the glacier. In esker aquifers, a gravel core is often found at the center of the formation, as the first phase of the glacial sediment stratified in high velocity flow (Banerjee & McDonald 1975, Hebrand & Åmark 1989). As the glacier withdrew, flow conditions usually slowed and finer elements such as sand sedimented on the top of the gravel core (Fig. 1). At the end phase of the formation period, when the glacier had fully withdrawn, the esker might have been part of the flow delta formation left behind by the glacier. In this part, even finer elements might have sedimented onto the top or into the bearings of the formation.

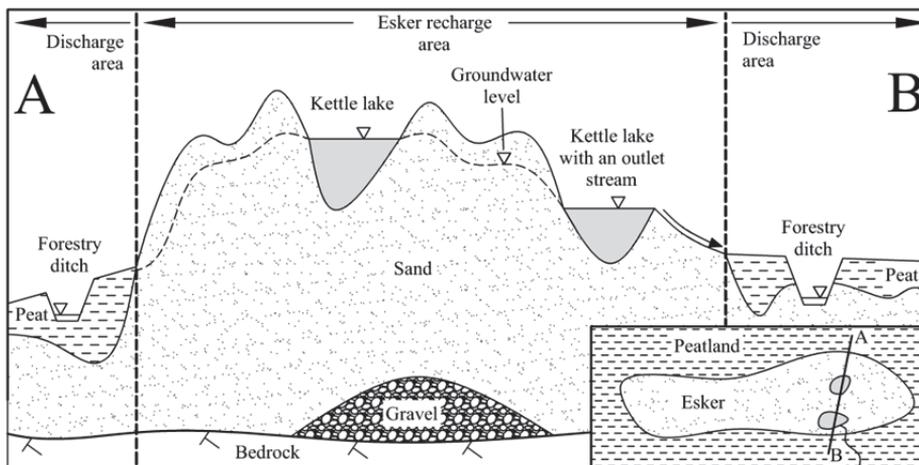


Fig. 1. Conceptual cross-section (A-B) of an esker rising from the surroundings with kettle lakes in the area. The esker formation is divided into a recharge area and a peatland-covered discharge area.

With the glacier melting and withdrawing, ice blocks and boulders became embedded in the sediment of the meltwater flow. When these blocks and boulders eventually melted the ground sank, forming kettle holes (Mälkki 1999). These kettle holes are mostly found in the vicinity of the main channel of meltwater

flow and can be up to 50 m deep (Aartolahti 1973). When the groundwater level is above the bottom of the kettle hole, a groundwater-dependent kettle lake emerges (Fig. 1).

The esker formations are often shallow, unconfined aquifers, rising 10–100 m above the surrounding landscape. However, eskers can also be completely covered by other sediment formations, as in the coastal areas surrounding the Ostrobothnian Bay in Finland (Kløve *et al.* 2011a). The typical esker formation, rising above its surroundings, forms groundwater within the recharge area as rainwater infiltrates to the aquifer. The recharge area usually comprises the main part of the esker formation (with sand and gravel) and the groundwater discharge area comprises nearby features such as springs, lakes, rivers and peatlands (Fig. 1). Since 1984, many eskers in Finland have been protected within the Esker Protection Programme or by the European Union Habitat Directive and its Natura 2000 network.

Around many of eskers in the boreal zone, peatlands cover large parts of the discharge area and can locally confine the groundwater. In many regions of the world, fens have been drained for agriculture, forestry, or peat harvesting. Despite their potential importance, the impacts of discharge area drainage or other land uses on groundwater levels or discharge conditions have not been thoroughly taken into account. Rather, the main focus has been on protecting the aquifer recharge area conditions. The main threats to esker aquifer groundwater levels and ecosystems in Finland to date have been the extraction of gravel and the increasing use of groundwater as a drinking water supply (Britschgi *et al.* 2009, Rintala 2006). The impact of land use in the discharge zone, such as peatland drainage for forestry, has not been considered to have direct effects on esker ecosystems e.g., kettle lakes. A key to understanding whether a particular land use in a discharge area fen affects aquifer groundwater is the hydraulic connection between the discharge peatland area and the upslope esker aquifer.

The hydraulic properties of peat have been studied in various field and laboratory studies in recent decades (e.g., Price 1992, Schlotzhauer & Price 1999, Beckwith & Baird 2001), but groundwater exfiltration into peatlands is not well understood. The hydraulic conductivity of peat decreases with depth and changes drastically at the interface between the acrotelm (layer above the lowest point of varying groundwater level) and catotelm (layer continuously below the groundwater). In studies by Päivänen (1973), Holden & Burt (2002) and Ronkanen & Kløve (2005), the hydraulic conductivity of the peat matrix was found to vary from 10^{-2} to 10^{-10} m s⁻¹. Peat can also have double porosity, where

water flows through the peat matrix and in concentrated passageways as pipeflow (Gilman & Newson 1980, Ours *et al.* 1997). Horizontal pipeflow has been noted in studies of hilly blanket mires, where stormwater moves downstream rapidly via surface runoff and horizontal pipeflow (Holden & Burt 2002, Holden 2005). Studies by Lowry *et al.* (2009) suggest that the double porosity could be the cause of spring formation in peatlands. If the piezometric head is higher in the mineral soil below the peat, the confined groundwater can eventually find its way through the peat in the form of vertical pipeflow. Confined groundwater seepage through peat has also been conceptually presented by Langhoff *et al.* (2006). In both cases, the groundwater discharged in areas where the peat depth rapidly decreased from 3–4 m to less than a meter.

As the hydraulic conductivity of peat can be very low, it can in theory work as an aquitard. For example, in a Danish fen ecosystem, Johansen *et al.* (2011) showed that peat functions as a partially impermeable layer. Those authors concluded that the groundwater intake from the confined sand aquifer under the fen peat does not affect the peat layer groundwater level, but lowers the discharge of natural springs and confined piezometric heads in the area. For assessment of ecosystem impacts after groundwater withdrawal, the interaction between fens and groundwater must thus be understood (Dahl *et al.* 2007). The recent EU Groundwater Directive asks for a better understanding of how terrestrial ecosystems are connected to groundwater (European Commission 2008). The assessment of groundwater body status also depends on the status of ecosystems relying on groundwater.

For peatland-aquifer interactions, groundwater modeling has been used in the past to study the role of peat thickness in spring formation (Lowry *et al.* 2009), to examine the relationship between peatland flow paths and the fate of pesticides (Kidmose *et al.* 2010), to reconstruct historical peatland flow conditions (van Loon *et al.* 2009b), and to define how peatland throughflow defines habitats (van Loon *et al.* 2009a). However, modeling has not been applied in peatland-aquifer land use management.

3 Description of the Rokua esker study area

The Rokua esker aquifer (Fig. 2) is part of a chain of consecutive eskers in Northern Finland formed during the last deglaciation period (Aartolahti 1973). Rokua is a deltaic anticline esker (i.e., the groundwater from the esker discharges to the surroundings) sand formation that rises on average 30–40 m above the surrounding landscape (90 m at maximum; Fig. 3). The groundwater discharge area is covered with peatlands formed after glacial melt, with a maximum peat thickness of more than 5 m (Pajunen 1995, Häikiö 2008). Rokua has a recharge area of 92 km² and a current groundwater protection area of 139 km² in the discharge zone.

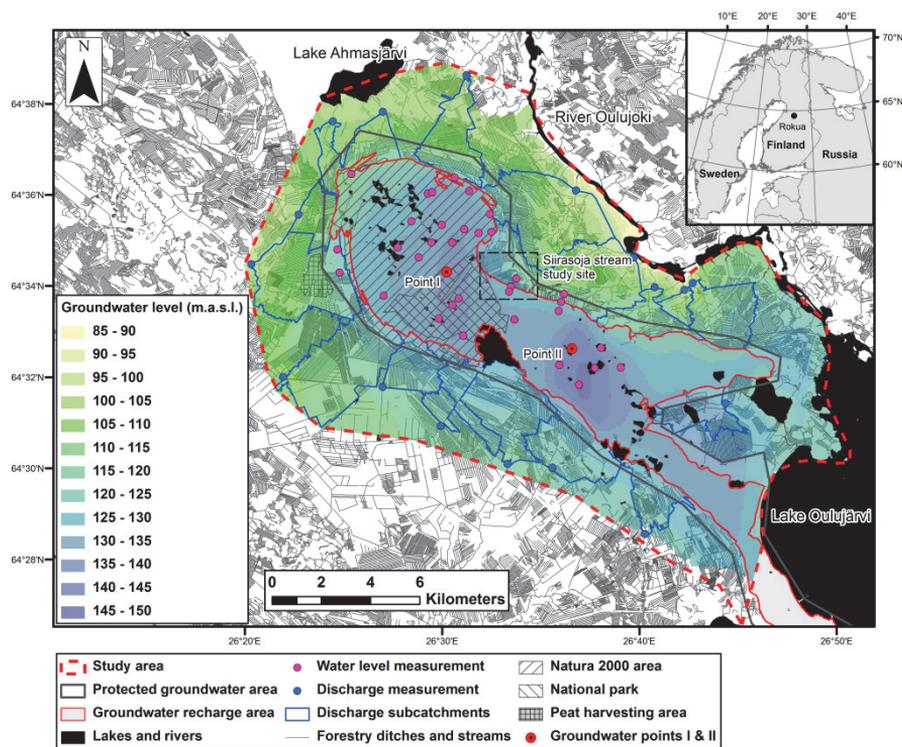


Fig. 2. Rokua esker aquifer with protected areas, groundwater level contours, water level measurements, discharge subcatchments, and discharge measurement points. The Siirasoja stream was the study site in Paper I and non-measurement groundwater mound points I and point II were used for water level analysis in modeling in Paper II.

Rokua is one of the largest individual esker groundwater bodies in Finland. It is a member of the UNESCO Geoparks Network, its western part is protected under the European Union's Natura 2000 network, and part of the esker is protected as a national park (Fig. 2). Rokua is a popular recreation area and holiday resort, with hotels and second homes. The economic impact of the 120,000 tourists per annum (mainly hikers and cross-country skiers) on the local economy is significant (Jurvakainen 2007). Rokua is an example of unique dune formations caused by the wind and fluvial and coastal currents after deglaciation, as well as deep kettle holes and kettle lakes (Fig. 3, cross-section). Among the area's key ecosystems are the crystal clear, oligotrophic, groundwater-dependent kettle lakes. A consistent decline in lake water levels, especially after a dry period at the beginning of the 2000s, raised concerns about their future state. At this point, several factors were cited as the reason for the decline, with land use (forestry drainage and peatland harvesting) in the surrounding peatlands suspected of being one of the main reasons.

Rokua has been geologically surveyed in previous decades by the local authorities. These surveys included borehole drillings, but only to a maximum depth of 20–30 m, without any bedrock confirmation (Fig. 3). Peat depth in the surroundings of Rokua has been studied by the Geological Survey of Finland using point measurements ($n = 4000$) of peat layer depth (Häikiö 2008, Pajunen 1990, Pajunen 1993, Pajunen 2009) but the data do not cover all of the peat area. From 2008 to 2010, the University of Oulu and the Geological Survey of Finland mapped the Rokua esker geology with a 150 km line length of ground-penetrating radar (using Malå 50 and 100 MHz GPR system), a 5 km line length of seismic refraction/reflection measurement, six borehole drillings to the bedrock, and two partially penetrating boreholes (Fig. 3). These surveys revealed fine and medium sand layers to a thickness of over 80 m above the bedrock in the esker area. In one of the boreholes (borehole number 3 in Fig. 3), a 40 m thick sandy gravel core was found beneath 50 m of sand. Coarse material was also found in eastern parts of the Rokua esker near Lake Oulujärvi in earlier surveys, but besides these observations no continuous gravel has been found in the other boreholes or in any of the geophysical analyses. Apart from the borehole gravel observations, other different stratigraphical layers, which could have been used to classify esker soil layers of different permeability, were not evident in the geological data. However, the esker branches in two directions in the eastern part, and most of the borehole samples from this part of the esker consist of finer sand. This suggests a deltaic

formation rather than an esker, and may be associated with lower hydraulic conductivities in the eastern part of the Rokua area.

Water levels in 12 lakes and 12 groundwater piezometers at Rokua were measured monthly in the period 2006–2008 by the local environmental agency. In 2008–2009, 25 automatic water level loggers were installed in lakes and piezometers in the area by the University of Oulu. According to water level observations, the groundwater at Rokua forms two separate mounds, which are represented and studied by modeling in Paper II of this thesis as points I and II (Fig. 2). From these mounds, groundwater discharges to the surrounding drained peatlands in a radial direction. The University of Oulu measured discharge from 18 subcatchments to the surroundings (Fig. 3) of Rokua on 4–6 occasions per year in the period 2009–2012. Subcatchment areas were defined using a LIDAR digital elevation model provided by the National Land Survey of Finland. The LIDAR data have an accuracy of 0.15 m vertically and 0.6 m in the horizontal direction.

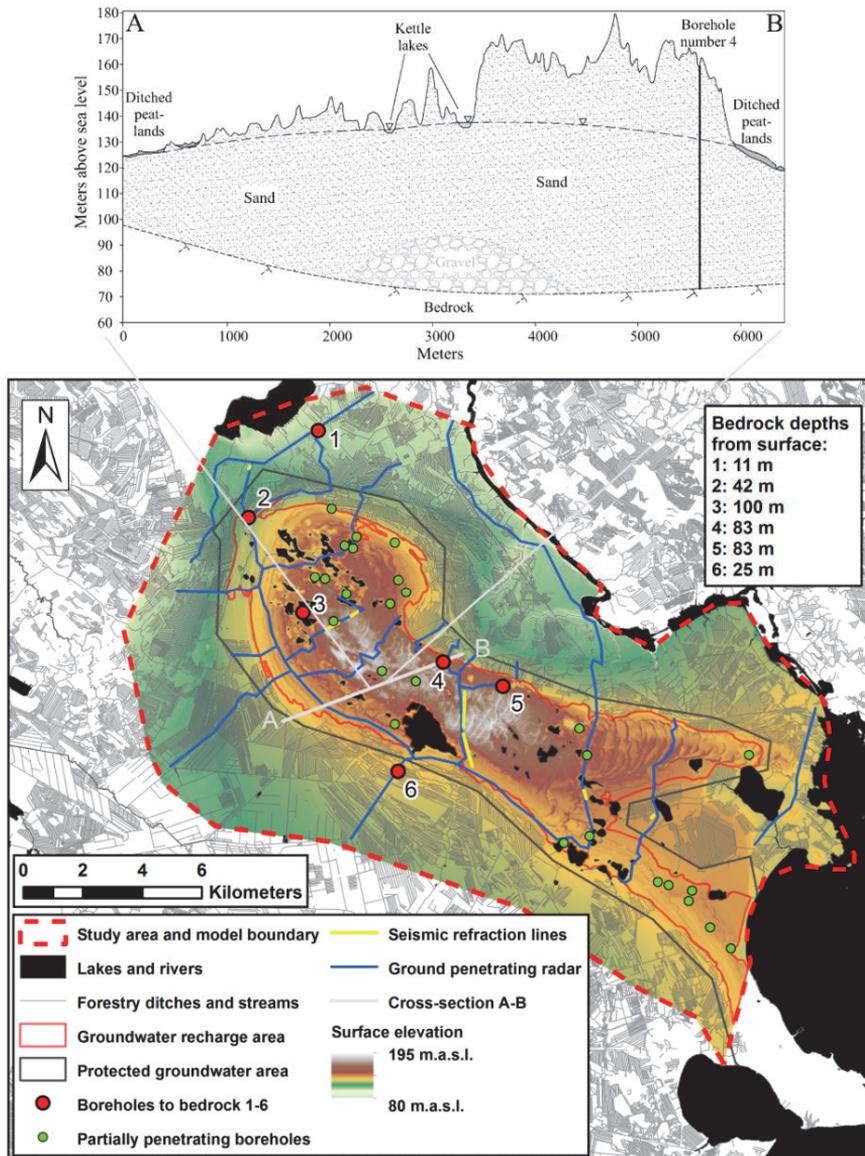


Fig. 3. Surface elevation, geophysical measurements, boreholes, partially penetrating boreholes reaching depths of 20–30 m below the surface, and a cross-section A-B of the Rokua esker with drained peatlands and kettle lakes. The esker consists mostly of sand with no continuous stratigraphical layers, but local gravel deposits occur. The vertical axis of the cross-section is exaggerated for clarity. Reprinted with permission from Springer.

4 Materials and methods

4.1 Groundwater-surface water interaction of a peatland discharge area (I)

In order to study groundwater discharge to a drained peatland, a study site area located in the upper catchment area of the Siirasoja stream was chosen (Fig. 2). The Siirasoja stream had one of the highest runoff amounts of the streams surrounding Rokua during dry season measurements conducted in July 2009 and July 2010. The study area (1.5 km²) was divided into subcatchments A - D (Fig. 4). The drained peatland areas had a mixture of forest types, from dense new forest to thin older forest and clear-cut areas. The Rokua esker formation rises steeply (30%) on the southern side of the peatland.

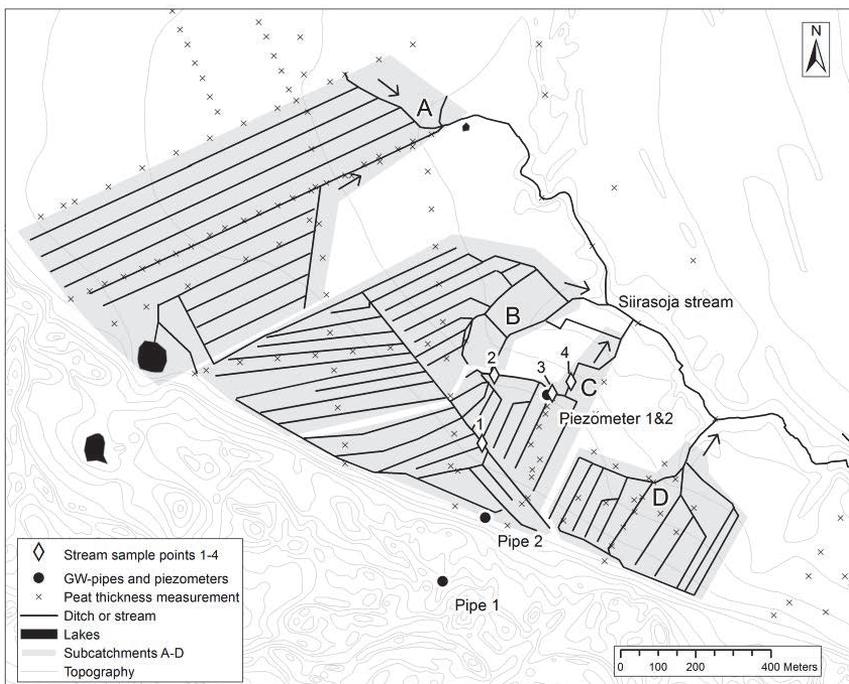


Fig. 4. Map of the Siirasoja stream study site and subcatchments A-D, showing the groundwater pipes, piezometers, stream sampling points, and peat thickness measurement points. Peat thickness measurements were done with ground penetrating radar and manual sounding. Pipe 1 is at the same point as borehole number 4 in Fig. 3. Reprinted with permission from Elsevier.

All ditches in the study area were examined *in situ* during the low-flow season of July 2009 and classified by their discharge volumes according to measurements recorded with a flow meter. In addition, in May 2010 two V-notch weirs were installed at sub-catchment C for continuous discharge measurements (sample points 2 and 4 in Fig. 4). Water level loggers (Solinst Levelogger Gold) were installed at the weirs for hourly measurements.

Groundwater exfiltration points in ditches were identified and classified as either point or diffuse exfiltration types. Spring-like groundwater point discharges were first visually observed and then confirmed with water temperature measurements from the ditch water before and after the observed point. Because groundwater temperature was approximately 10 °C colder than that of the surface water during the *in situ* study period, it was possible to use the temperature difference as a tracer (see e.g., Anibas *et al.* 2011). If no point discharge was observed, the discharge of a ditch increased, and water temperature was low, the ditch was classified as having groundwater seepage discharge.

The hydrogeological structure of the area was studied using a variety of methods. Esker formation thickness was studied with drilling to the bedrock at groundwater pipe 1 (see Fig. 4). At the drilling point, the esker consisted of an 83.4 m thick layer of homogeneous sand (see Fig. 3, cross-section) with a mean d_{50} grain size of 1.961 mm and a standard deviation of 0.065 mm (10 samples). Peat layer thickness in the area has been reported previously by Häikiö (2008). Those data were supplemented with additional manual peat drillings and ground-penetrating radar measurements in 2009 and 2010 (Fig. 4). The spatial distribution of peat thickness was interpolated for the area using the natural neighbor method (140 measurement points at the study site). The groundwater level in sand and peat layers was recorded hourly in piezometers and groundwater pipes in the area (Figs. 4 and 5), using water level loggers (Solinst Levelogger Gold).

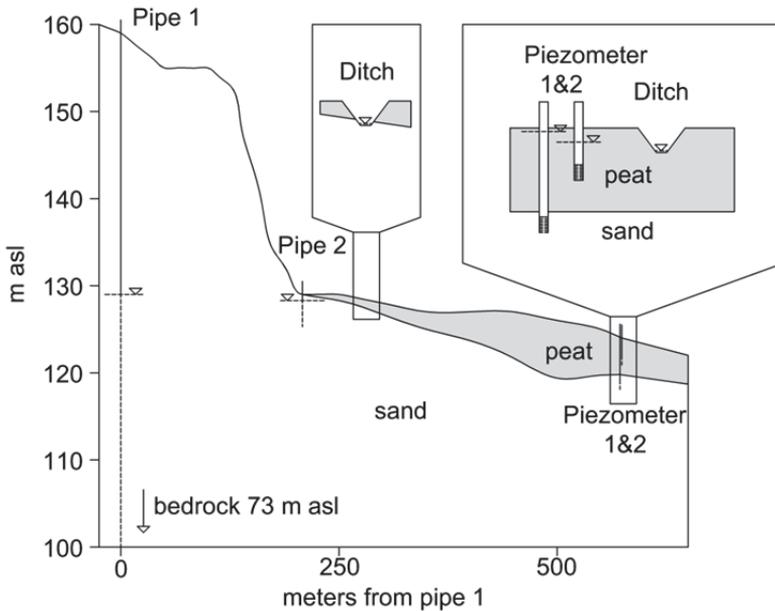


Fig. 5. Cross-section of the Siirasoja study site from groundwater pipe 1 to piezometers 1 and 2. Horizontal axis has 10:1 exaggeration. Reprinted with permission from Elsevier.

The hydraulic conductivity of the peat was measured using a direct-push piezometer with a falling head (Hvorslev 1951). Measurements were taken from different depths (20–200 cm) at four locations in the study area. The hydraulic conductivity varied in these measurements from 10^{-5} m s^{-1} at 20 cm depth to 10^{-9} m s^{-1} at 200 cm depth. The hydraulic conductivity for sand of 2 mm d_{50} grain size is usually 10^{-3} to 10^{-6} m s^{-1} (Davis 1969). Hydraulic conductivity values were used in the Geoslope (Geostudio 2007) and Topodrive (Hsiesh 2001) programs to outline groundwater flow routes.

Precipitation records from 1 July 2009 to 1 July 2010 were obtained from the Finnish Meteorological Institute's (FMI) Pello Climate Station, located 10 km south of the study site. Moreover, local precipitation was determined at the Siirasoja stream using a tipping bucket gauge at one-hour measurement intervals during the period 22 May 2010–1 July 2010. The snow water equivalent (SWE) was measured by the Finnish Environment Institute at the snow line in Vaala, 11 km north-east of the study site. Evapotranspiration at the study site was estimated using the United Nations Food and Agriculture Organization (FAO) Penman-Monteith equation (Allen *et al.* 1998).

Data on meteorological variables were provided by FMI. Daily temperature was measured at the Pelso Climate Station, while data on relative humidity, wind speed, and global radiation were obtained from nearest 10 km x 10 km FMI grid interpolation point of Finland. Applying the FAO Penman-Monteith equation during winter can lead to erroneous results, because assumptions for reference evapotranspiration calculations are contradicted for the snow cover period (Allen *et al.* 1998). This was taken into account by setting the evapotranspiration to zero for days when the maximum temperature was below 0 °C.

In addition to field observations and discharge measurement, natural tracers (SiO₂, Ca, pH, and electrical conductivity) were measured at the study site to identify groundwater flow paths and exfiltration to the ditches on the hillslope scale. Water samples were taken in June 2010 from stream sample points 1 to 4, groundwater pipes, piezometers (Fig. 4), and rainwater (2 km west from study site). In addition, in one stream section a mixing analysis was conducted, using SiO₂ as a natural tracer. SiO₂ is typically used in groundwater and surface water mixing studies (e.g., Hooper & Shoemaker 1986, Wels *et al.* 1991, Iorgulescu *et al.* 2005), as precipitation usually has a very low concentration of SiO₂. All samples were analyzed by the Finnish Environmental Institute (SYKE) laboratory, which is accredited for water sample analyses by the Finnish Accreditation Service.

The mixing analysis was based on conservation of mass and water balance and the assumption that the SiO₂ tracer is chemically conservative. The mixing ratio was calculated between the stream sampling points 2 and 4, where discharge was measured with V-notch weirs. Mixing analysis was used to define the ratios of water exfiltrating from the peat aquitard and from the sand aquifer to the stream section between the V-notch weirs. The mixing analysis was calculated using four end-points in eq. (1) and (2):

1. Upstream V-notch weir (stream sample point 2)
2. Peat aquitard (tracer sample from piezometer 1)
3. Sand aquifer (tracer sample from piezometer 2)
4. Downstream V-notch weir (stream sample point 4).

$$Q_4 C_4 = Q_1 C_1 + Q_2 C_2 + Q_3 C_3, \quad (1)$$

$$Q_4 = Q_1 + Q_2 + Q_3, \quad (2)$$

where Q_{1-4} is the discharge of components 1–4 ($\text{m}^3 \text{d}^{-1}$) and C_{1-4} is the concentration of end-point samples 1–4 (mg L^{-1}). From eq. (1), discharge for the peat aquitard and the sand aquifer was calculated:

$$Q_2 = \frac{Q_4(C_3 - C_4) + Q_1(C_1 - C_3)}{C_3 - C_2}, \quad (3)$$

$$Q_3 = \frac{Q_4(C_2 - C_4) + Q_1(C_1 - C_3)}{C_2 - C_3}, \quad (4)$$

Rainwater was not taken into account in these calculations, as all samples were taken during a dry period defined as no rain in three days.

4.2 Modeling future management scenarios (II)

Rokua is an anticline type esker, where the groundwater is discharged from the groundwater mounds of the esker to the surrounding drained peatlands (Fig. 6a). The humified peat deposits have a lower hydraulic conductivity than the esker aquifer and have features of a semi-confined layer, with water flow in preferential channels within the peat (see section 5.1). Groundwater flow from the esker to the whole surroundings was simulated by a steady state model. The MODFLOW groundwater model (McDonald & Harbaugh 1984) was built as a one-layer model (because, as stated earlier, no continuous stratigraphy was detected), with a uniform cell size of 100 m x 100 m. Boundary conditions fell into three categories. Regional dammed lakes and a large dammed river surrounded part of the model area, and were modeled as first type constant head boundaries (Fig. 7). Based on the geological data, the soil layers situated south of the esker are thin (Fig. 3, south of the cross-section), with local bedrock exposure, and therefore a no-flow boundary was defined for these areas. Some of the lakes located in the esker area have an outlet and were modeled as general heads (Fig. 7), as the stream outlet from the lake keeps the lake water level constant as recharge and runoff replenishes it.

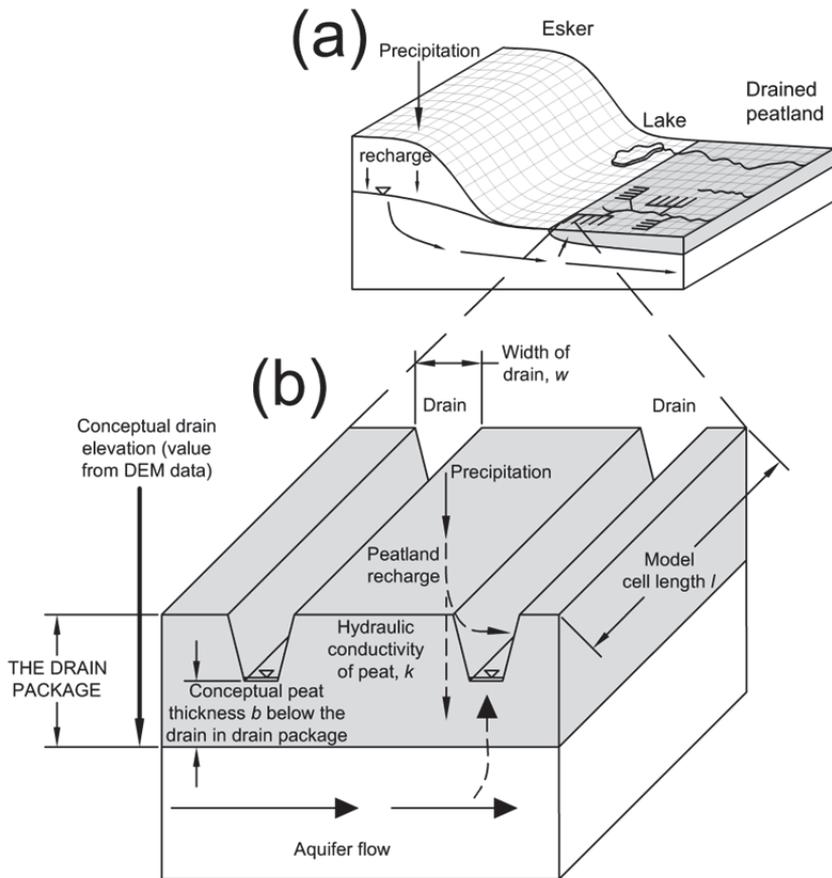


Fig. 6. (A) Groundwater flow discharge from the Rokua esker to surrounding peatlands and (B) peatland drain boundary condition concept in the MODFLOW model cell. Reprinted with permission from Springer.

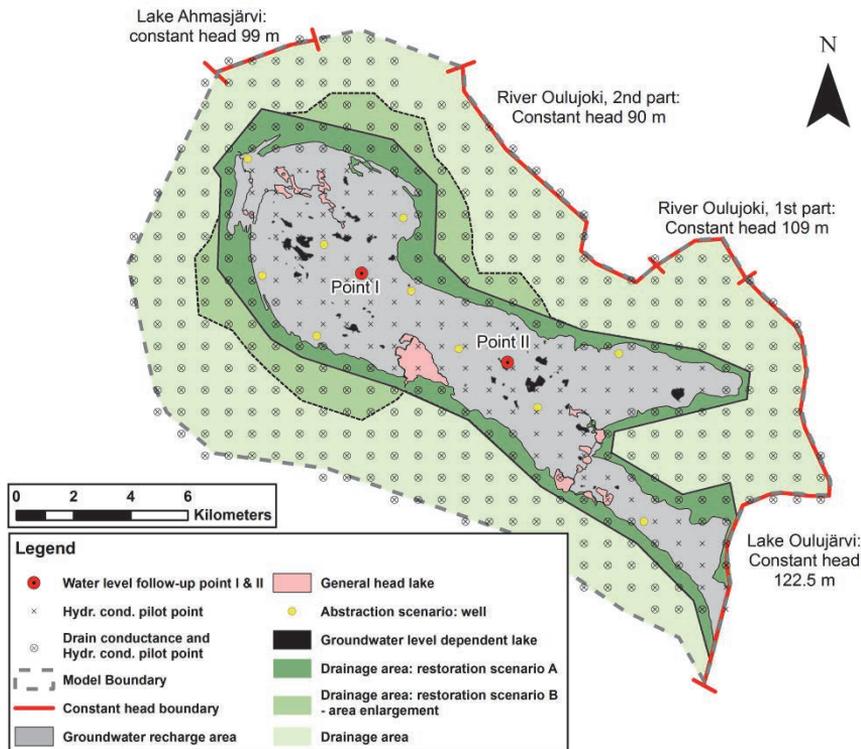


Fig. 7. Rokua MODFLOW model conditions, pilot points, and land use scenario conditions. Constant head boundary conditions were defined for the River Oulujoki with two dams, Lake Ahmasjärvi and Lake Oulujärvi. Lakes with outflow were defined as general heads. Groundwater points I and II were used for water level follow-up before and after calibration and in scenario runs. Reprinted with permission from Springer.

The peatland drainage system covers almost all the peatlands surrounding the Rokua esker (forestry ditches and streams in Fig. 2). The MODFLOW drain package was used in all of the cells surrounding Rokua as a boundary condition (Fig. 6b), to simulate water outflow to peatland drains from this part of the model domain. Use of the drain package requires a drain elevation (level of the drain bottom) and a drain conductance to be defined. When the simulated groundwater level in a cell rises to the drain elevation, groundwater discharges to the drain. In the modeling approach employed in Paper II, the conductance value represented how the peat layer resists groundwater discharge. The physical properties of the

confining peat layer were used to define the drain conductance value in the drain package as:

$$Con = \frac{K_{peat}lw}{b} \quad (5)$$

where Con is the drain conductance ($m^2 s^{-1}$), b is the thickness of the peat below the ditch (m), k_{peat} is the hydraulic conductivity of the peat ($m s^{-1}$), l is the model cell length (m), and w is the width of the ditch (m). The values for ditch width (2 m, 3 ditches in a cell) and depth (0.8 m) were defined from drainage standards used in Finland (Koivusalo *et al.* 2008). The average peat thickness below the ditch was 0.6 m, based on Geological Survey data. An estimated value of $1.15 \times 10^{-3} m^2 s^{-1}$ ($100 m^2 d^{-1}$) for conductance was used as an initial condition for the modeled area. This corresponds to a peat hydraulic conductivity of $10^{-6} m s^{-1}$ and represents the situation where drainage has increased the hydraulic conductivity from the natural value of $10^{-7} m s^{-1}$ (Päivänen 1973, Holden & Burt 2002). This starting value for conductance was considered to represent the preferential flow channels and seepage found in these drained discharge areas (see section 5.1). The cell top elevation value in MODFLOW was calculated from LIDAR data over the cell area. Using the cell top elevation as the drain elevation would overestimate the drain depth, because the drains occupy the lowest elevations of a cell. Therefore the lowest elevation within each cell in the groundwater discharge area was calculated from LIDAR data and assigned the drain elevation in that cell.

Aquifer recharge was estimated using the COUP model, which is often used in Nordic conditions to simulate water flow in the soil-vegetation-atmosphere continuum (Jansson & Karlberg 2004). Driving climate data for recharge (precipitation, temperature, global radiation, wind speed, and relative humidity) were obtained from the Finnish Meteorological Institute (1960–2010) and downscaled regional climate change data (2010–2100) from four different global climate models (GCMs) based on the SRES A1B (Special Report on Emissions Scenarios A1B) greenhouse gas emission scenarios (Nakićenović & Swart 2000, IPCC 2007). The recharge area was subdivided into different zones, similar to those used by e.g., Jyrkama *et al.* (2002), which were defined by high resolution data for leaf area index and unsaturated soil profile thickness. Water flow in the soil profiles for each zone was simulated with the recharge equation. Transient model runs resulted in daily time series of recharge, which were summarized to annual values for hydrological years (1 Oct–30 Sept). The annual 440 mm recharge, averaged for the period 2000–2010, was used as the steady state

recharge in MODFLOW. However, a lower level of detail was deemed adequate for the study, so the data from the simulations were averaged spatially and temporally. Previous estimates of esker aquifer recharge in Nordic conditions range from 50 to 70 % of annual rainfall (Zaitsoff 1984, Lemmelä & Tattari 1988, Lemmelä 1990). Recharge simulation results from the COUP model fell within the range reported in previous studies and were considered to give a more site-specific estimate.

4.2.1 Calibration and uncertainty analysis using PEST

The pilot point method (de Marsily *et al.* 1984, Doherty 2003) was used to parameterize the hydraulic conductivity and the spatial distribution of drain conductance within the model. Parameter values were estimated using PEST (Doherty 2013). In the pilot point method, parameter values are estimated at discrete locations and then interpolated to model cells. Pilot points were also used to study the spatial identifiability of the parameters. Hydraulic conductivity was parameterized using 489 pilot points and drain conductance was parameterized using 375 pilot points within the model (Fig. 7). Long-term average data on water levels during 2006–2011 and discharge values during 2009–2011 were the calibration targets. Water levels were assigned different weights according to the temporal data available and the quality of the measurement at each point (weight 0.5–1, where 0.5 corresponds to a short time span of measurements). Subcatchment discharge data weights were smaller (weight 0.0005), as the data had a relative difference in accuracy compared with water level data (hundreds of cubic meters for discharge compared with 0.1 m for water level). Furthermore, discharge was only measured 4–6 times a year for three years. The use of these weights also ensured that discharge data contributed roughly the same as head data to the overall objective function at the commencement of the inversion process. Such a strategy can be used to ensure that information contained within different types of data achieves its objective of informing parameters during the overall calibration (Doherty & Welter 2010).

The starting value used for hydraulic conductivity of the aquifer was 10^{-5} m s^{-1} . Parameter upper and lower bounds were based on common values for sand (e.g., Davis 1969) and grain size analysis data on soil samples from the Rokua area. In total, 36 soil samples from eight boreholes were analyzed for grain size distribution. When a borehole with grain size analysis data was near a pilot point, the soil sample-based K value estimated for the borehole was used to give

the pilot point a starting value and calibration upper and lower limits. The initial condition for drain conductance was the value of $1.15 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ (100 m d^{-1}) for the drainage area, as stated in section 4.2.

In solving the inverse problem of calibration of the Rokua model, two types of regularization were implemented by PEST. One of these was Tikhonov regularization (Tikhonov & Arsenin 1977), which imposed the constraint that parameters vary from their initial values (informed by geological knowledge, as described above) to the smallest extent possible in order to fit the calibration dataset. The other was singular value decomposition as described by e.g., Aster *et al.* (2005), which ensures numerical stability by partitioning parameter space into solution and null spaces; a solution to the inverse problem is sought only in the former space. In implementing PEST's Tikhonov regularization functionality, the target objective function specified was somewhat higher than the lowest that could be achieved with this measure. This target was chosen to provide a level of fit commensurate with the measurement noise associated with the data and the structural noise associated with the model. The latter was assessed through the fact that such an objective function results in estimation of parameter fields which are geologically reasonable (based on measurements of the area and the literature concerning eskers) and do not appear to show signs of "over-fitting", such as high levels of spatial hydraulic property heterogeneity.

To study how much information the calibration dataset held with respect to different parameters employed by the model, the identifiability described by Doherty & Hunt (2009) was used. The identifiability of a parameter is defined as the cosine of the angle between a vector in the direction of the parameter in parameter space, and the projection of that vector onto the calibration solution space. It can have a value between zero and one. If the value is one, the parameter is completely identifiable on the basis of the calibration dataset. If its value is zero, nothing about the parameter's value can be inferred from the calibration dataset.

Nonlinear uncertainty analysis: Null-space Monte Carlo

The null-space Monte Carlo (NSMC) method (Tonkin & Doherty 2009) can be used for efficiently generating many different random parameter fields, all of which are geologically reasonable and all of which allow the model to fit the calibration dataset. Efficiencies are gained through: (1) generating random realizations of only null-space components, centered on the calibrated parameter field; (2) re-calibrating the model on each occasion (no re-calibration would be

needed if the model were truly linear) using so-called “super parameters”, which are typically small in number as they span the solution subspace of parameter space; and (3) using pre-calculated sensitivities for the first iteration of these re-calibration procedures for all parameter realizations.

In implementing the NSMC process for the Rokua model, the random field recalibration process was halted either when the target objective function was achieved, or after two iterations. A total of 900 stochastic parameter fields were generated and subjected to re-calibration in this way; 870 of these re-calibration exercises achieved the target objective function within two iterations. Only those which achieved the target were retained for subsequent uncertainty analysis. An average of 24 model runs was needed per parameter field. Outputs calculated using NSMC-generated parameter fields were compared with the same outputs generated using the 900 stochastic parameter fields prior to the NSMC process. The comparison was made for two non-calibration points (points I and II, Fig. 2) to demonstrate how much the hydrological information on the calibration data could narrow the range of uncertainty of these model predictions.

4.2.2 Land use change and climate variability scenarios

To demonstrate the impact of different land use or climate condition scenarios on the status of groundwater in the esker aquifer, a calibration-constrained uncertainty analysis was undertaken with the model. The fact that the model is steady state removes its ability to predict the timing of changes undergone by the groundwater system. However, the final state of the system after land use changes or periods of constant (high or low) driving conditions (the most important information required for the decision-making process in the present context) is still predictable. At the same time, the relatively short computation requirements for steady state simulations allow uncertainty analysis of the type described here to be undertaken. In making each prediction of future groundwater state, the model was run 870 times under the pertinent altered conditions (see Table 1), i.e., one model run was undertaken using each of the parameter fields computed through the null-space Monte Carlo process. The effects of scenarios on esker water levels were studied for groundwater mound points I and II (see Fig. 2), as these points represent the average groundwater state in the esker area.

Table 1. Summary of land uses tested and different climate scenarios with changed conditions for each model (gw = groundwater; see text for explanation of scenarios). Reprinted with permission from Springer.

Scenario name	Drained peatland restoration hypothesis			GW-abstraction	Climate data
	Restoration area	Drain elevation rise	Factor to peat hydr. cond.		
Restoration 1A	current gw-area	0.5 m	-	-	2000–2010
Restoration 2A	current gw-area	0.5 m	0.5	-	2000–2010
Restoration 3A	current gw-area	0.5 m	0.1	-	2000–2010
Restoration 1B	expanded gw-area	0.5 m	-	-	2000–2010
Restoration 2B	expanded gw-area	0.5 m	0.5	-	2000–2010
Restoration 3B	expanded gw-area	0.5 m	0.1	-	2000–2010
Abstraction	-	-	-	27 000 m ³ d ⁻¹	2000–2010
Abstraction and Restoration 3A	current gw-area	0.5 m	0.1	27 000 m ³ d ⁻¹	2000–2010
Dry	-	-	-	-	1970–1980
Dry and Restoration 3A	current gw-area	0.5 m	0.1	-	1970–1980
Dry and Restoration 3B	expanded gw-area	0.5 m	0.1	-	1970–1980
Dry 2050–2100	-	-	-	-	2050–2100 climate scenario data

Drained peatland restoration

Drain blocking is a common method for restoring the hydrological and ecological conditions of a peatland (e.g., Armstrong *et al.* 2009, Wilson *et al.* 2010, Aapala *et al.* 2013). Drained peatland restoration has been considered as a potential method to maintain the aquifer water levels at a higher elevation. Here, the effect of such restoration was modeled by: 1) raising drain water levels (drain elevation parameter) with dams; and 2) filling the ditches and reducing the hydraulic conductance of drains (see Fig. 6b). Both of these methods have been used in practise for peatland restoration. Drains were assumed to reduce the confining effect of the peat layer, thereby enabling more exfiltration from the aquifer to the

drainage ditches. Restoration of the drained area, e.g., through filling in the ditches, reduces the hydraulic connection between the aquifer and drainage ditches. Thus the elevation of the groundwater exfiltration point (elevation of the ditch) in the restored peatland also rises. Six different restoration scenarios were tested:

- Restoration 1A: Restoration is carried out within the current groundwater protection area. A 0.5 m rise in drain elevation (as the ditches are dammed) was imposed in the model.
- Restoration 2A: As in scenario 1A, except drain restoration decreases drain conductance by a factor of 2 as the drains are filled in (i.e., drain conductance was multiplied by a factor of 0.5) within the restoration area.
- Restoration 3A: As in scenario 1A, except drain restoration decreases drain conductance by a factor of 10 (i.e., drain conductance was multiplied by a factor of 0.1) within the restoration area. This value is considered to represent more natural state conditions of the peatlands (see section 4.2).
- Restoration 1B: Restoration is carried out in a groundwater protection area expanded at the western edge of the esker, where a sensitivity analysis suggests that changes in drainage conditions will affect aquifer water levels (Fig. 7). Drain elevations were raised by 0.5 m in this area.
- Restoration 2B: As in scenario 1B, except drain restoration decreases drain conductance by a factor of 2 (i.e., drain conductance was multiplied by a factor of 0.5) in the expanded area.
- Restoration 3B: As in scenario 1B except drain restoration decreases drain conductance by a factor of 10 (i.e., drain conductance was multiplied by a factor of 0.1) in the expanded area.

Small-scale restoration comprising blocking a single ditch within the Rokua discharge area was tested by Kupiainen (2010) and a groundwater discharge decrease and groundwater potentiometric level rise adjacent to the restoration area showed local potential for restoration. That study represented a situation where drain elevation was raised with a dam, as in the Restoration 1A scenario. As no local data were available on the effects of filling in the ditches, the factors 0.5 and 0.1 were used as representative end results of restoration.

Groundwater abstraction

Oulu, the main city in Northern Finland (population 190 000), is situated 70 km from the Rokua esker. There are no current or future plans to extract groundwater for use in Oulu from the vicinity of Rokua, but this scenario was nevertheless tested using the model developed in this study as a further demonstration of its use as a management tool, and to have a comparison point for the effects of peatland drainage on aquifer storage. The city currently uses 27 000 m³ of water per day, which is approximately 25% of the daily recharge of the Rokua aquifer (average for 2000–2010). In the Abstraction scenario, this amount was assumed to be pumped from 10 abstraction wells around Rokua (Fig. 7). The Abstraction scenario was also combined with the Restoration 3A scenario in order to investigate whether the effects of abstraction on water levels could be reduced with concomitant drain restoration.

Past and future dry climate seasons

The driest 10-year period within the available local climate data (1960–2010) was 1970–1980. The average recharge for this 10-year period was used to examine how the model responded to periods of lower than average recharge compared with the climate conditions used for calibration (2000–2010). This dry period scenario was also combined with the Restoration 3A and 3B scenarios. Future recharge was estimated with the same simulation approach as the historical recharge, using the downscaled projected climate change scenario data for precipitation, temperature, global radiation, wind speed, and relative humidity as the driving variables in the recharge model for the period 2010–2100. As for the historical dry period, a 10-year moving average was calculated from the simulated recharge for each of the four climate change scenarios to obtain a recharge estimate for drier than average periods for 2050–2100. The minimum 10-year moving average for each climate scenario was considered as the recharge for dry periods in the future climate conditions, all of which were used as model inputs in NSMC predictive runs.

4.3 Decision analysis framework (III)

The aim of the MCDA process was not to obtain a definitive solution to the problem of the Rokua aquifer, but to support stakeholder participation and

increase the overall understanding of the problem for all parties. In the beginning of the MCDA process in spring 2011, the groundwater management issue seemed to be an ‘unstructured problem’ (see Turnhout *et al.* (2008) for problem definition), with no consensus concerning either the goals or the means and with great scientific uncertainty. For example, the groundwater modeling for management (Paper II) was in preparation, and therefore only preliminary modeling results were available for the MCDA process. In this kind of context, decision making requires a high level of participation by actors holding conflicting perspectives and interests. Policy development becomes a learning process, a dialogue where actors develop and reflect upon conflicting perspectives (Turnhout *et al.* 2008).

The MCDA method applied in the Rokua case is based on multi-attribute value theory (MAVT) (Keeney & Raiffa 1976), and it takes advantage of the DAI approach (Marttunen & Hämäläinen 2008, Marttunen 2011), based on personal interviews using a multi-criteria model. At the core of the DAI framework is MCDA-based interactive and individual analysis. In the DAI approach, framing and structuring, as well as impact assessment, are carried out in close co-operation with all key stakeholders. In the interviews, the decision analyst uses MCDA software and poses questions to the interviewee, ensuring that the answers reflect the interviewee’s views as closely as possible.

In MAVT, a decision problem is formulated with multiple attributes, and these attributes are used in the evaluation of the alternatives. MAVT has been proven to be a systematic and a transparent way to model problems with multiple criteria and alternatives when working with stakeholders (see e.g., Mustajoki *et al.* 2011). In the interview process, the stakeholders or decision-makers are asked to give numerical preference statements, which are used to calculate the attribute weights describing the trade-offs between the attributes in the additive value function model. In eliciting the weights of the criteria, the interviewees are encouraged to profoundly consider their own values and the trade-offs. This ‘learning by analyzing’ technique is one of the main advantages of the DAI approach (Marttunen & Hämäläinen 2008).

The DAI approach has been observed to help the participants in assigning consistent and unbiased weights. In an interactive interview, the analyst can notice possible inconsistencies, misunderstandings, and biases in the interviewee’s answers (Marttunen & Hämäläinen 2008). For example, in watercourse planning, MCDA methods are reported to inspire learning and understanding in a different manner than conventional meetings, while interactive

use of the methods has supported systematic analysis of stakeholder preferences and has helped analyze how these preferences affect the ranking of the alternatives (Marttunen & Suomalainen 2005, Marttunen & Hämäläinen 2008).

The decision analysis process in Rokua was led by an expert group consisting of researchers from the University of Oulu. The expert group organized a total of four different meetings or workshops with the stakeholders (see Table 2), where the MCDA work was processed. Figure 8 describes the main phases of the decision analysis process.

Table 2. List of stakeholder groups and representatives in the decision analysis interviews.

Stakeholder	Representation	Number of interviewees
Forestry	Forest Centre (state organization)	2
	Forestry association	1
	Forest owner	3
Regional administration	Groundwater management	3
	Conservation of habitats	2
Nature park administration	Forest park services	1
Municipalities	Chief engineers	2
Tourism	Hotel manager	1
Local NGO	Rokua association	1
Second house owners	Association of owners	1
Development organization	Humanpolis/Geopark	1
Peat production	Turveruukki company	1

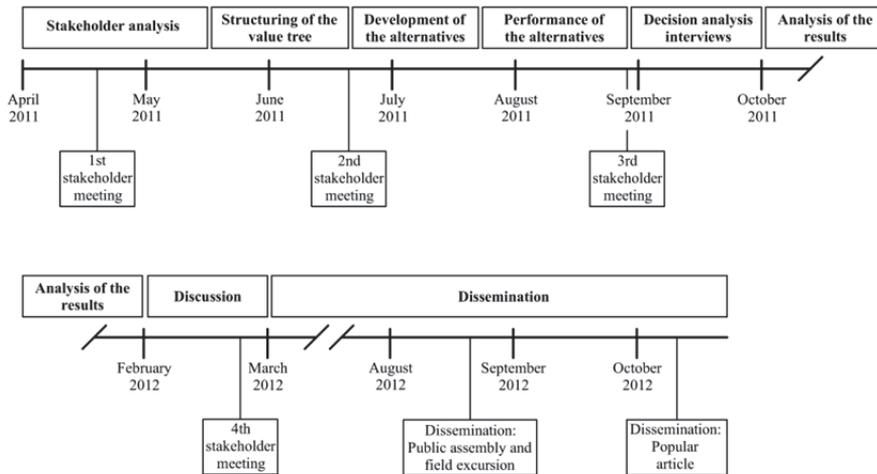


Fig. 8. Decision analysis process in the Rokua case.

4.3.1 Stakeholder analysis and structuring the value tree

In the first stakeholder meeting, the initial list of stakeholders and the definition of the decision context in the Rokua esker area and groundwater management were presented to the various interest group representatives. As a result of that meeting, a list of stakeholders (see Table 2) to be involved was finalized, and a first draft of the value tree, including the stakeholders' objectives concerning groundwater management and land use in the Rokua esker area, was formed (see Fig. 9). The next step was to finalize the value tree. In the second stakeholder meeting, the objectives (reflecting 'what matters' to those whose views should be considered in a given decision context) on the basis of the initial proposal for the value tree were discussed. In the same meeting, the attributes for the measurement of each objective were set up (Table 3, see next section).

The meeting mainly focused on discussing the objectives and their measurement. For example, there was discussion about how to measure the change in tourism if the water levels in the kettle lakes continue to decrease. It was generally accepted that changes in the number of tourists visiting the area due to water level variations cannot be evaluated convincingly, since many other issues (e.g., the overall standard of tourism services) influence the attractiveness of the area in the future. The ecosystem services of the kettle lakes that provide

recreational and aesthetic benefits for visitors are one of the area’s attractions, but they do not form the only and decisive factor for the whole tourism sector. Indirect economic benefits of tourism and forestry for the local and regional economy were also discussed. It was decided not to focus on these benefits in the assessment, due to the considerable level of uncertainty concerning how much water level changes may affect these factors.

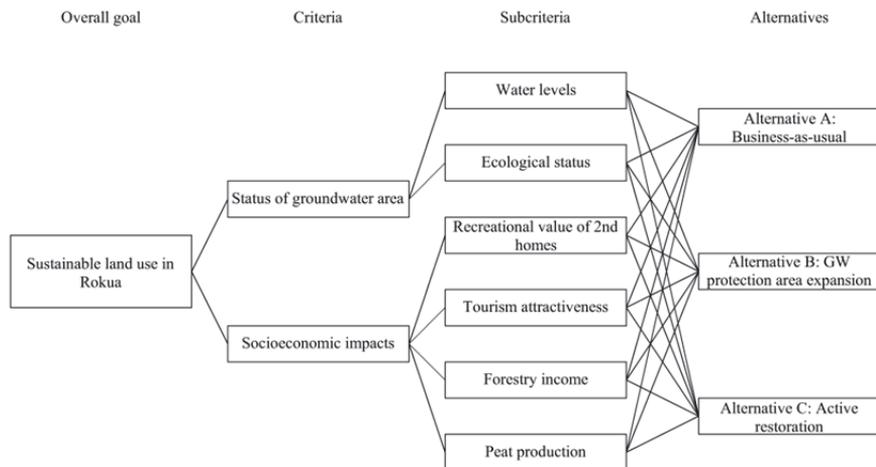


Fig. 9. Value tree for the multi-criteria decision analysis of Rokua.

4.3.2 Development of alternatives and impact assessment

The possible land use management alternatives were considered while structuring the value tree. The set of alternatives was initially developed by the expert group and discussed and revised in the second stakeholder meeting. The alternatives developed reflect the main objectives and interests, as well as issues of conflict:

Alternative A: Business-as-usual

Forestry practices continue as usual; reopening of drainage ditches in the groundwater area is not prohibited, but is under case-by-case consideration by the regulators.

Alternative B: Expansion of the groundwater protection area

A 3–5 km² expansion of the Rokua groundwater protection area into the surrounding peatlands, where groundwater is confined under peat. Forestry is limited or forbidden in these areas. The environmental administration's control over the area is strengthened.

Alternative C: Active restoration (technical solutions) of peatlands

Restoration of critical groundwater exfiltration areas either by damming or filling in drainage ditches. The alternative focuses on adaptive management efforts to locate the most critical areas of groundwater exfiltration instead of protecting larger land areas.

Locations for groundwater area expansion (Alternative B) and restoration targets (Alternative C) were estimated by using the groundwater exfiltration risk prediction method developed for Rokua by Eskelinen (2011). The method estimated the most likely locations of groundwater exfiltration from the slope of the esker, distance from the recharge zone, distance from springs, baseflow of the discharge area watersheds, and peat thickness.

The impact assessment of the selected alternatives was conducted by the expert group after the second stakeholder meeting. The hydrological, ecological, and socio-economic impacts of the proposed alternatives during a 30-year period are presented in Table 3. The impact assessment was based on the studies conducted and the preliminary results of ongoing research in the area. As the assessment was partially based on preliminary results and the time span of the assessment was 30 years, the uncertainty of the impact assessment was considered to be high. For this reason, some of the impacts were studied using less precise, qualitative measures. These qualitative measures indicated whether the alternative had a negative impact (–), no change from the current situation (0), or a positive (+) or highly positive impact (++). For example, active restoration was assessed to have a highly positive impact on the springs surrounding Rokua.

Table 3. Objectives, attributes, and impact matrix of different alternatives (GWP = groundwater protection).

Objective	Attribute(s)	Business-as-usual	GW-expansion	Active restoration
Normal level of groundwater and dependent lakes	Change in average Rokua water level in 30 years (groundwater and lakes)	-1 m	-1 to 0 m	+1 m
Good ecological status in lakes and springs	Chemical state of lakes	0	0/+	+
	Chemical/ecological state of springs	0	0/+	++
Good recreation value of second homes	Recreation value change of second homes in 30 years	-150,000 to	0 to	0
		-230,000 €	-230,000 €	
Attractive tourist resort	Change in attractiveness of Rokua for tourists in 30 years	-	0	+
Profitable forestry	Forestry income loss in 30 years	0	-50,000 to	-500,000 to
			-250,000 €	-2,500,000 €
Minimal loss of peat production	Income loss in peat production or losses caused by restoration of peat harvesting area	0	0/-	-

Water levels of Rokua

Forestry ditches have changed the groundwater exfiltration patterns of the Rokua groundwater discharge area. How much these changes have actually affected the Rokua water levels was modeled during the MCDA process. For the MCDA, the best currently available information from hydrological studies at that time was used to assess how the water levels would behave in the following 30 years in different alternatives (Table 3). If Alternative A prevails, the long-term decline in water levels will continue and can cause a water level decline of approximately 1 m (from the average value) within 30 years. During dry periods, this would cause lower minimum water levels which could be more drastic than during the dry periods of the 1980s and the 2000s. In Alternative B, the long-term decline in water levels is stopped, but water levels would not return to the level preceding drainage. In Alternative C, water levels return to the assumed natural state, on average 1 m higher than the current situation. This level is indicated by the kettle lake shoreline region occupied by the oldest trees. This alternative can be estimated to be less uncertain than Alternative B, as there are active procedures aimed at restoring the groundwater exfiltration patterns to a natural state.

Ecological state of lakes and springs

Preliminary studies of groundwater-surface water interactions in Rokua have shown that phosphorus is leaching into the groundwater from sandy soil, especially when the groundwater has a long contact time with the sand (i.e., old groundwater). As the clear oligotrophic kettle lakes are groundwater-dependent, the risk of eutrophication increases due to water level decline. The risk also increases as older groundwater might seep into lakes and increase the proportional amount of incoming phosphorus. Additionally, lake water volume decreases due to water level decline, increasing the proportional amount of phosphorus entering the lakes.

Another ecological issue is that drainage has dried up natural springs that formerly acted as natural groundwater exfiltration locations in the peatlands surrounding Rokua. As they are dry, a poor ecological state currently exists in these spring ecosystems. If drained areas are restored, the springs will most probably return to a more natural state. Spring locations have not been mapped thoroughly and therefore the question of how many springs can be restored increases the uncertainty of this factor. The ecological status of both lake and spring ecosystems is predicted to have a positive impact as a result of implementing Alternatives B and C.

Recreational value of second homes

One of the key factors in the recreational value of Rokua is the pristine, clear-water, oligotrophic kettle lakes. To date, 53 second homes have been built on the shores of these lakes and the recreational value of these houses is partially dependent on the shoreline. The water level decline is moving the shoreline away from the houses and revealing former lake bed areas. This will decrease the recreational value of the lake shore as thickets start to grow and the pristine landscape changes. The link between the recreational value of second homes and lake water level was calculated using the VIRKI model. The model was originally developed to calculate the effects of water level variations on the value of properties on lake and river shorelines (Keto *et al.* 2005). In the present case, the model was used to calculate how much the recreational value of Rokua would decrease if the shoreline recedes from the level observed in 2008, when lakes no longer showed significant effects due to previous dry years and water levels were close to the estimated average of the past 30 years. In Alternative A, the water

level is presumed to decrease by approximately 1 m, and this would cause a shoreline retreat of approximately 5–6 m. This retreat would cause an annual decrease in recreational value of 94–145 € for each of the second homes. In 30 years, this would mean a 150 000–230 000 € decrease in the recreational value. In Alternative B the decline would presumably stop, but as the future level variation is uncertain, the value decrease would be somewhere between 0 and 230 000 €. In Alternative C, the water levels should return to a more natural state and would be at those of 2008 or above.

Attractiveness of the Rokua area

Lakes are also one of the key factors in the attractiveness of Rokua for tourism. Lake level decline might change the landscape and recreational use of lakes. This again might reduce the amount of visitors to Rokua. As the lakes are only one part of the landscape in Rokua and as tourism is not only dependent on the lakes, the impact of lake level change can be considered to have less of an effect on tourism than, for example, on the recreational value of second homes.

Economic impacts on forestry income

The impacts of the restoration of drained peatland areas on the forest economy were studied by using exfiltration risk analysis (Eskelinen 2011). Watersheds in high exfiltration risk areas were defined as areas where active restoration procedures in Alternative C would be allocated. In these areas, restoration can be presumed to wet the forest and affect tree growth. As the growth potential of the forest would then be drastically reduced, the income of the forest owner would decrease. Using different input data (different combination sets of available data) in risk scenario maps, the value of income losses in 30 years was calculated to vary from 500 000 to 2 500 000 € (Eskelinen 2011). The change in land value was not taken into account. In Alternative B, where the groundwater protection area is expanded, defining forestry income loss was more problematic. As the expansion would restrict forestry management practices in some of the areas where the groundwater area is expanded, some new areas might become wet. As this is less certain, it was estimated that Alternative B would result in only 10% of the effect on forestry of Alternative C.

Income loss of peat production

Peat production by harvesting in the vicinity of Rokua (Fig. 2, the peat harvesting area west of the esker) is scheduled to end in 2018. Furthermore, the hydrological studies showed that approximately 1% of groundwater discharging from Rokua was flowing from the peat harvesting area. This demonstrated the minimal effect of the harvesting area on the whole Rokua esker hydrology. Therefore, different scenarios were presumed to have only a small effect on peat harvesting. In Alternative B, peat harvesting may end earlier, in the event of the groundwater area expanding to the peat harvesting site. In Alternative C, a new method is planned for the restoration of the peat harvesting area to prevent groundwater exfiltration to the harvesting site. This again might be more expensive than current methods and reduce the income from peat production.

4.3.3 Decision analysis interviews

Stakeholder preferences were taken into account in the MCDA model by means of decision analysis interviews. In the third stakeholder meeting and learning workshop with selected interviewees, the results of the impact assessment were presented and the framework and process of the decision analysis were described. The interviewees were given a questionnaire for the interview and an information package with background information about the case, the decision analytical approach, and the interviewing process. The package also described in detail the value tree applied, including the grounds for the alternatives, criteria, and measurement value estimates.

The interviews, conducted by two researchers in September 2011, involved 19 representatives of the stakeholder groups (see Table 2). In one case, three interviewees (representing the same stakeholder group and organization) wanted to give mutual criteria weights, so finally 17 different weighting profiles and evaluations were gathered in order to infer the preferences of the main stakeholder groups. Local scales were used as attribute measurement values on a 0–1 value scale. Thus, for each criterion, the lowest attribute value among the alternative set was mapped to 0 and the highest value to 1, while the other attribute values were mapped linearly to this scale (Belton & Stewart 2002).

The SWING method was selected for eliciting the weights for the criteria (von Winterfeldt & Edwards 1986). In this method, an interviewee is first asked to allocate 100 points to the most important criterion, i.e., the criterion whose

value he/she would most prefer to change from its lowest possible level to its highest level. After this, the decision maker is asked to allocate 0–100 points to every other criterion to indicate the importance of value change in these criteria in relation to the value change in the most important criterion. The actual weights are obtained by normalizing the sum of the given points to 1. The SWING procedure was chosen in order to ensure that the participants accounted for the decision context by identifying the most important attribute first, and then the relative importance of the other attributes was compared against this. It is crucial that when eliciting weights for the highest level attributes, the participant is fully aware of the meaning of the attributes. Thus, a bottom-up approach was used in which the weights were first elicited for the attributes on the lowest level.

The interviews lasted from 1.5 to 4.5 hours. In the first half of each interview, the interviewers laid out the general principles of the DAI approach, the case, and the model applied, in order to ensure that the interviewee had understood all of the details relating to the interview process. After this, the interviewee's preferences were entered into the model using the decision analysis software Web-HIPRE (Mustajoki & Hämäläinen 2000). The final phase of the interview consisted of analyzing the results and explaining the reasons behind them to the interviewee.

The data for the evaluation mainly comprised the results of the decision analysis interviews and the feedback survey for the participating stakeholders. The feedback questionnaire was introduced in the fourth stakeholder meeting, where the results of the MCDA process and interviews were presented and discussed. The participants were asked, for example, to evaluate the suitability of the MCDA approach applied for meeting the different objectives and the success of implementation of MCDA in Rokua in supporting learning.

5 Results and discussion

5.1 Groundwater-surface water interaction between an esker aquifer and a drained fen (I)

The groundwater from the esker to the Siirasoja subcatchments discharged into the drained fen in a complex spatial pattern. A high variation in the amount of base flow, 24–121 l s⁻¹ km⁻², was observed between the four Siirasoja stream subcatchments, A-D (Fig. 10). These runoff values are much higher than the typical base flow values of 1.5–3 l s⁻¹ km⁻² in Northern Finland (Mustonen 1986), indicating strong groundwater exfiltration. A high variation was also seen within each subcatchment, as some ditches had discharge amounts above 500 m³ d⁻¹, whereas adjacent ditches had no flow.

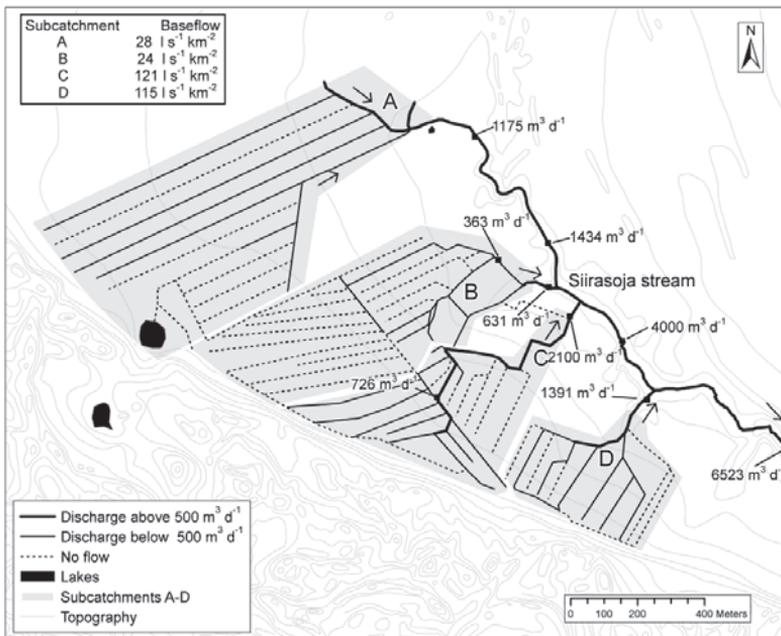


Fig. 10. Distribution of groundwater discharge to subcatchment ditches and subcatchment baseflow during low flow conditions. Flow in the ditches was quantified into three categories: more than 500 m³ d⁻¹, less than 500 m³ d⁻¹, and no flow. The largest discharge was measured from subcatchment C. Reprinted with permission from Elsevier.

The groundwater exfiltration occurred as point discharge and even diffuse seepage along the ditch bed. Point discharges were mainly found in subcatchment C, with the highest baseflow and deepest peat layers (maximum GPR-estimated thickness approximately 8 m) (Fig. 11). These point discharges show a direct connection between esker groundwater and surface runoff in ditches, despite deep peat layers of low hydraulic conductivity. In subcatchment D, no point discharges were observed, but the baseflow was almost as high as in subcatchment C. The peat layer in subcatchment D was shallow (0.5–2 m) and some ditches cut through the peat into the mineral soil, providing a direct connection between the aquifer and the ditches.

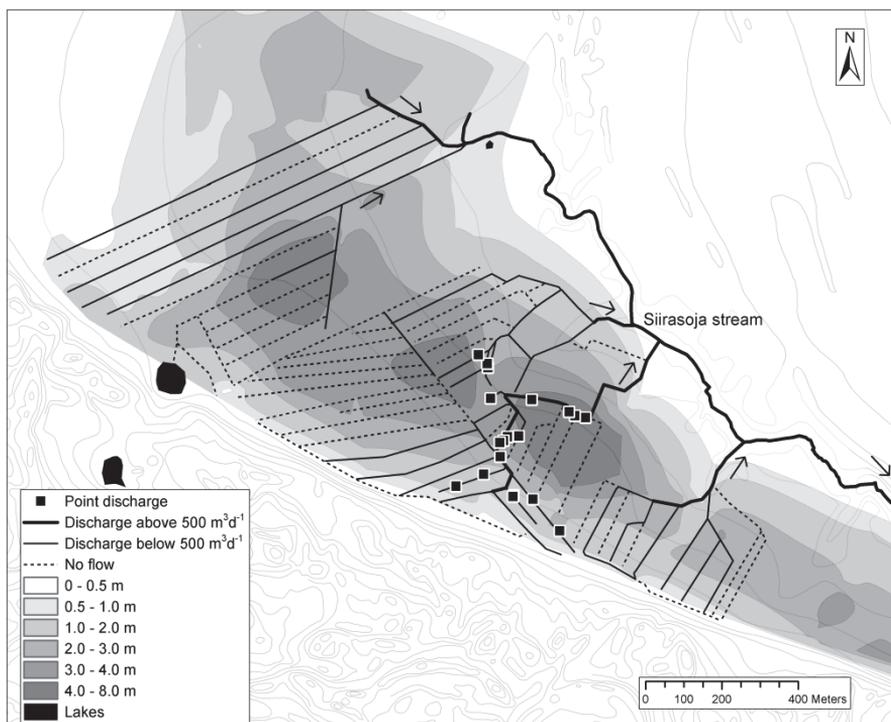


Fig. 11. Peat thickness interpolation from measurement points in the Siirasoja stream study area and groundwater point discharges into ditches. The thickest peat layer was measured in subcatchment C. Point discharges were mostly observed in subcatchment C. No point discharges were observed in subcatchment D. Reprinted with permission from Elsevier.

The double porosity point discharge through the peat was induced by a high pressure level in the aquifer below the peat layer. The pressure head in the sand layer beneath the peat (measured from piezometer 1) was always higher than the groundwater level in the peat layer (measured from piezometer 2) during the measurement period (Fig. 12). On the edge of the esker hillside (groundwater pipe 1) and at the esker (groundwater pipe 2), the aquifer was unconfined. During the measurement period, the groundwater level and pressure level in all of the sand layer measurement points varied between 11 cm (piezometer 2) and 14 cm (groundwater pipe 2).

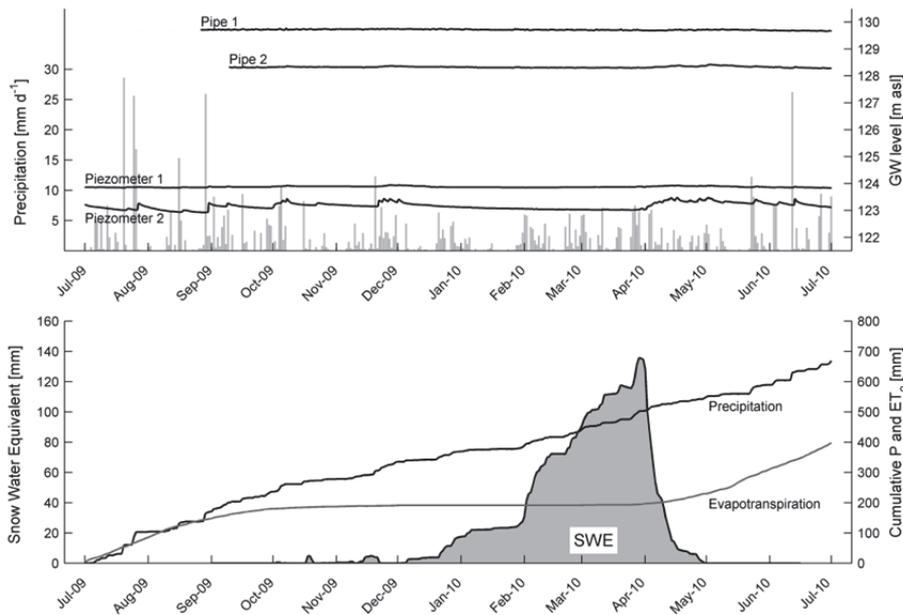


Fig. 12. Groundwater levels at the Siirasoja stream (upper plot), precipitation, calculated FAO reference evapotranspiration, and snow water equivalent (lower plot) for the period 1 July 2009–1 July 2010. Reprinted with permission from Elsevier.

The groundwater pressure directly below the peat deposit and further uphill in the recharge area showed a clear response to rainfall. Both peat layer water level (piezometer 2) and sand layer pressure level (piezometer 1) peaked after rain events, with a 1–2 hour delay (Fig. 13). The increase in sand layer piezometric pressure level was similar to the depth of areal precipitation (Table 4). Considering the three longest rainless periods (Table 4), the average rate of

piezometric level decline in the sand layer was 2.9 mm d^{-1} . When piezometric data were compared with climate data, it was noted that the rate of piezometric level decline during the dry periods was of same magnitude as the average daily reference evapotranspiration calculated using the FAO Penman-Monteith equation (3.1 mm d^{-1}).

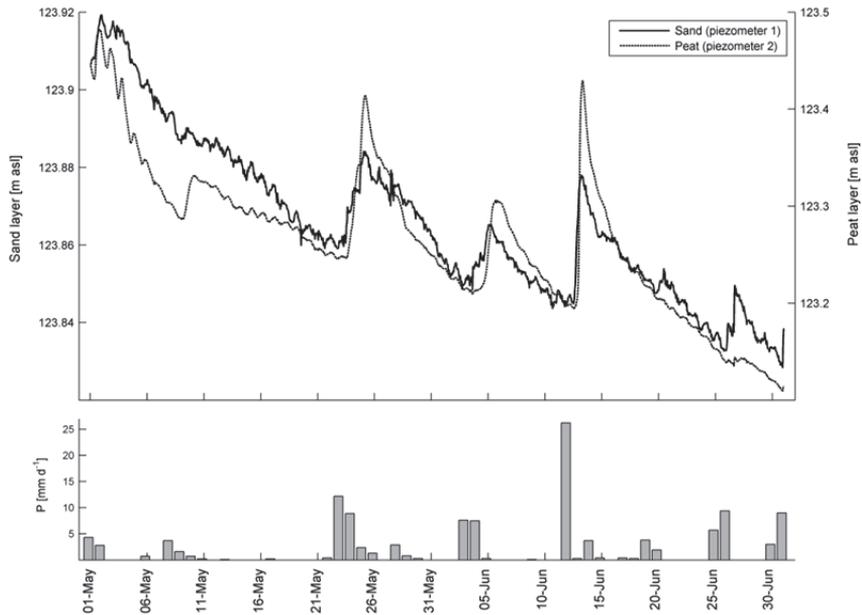


Fig. 13. Groundwater levels in sand (piezometer 1) and peat (piezometer 2) in comparison with daily precipitation for the period 1 May 2010–1 July 2010. Reprinted with permission from Elsevier.

Table 4. Changes in sand layer piezometric head level compared with precipitation (P) and reference evapotranspiration (ET₀). Reprinted with permission from Elsevier

Time of recorded level rise	Piezometric level rise in sand [mm]	P [mm]
22 May 2010 20:00–25 May 2010 04:00	25.1	25.2
3 June 2010 14:00–5 June 2010 02:00	15.6	15.4
12 June 2010 09:00–13 June 2010 05:00	32.9	30.2
25 June 2010 18:00–26 June 2010 17:00	17.1	15.1

Time of recorded level decline	Piezometric level decline in sand [mm]	ET ₀ [mm]
11 May 2011 0:00–20 May 2011 0:00	23.0	29.8
5 June 2011 0:00–11 June 2011 0:00	19.5	15.9
21 June 2011 0:00–24 June 2011 0:00	8.8	10.3

The water at the study site showed a high variability in chemical composition (Fig. 14). For example, the SiO₂ concentration in ditches varied between 11–14 mg l⁻¹ and in the sand layer between 7–16 mg l⁻¹. In peat, the SiO₂ concentration (1.2 mg l⁻¹) was closer to the rainwater concentration (<0.1 mg l⁻¹). All measured concentrations and parameters were highest in the sand layer beneath the peat (piezometer 1). The flow rate in the ditch between sample points 2 and 4 increased by 1400 m³ d⁻¹. Using esker groundwater and peat water as end-points, the mixing analysis with SiO₂ showed a discharge increase of 1300 m³ d⁻¹ from the sand aquifer and 100 m³ d⁻¹ from the peat layer.

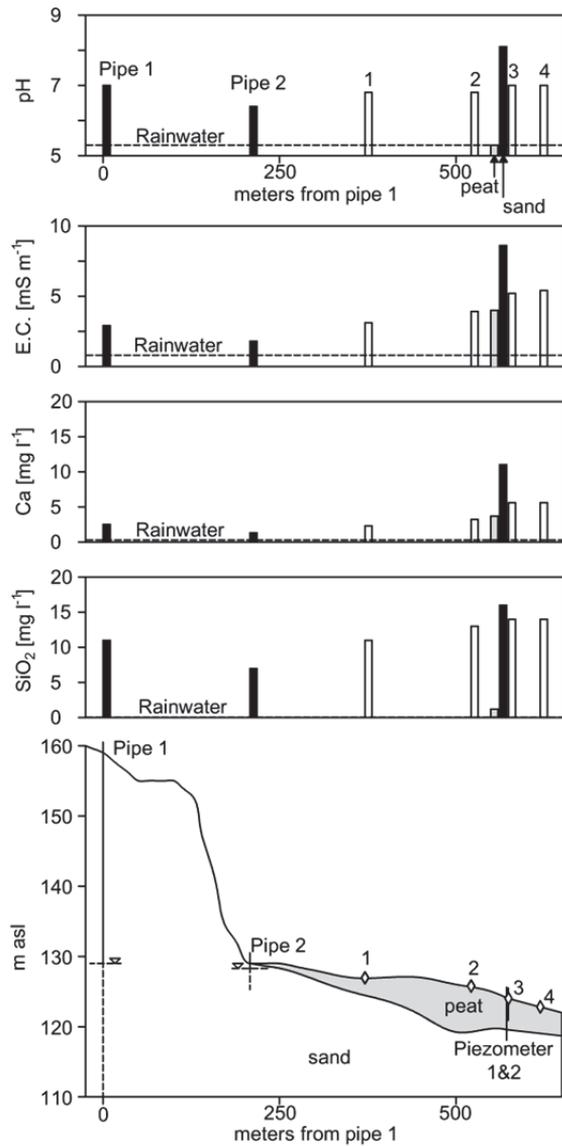


Fig. 14. pH, electrical conductivity (E.C.), calcium (Ca), and silicon dioxide (SiO₂) measurements in groundwater pipes, piezometers, and stream water samples in June 2010. Black columns represent samples from the sand layer, the grey column samples from the peat, and the white columns samples from the ditch. The dashed line represents the rainwater sample. Reprinted with permission from Elsevier.

5.1.1 Groundwater exfiltration in drained fens

In order to assess groundwater flowpaths in eskers, the discharge patterns must be properly understood to set correct boundary conditions. The groundwater discharge patterns can be observed by dividing the study area into subcatchments of ditches and measuring the discharge rates during low flow. For a detailed analysis, each ditch must be observed and areas of point discharge and diffuse seepage must be determined.

As suggested by Lowry *et al.* (2009), vertical pipeflow (or preferential flow) can form in peat and can cause spring-like point discharge formations, as happened at several points in the Rokua Siirasoja study site ditches. These point discharges seemed to occur where the peat was fairly deep, indicating that peat depth or matrix hydraulic conductivity does not prevent exfiltration. The mixing analysis suggested that point discharges can increase the discharge in a 200-m ditch section by as much as $1300 \text{ m}^3 \text{ d}^{-1}$, whereas surface runoff from the peat layer was $100 \text{ m}^3 \text{ d}^{-1}$.

The detailed survey of sand and peat topography showed that the point discharge occurred in transition areas where peat layer thickness changed from thick to thin (Fig. 15). It is not known whether the point discharges emerged in the area after drainage, or whether they already existed as natural springs before drainage. Groundwater diffuse seepage into ditches occurred in places where the peat layer was penetrated and the ditch had a direct connection to the sand layer. Both of these exfiltration types were caused by a higher water pressure level in the sand layer than the ditch water level (Fig. 15). Generally, the drainage network facilitated exfiltration into ditches by providing a network for conveying water from the discharge area. The drainage ditches also increased the piezometric pressure difference between the free water surface (ditch water level) and the sand aquifer.

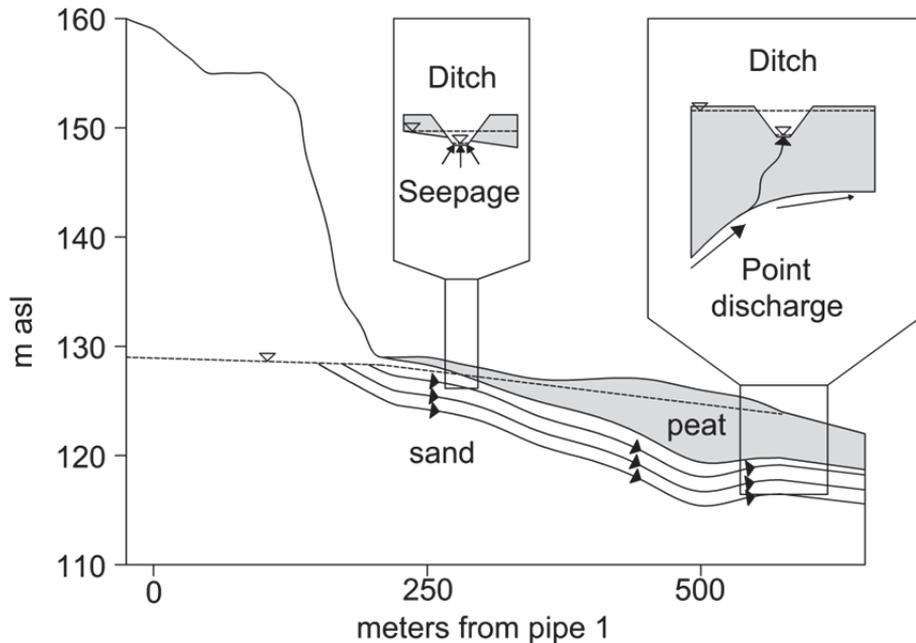


Fig. 15. Conceptualization of groundwater flow below the peat layer and groundwater flow mechanisms to ditches at the Siirasoja stream study site. Reprinted with permission from Elsevier.

5.1.2 Sand aquifer response to rain events and to evapotranspiration

Wetting of the peat during rain events seemed to have a direct impact on the groundwater pressure head in the sand aquifer. As the peat is an aquitard above the sand, rain events should not directly affect the sand layer pressure level. However, the results showed a quick pressure level response to rain. This pressure level change could also be caused by recharge at the unconfined part of the esker aquifer, but the response would be less immediate due to the considerable residence time in the thick unsaturated zone. Thus, the pressure level rise in the sand layer below the peat was most likely caused by the mass increase of the peat layer by rainwater. Data analysis showed that the piezometric level increase was close to the precipitation depth measured at the Pelso Climate Station (Table 4).

The observation that precipitation affects groundwater levels in both the peat layer and sand aquifer can be explained by peat soil water retention characteristics and the depth of groundwater level in the peat layer. During dry conditions in the

fen, the rainwater is presumably absorbed into the unsaturated zone of the peat layer, because no increase in peat groundwater level was observed. This is apparent after the rain event of 25–26 June (Fig. 13). This rain event only increased the sand layer pressure level, probably induced by increased mass in the peat layer due to retained water in the unsaturated peat soil.

On the other hand, a quick response in the peat groundwater level was observed during the rain events of 8–9 May. On that occasion, only a small amount of precipitation changed the peat groundwater level considerably. This might have been caused by the peat soil water content being closer to full saturation after spring snowmelt. The dependence of the peat layer groundwater level on the moisture status of the peat soil preceding the precipitation event indicates threshold behavior. The sand aquifer underlying the peat responded consistently to all precipitation events with a level rise closely matching the depth of precipitation (Table 4).

During the dry seasons of May and June 2010, the piezometric water level in the sand and the water level in the peat decreased. The average rate of piezometric decline in the sand layer was consistent with the average reference evapotranspiration rate (ET_0) calculated using the FAO Penman-Monteith equation. This observation can be considered the reverse phenomenon to the precipitation events discussed above, where the depth of precipitation was consistent with the pressure level rise in the sand layer piezometer. The mass of water evaporating from the peat layer and vegetation reduces the pressure in the sand layer.

Assuming that water losses from the peat layer to the drainage ditches during dry seasons are minor compared with evapotranspiration in the peat layer water balance, the rate of pressure head decline in the sand layer can be expected to be equal to the rate of evapotranspiration, as observed. It is still possible that the calculated ET_0 overestimated the amount of daily evapotranspiration. Parameterization in the reference ET_0 was not modified to match study site vegetation and the method calculates potential, not actual, evapotranspiration. Part of the piezometric head decline in the sand layer can also have been caused by loss of water from the peat layer to the drainage ditches, as some drainage flow from the peat layer was also seen in the results of the mixing analysis.

5.2 Impact of peatland drainage and restoration on esker aquifer – future model scenarios (II)

5.2.1 Model calibration and analysis

Based on the results, the hydraulic conductivity values of the model were informed and constrained by the calibration data, but the drainage conductance parameter values were less informed by the data (Fig. 16). The area surrounding the eastern groundwater mound (point II) had lower values and a more complex pattern of hydraulic conductivity than the area in the vicinity of the western mound (point I). However, drain conductance values did not change from their initial values, with a few exceptions where data were able to guide the calibration. In the Siirasoja stream subcatchment area on the north-central side of the esker (Fig. 2), the values were almost an order of magnitude lower than that initially set. Regularized inversion defined a lower conductance of $10^{-4} \text{ m}^2 \text{ s}^{-1}$ for the Siirasoja stream area, as inferred from available piezometric data. The peat caused semiconfined aquifer conditions in the area and the piezometric pressure level of the aquifer beneath the peat was measured to be above the land surface. Piezometric data from peatlands were almost non-existent for other areas. As an outcome of Tikhonov regularization, most of the model area was assigned initial parameter values after calibration.

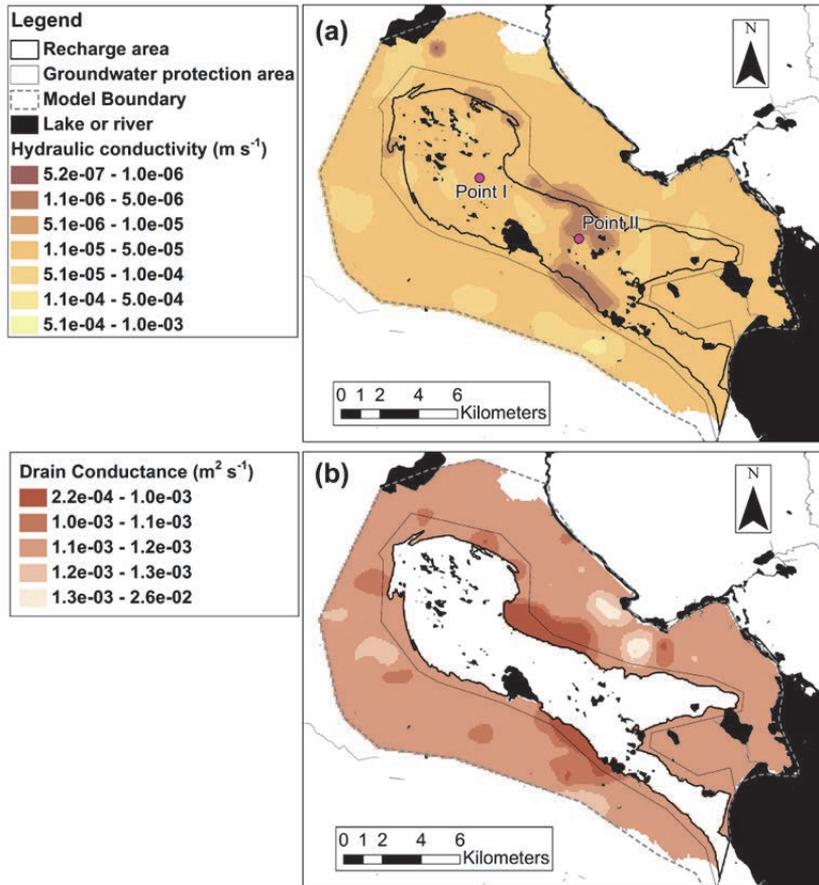


Fig. 16. Hydraulic conductivity and drain conductance of the calibrated model. Reprinted with permission from Springer.

Hydraulic conductivity values over the western part of the esker were more identifiable than those over the east (Fig. 17). Piezometers on the edge of the recharge area and in the discharge area appeared to hold a large amount of information with respect to hydraulic conductivity. Some of the discharge subcatchment areas with discharge calibration data had above zero values for spatial identifiability, but water levels were clearly more informative of model parameters. For drain conductance, identifiability was significantly non-zero in the Siirasoja stream subcatchment, where drain conductance values varied considerably from their initial values as a result of the calibration process.

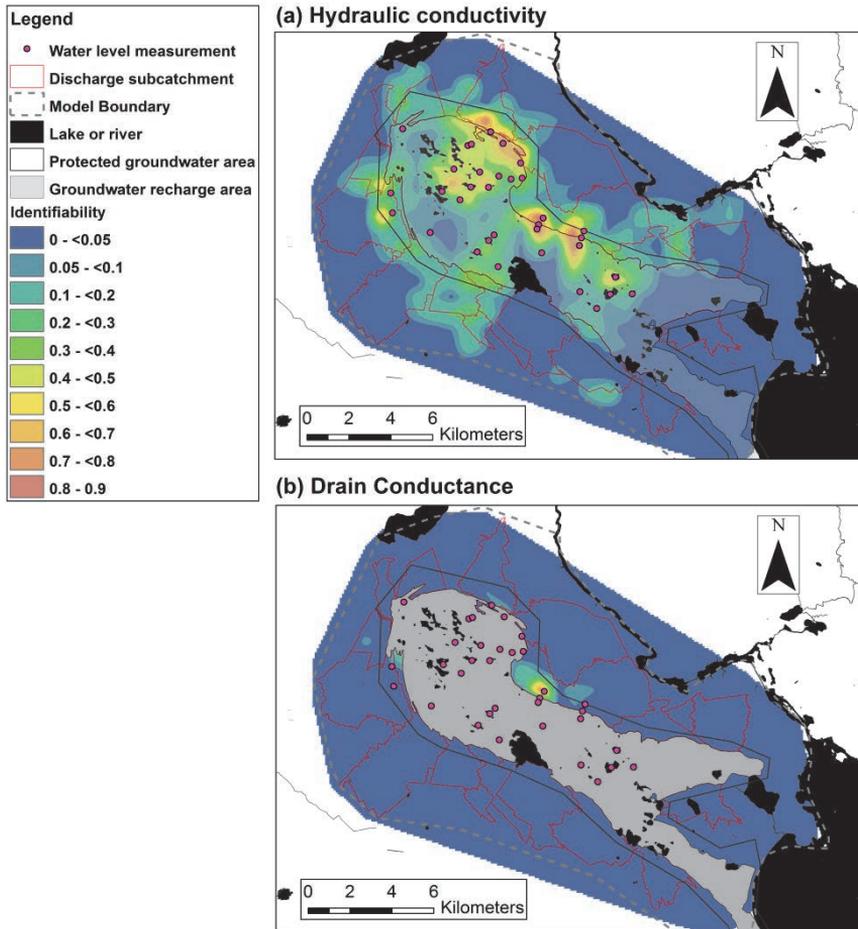


Fig. 17. Identifiability of hydraulic conductivity and drain conductance. Reprinted with permission from Springer.

Calibration-constrained NSMC parameter fields show a far greater degree of variability than that achieved through regularized inversion using Tikhonov regularization. This is a result of the fact that the latter process purposely seeks a minimum error variance solution to the inverse problem by minimizing parameter variability; in other words it tries to find the parameter heterogeneity that *must* exist to explain the data (see Moore & Doherty 2005). The NSMC process, on the other hand, seeks a suite of parameter fields that express hydraulic property variability which *may* exist and is *compatible* with the data. At places within the model domain, information within the calibration dataset is uninformative, so the

degree of spatial property heterogeneity will be constrained by expert knowledge alone. However, at other places within the model domain, spatial variability may be further constrained by the data. This appears to have occurred at the western groundwater mound point I (Fig. 18), but not so much at the eastern groundwater mound point II (Fig 18), as parameter variability in any one parameter field and between parameter fields was greater at the latter than the former location.

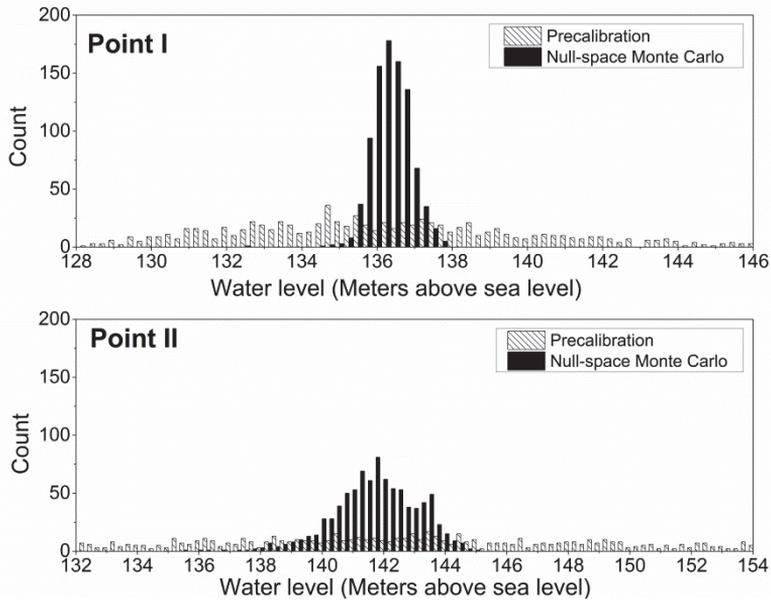


Fig. 18. Null-space Monte Carlo recalibration result frequency for the 870 parameter sets presented as histograms for groundwater level (meters above sea level) in comparison with precalibration results. Results are presented for the non-calibration points I and II to show the information content of the calibration data in different parts of the esker. Histogram columns are divided into 0.25-m intervals. Reprinted with permission from Springer.

5.2.2 Land use change and climate variability

Drained peatland restoration

The simulation results indicate that restoration of drained peatland areas by drain blocking could raise esker aquifer water levels (Fig. 19). For the scenarios Restoration 1A, where drains are only blocked by dams, and Restoration 2A,

where drains are filled, the rise in groundwater level was less than 1 m. The different NSMC model runs showed small variations between the results. For the Restoration 3A scenario, representing the situation where filling the drain would restore the peatland to more natural hydraulic conditions, the water level rise could be above 1 m. Because the drain conductance was not constrained by the calibration dataset, the NSMC-generated parameter fields showed great variability in conductance parameter values. The combination of parameter variability and sensitivity resulted in a spread of the simulation results. This shows the benefit of the NSMC method, with which the parameter uncertainty is now propagated to the results. Even though the drainage parameters were not informed by the calibration data, the analysis showed that the uncertainty of these parameters did have an impact on predictions.

Scenarios including restoration of areas outside the current groundwater protection zone (Restoration 1B, 2B, and 3B) did not change the groundwater level dramatically. Based on the results, restoration would have more impact within the current groundwater protection zone rather than on outside areas.

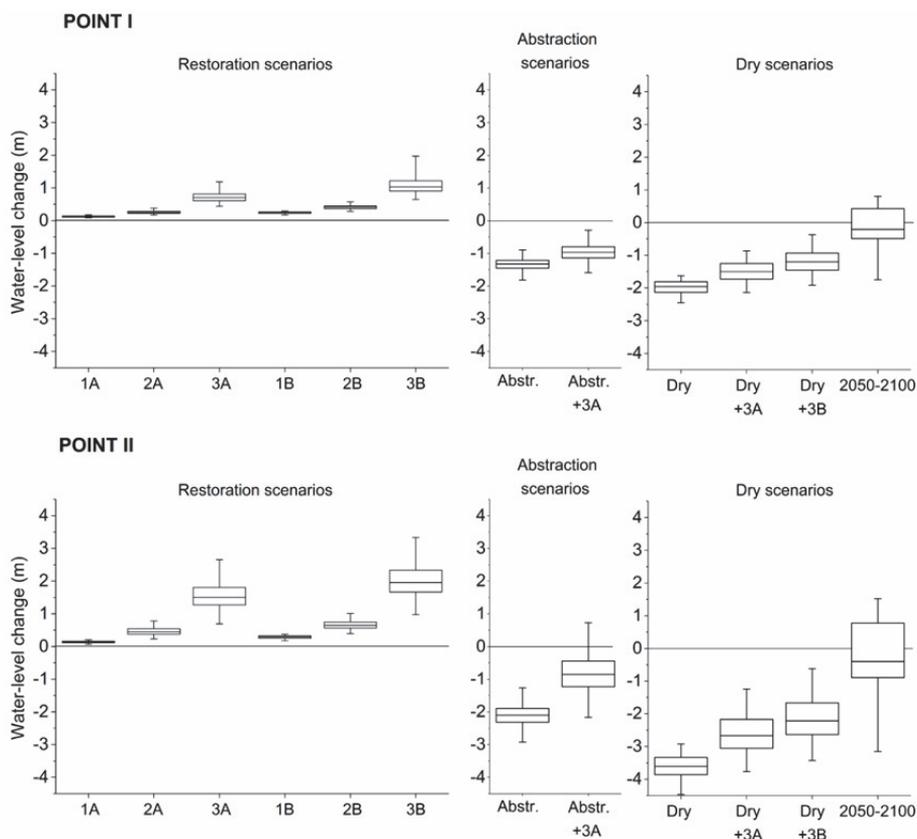


Fig. 19. Comparative box plots of the water level changes at points I and II in the drained peatland restoration, groundwater abstraction, and climate scenarios. Scenario outcomes were calculated with the 870 null-space Monte Carlo parameter sets. Predictions are shown as a change (in meters) from the 2000–2010 water levels. The box plots represent the median, 50% box, and 1–99% whiskers of the parameter ensemble. Reprinted with permission from Springer.

Groundwater abstraction

Hypothetical water abstraction from Rokua ($27\,000\text{ m}^3\text{ d}^{-1}$ to a city of 190 000 inhabitants) would lower the water level by 1–2 m, according to the median values of the null-space Monte Carlo runs (Fig. 19, abstraction scenarios), but drainage restoration would reduce the decline in water levels (Abstraction +

Restoration 3A scenarios). Based on this result, abstraction would have a larger impact on water levels in the present conditions than if the peatland in the discharge zone were in a more natural state.

Past and future dry climate seasons

Based on the groundwater model scenario runs, the water level variations and periodic declines in the Rokua aquifer are highly dependent on climate conditions. Conditions resembling those of the dry period 1970–1980 resulted in water levels which were 2–3 m lower than in 2000–2010 conditions (Fig. 19, dry scenarios). The combination of dry conditions and the Restoration 3A or 3B scenarios resulted in higher water levels. Scenario runs for the estimated future dry period indicated that future dry periods would be less dramatic than in former decades, owing to the overall increase in precipitation and thereby recharge. Recurring dry periods are important to consider if the combined effect of land use and climate on minimum water levels is of interest in groundwater management.

5.2.3 Impact of model scenarios

From a management point of view, the main outcome of the modeling concept in the study is the possibility to compare the effects of peatland drainage and restoration with those of climate (historical and future) or water abstraction. This is important information in order to answer the main management question of whether there is a critical need for expensive peatland drain restoration. Based on the models and considering the uncertainty analyses, peatland drainage does play a role in the hydrology of the Rokua esker aquifer and drainage restoration might affect the aquifer water levels, but the groundwater level seems to be more dependent on climate conditions. In this northern esker area, the future climate conditions might be more suitable for groundwater recharge (agreeing with e.g., Hiscock *et al.* 2011). This might mask the impacts of drainage on groundwater levels in the long run.

The drain water level rise brought about by blocking the ditches by dams decreased the hydraulic gradient between the ditch and the aquifer. However, as seen from the simulation results (comparing the Restoration 1 and Restoration 3 scenarios), the aquifer water level was much more responsive to restoration methods that would be able to affect drain conductance. Even though blocking ditches with dams can have an impact, e.g., on peatland and catchment hydrology

(Wilson *et al.* 2010) or the groundwater discharge amounts of an individual ditch (Kupiainen 2010), it should not be expected to change the whole esker aquifer water level. For example, in Finland, ditch blocking by dams is a common peatland restoration method (Aapala *et al.* 2013), but it is important to acknowledge that it should not be considered an aquifer restoration method, based on the findings in this thesis.

The filling of ditches might have more promising results. However, as no large-scale empirical data are available on how peatland restoration by filling the ditches would change the hydraulic conditions in the peat, questions remain regarding the best means of peatland restoration to reduce the “lumped” peat hydraulic conductivity. Filling in ditches or blocking preferential channels and seepage observed in the peat matrix, e.g., by bentonite injection, could reduce the total hydraulic conductivity. For the Rokua area, which will possibly experience less severe dry periods in the future, extensive drainage restoration by filling the ditches in the whole groundwater protection zone could be regarded as an overambitious and expensive measure relative to the benefits obtained.

Peatland drainage and drain restoration have not been included in esker aquifer scale groundwater modeling in previous studies, which forced us to devise novel conceptual thinking for the use of drainage boundaries. The identifiability of the drain conductance parameter from the calibration data was limited, but the NSMC method incorporated this uncertainty into the results. The flow through peatland could have been modeled in more detail (Ballard *et al.* 2011), but it is unlikely that the use of greater detail would have affected the conclusions presented here. Meanwhile the relative simplicity of the model allowed a comprehensive uncertainty analysis to be undertaken, so that all model predictions could be accompanied by an estimate of their uncertainty. The possibility of simulating peat as its own layer in the MODFLOW model was considered. However this would have added to the computational difficulties, and possibly instigated the appearance of cell drying/re-wetting. This, in turn, might have compromised the analysis through contributing numerical noise to the calculation of finite-difference derivatives of model outputs with respect to the parameters which formed the basis of calibration and subsequent NSMC analysis.

A previous study on the legal implications of EU directives relating to groundwater in Finland concluded that peatland drainage could be seen as a quantitative use of groundwater, comparable to groundwater abstraction (Allan 2011). The modeling results presented in this thesis agree with this conclusion, although the simulated effect in the Rokua esker was not as large as the modeled

extensive water abstraction. This finding emphasizes the necessity to have groundwater protection areas surrounding the esker aquifer, and to conduct thorough monitoring and issue permits (or bans in high discharge risk areas) for drainage within groundwater protection zones. By testing the effects of expanding the groundwater protection area and restoration area (Restoration B scenarios in this thesis), administrators can make an informed decision on the extent of the protection area. For example, in the case studied here, the benefits of protection zone expansion would be minor. Additionally, for areas with current or future groundwater abstraction, the model approach used in this thesis could be applied to find out if peatland drain restoration by filling the ditches could be used to compensate for the impacts of water abstraction.

The climate scenarios used in this study were admittedly simplified, as climate conditions are highly dynamic and variable in time. The method employed, i.e., the average dry period conditions run as steady state, could only be used to estimate the dynamics and the climate dependence of the aquifer, as the climate conditions deviated from average conditions for several years. This again could be compared with the dependence of the aquifer on land use, as done in this thesis. From a management point of view, the results of climate on water levels are therefore indicative. However, because the outcomes of the analysis included the uncertainties associated with important predictions of management interest, they provide a more robust basis for decision-making.

The hypothetical groundwater abstraction and the comparison of the effects of land use and climate were the key outcomes of the modeling work, enhancing the ability of managers and stakeholders to understand and discuss different management options. In the Rokua area, the approach eased the discussion on the impact and role of forest drainage in hydrology with the local stakeholders. Increasing the understanding and possible learning of stakeholders is emphasized by different environmental management strategies (e.g., Reed *et al.* 2010, Gregory *et al.* 2012) and it would be possible to link the modeling concept presented in this thesis with these strategies in groundwater management issues. For example, the preliminary model results for Rokua (Paper II) were used in the MCDA method (Paper III).

5.3 Decision analysis framework (III)

5.3.1 Importance of the objectives

The interviewees were asked to consider the range of impacts of the alternatives and the importance of the objectives/issues considered. As the results show (Fig. 20), there was agreement among stakeholders that the water level of the lakes and the aquifer (more than 30% share of the total weight; median value) is the most important criterion in the context of the Rokua area. Most of the interviewees considered this criterion to be the basic unit when measuring the success of land use management.

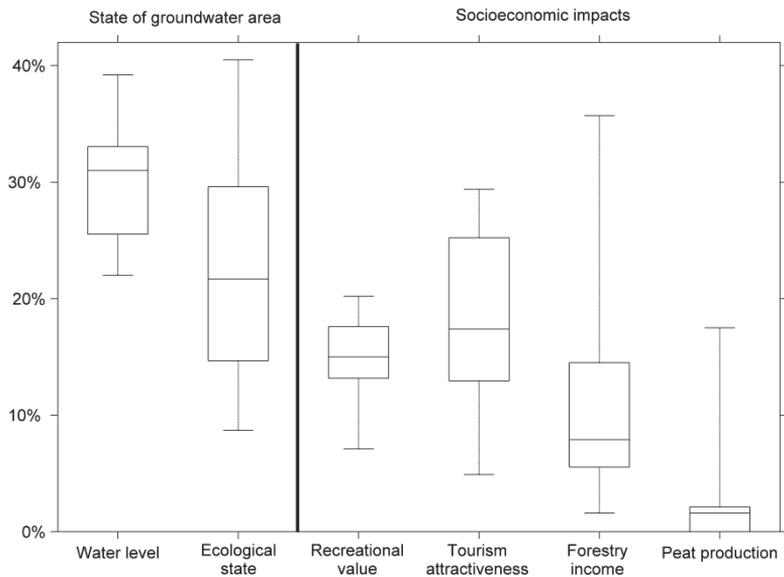


Fig. 20. Importance weights given by the stakeholders interviewed to the criteria in the Rokua groundwater case (min, median, 75th percentile, max).

The ecological status of lakes and springs received more than a 20% share of the total weight (median value, Fig. 21), but there was much more disagreement (range between min/max and 75th percentile) about how important this criterion is and about the impact that the proposed alternatives might cause. The recreational value of second homes was considered an important objective, but the impacts (measured by change in monetary value per second house) were rated

low by the participating stakeholders. Therefore, the overall importance of this criterion (median value of weights) was set as being smaller than that of lake water level, ecological status, and tourism attractiveness.

Tourism attractiveness was seen as a significant issue for the Rokua area and its surrounding municipalities. However, some interviewees rated the marketing and development of new tourism services as more decisive for the attractiveness of the area than the state of the water bodies or lake water levels. The importance of forestry to the local economy was generally recognized among the interviewees, but the impact of the alternatives on forestry income was considered peripheral. Here the forestry representatives disagreed, emphasizing (more than others) the indirect income and monetary flows to the regional and national economy. Peat production was considered to be the least important criterion. There are two reasons for this: i) risk analysis and hydrological studies showed that the role of peat production harvesting in the water level decline in the Rokua esker area was minimal, and ii) during the MCDA process, the representative from the peat company announced that peat harvesting in the area would end by 2018.

5.3.2 *Desirability of the alternatives*

The interview results (Fig. 21) indicated that all stakeholder groups are willing to accept that some measures should be promoted in the esker area in order to improve the hydrological and ecological conditions. The ranking of the alternatives showed that active restoration (Alternative C) was the preferred option for all interviewees. However, the difference in preferences for alternatives was not as substantial among the stakeholders stressing the significance of forestry (left side of Fig. 21) as it was among the stakeholders mainly emphasizing the ecological and hydrological issues (right side of Fig. 21), who clearly preferred Alternative B over A, and C over B.

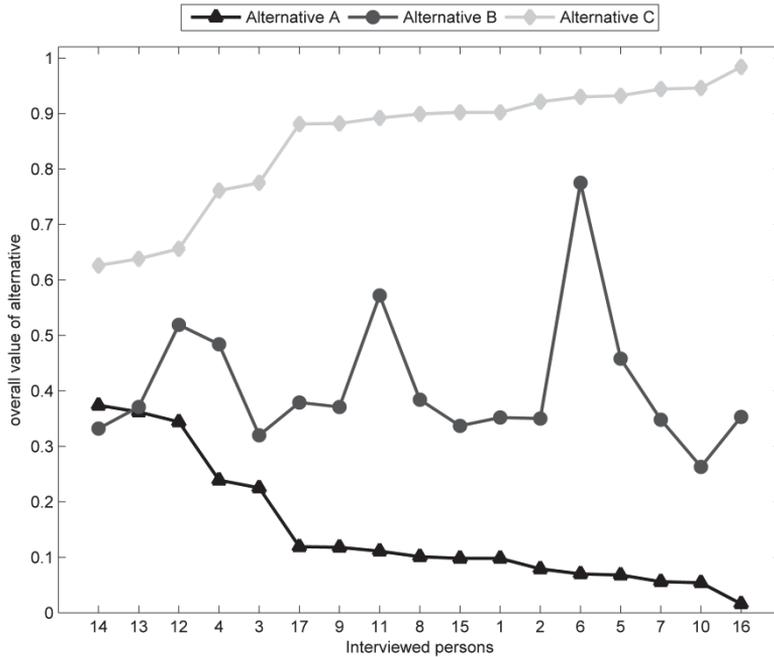


Fig. 21. Overall values of Alternatives A-C for each stakeholder interviewed.

5.3.3 Viewpoints of different stakeholders

Although there was some agreement regarding the preferences among the stakeholders, a detailed analysis of the stakeholders' interviews and weighting profiles revealed that there was disagreement concerning the effects of the different alternatives and the importance of the criteria. Three different viewpoints of stakeholders were elicited from the analysis: forestry, administrative, and the local economy.

The forestry viewpoint was mainly concerned about the adverse economic impacts on forestry (Fig. 22). This can be seen from the high value given to the business-as-usual alternative (Alternative A), where negative impacts on forest income can be avoided. The proponents of this viewpoint also emphasized the indirect impacts of forestry on the local, regional, and even national economy. The business-as-usual position, from this point of view, was preferred over Alternative B, which may cause income losses due to forestry restrictions on new areas. In addition, the uncertainty about impacts on the groundwater level was

much greater for Alternative B than C. Alternative C was also considered to be a more flexible management solution for forestry practitioners.

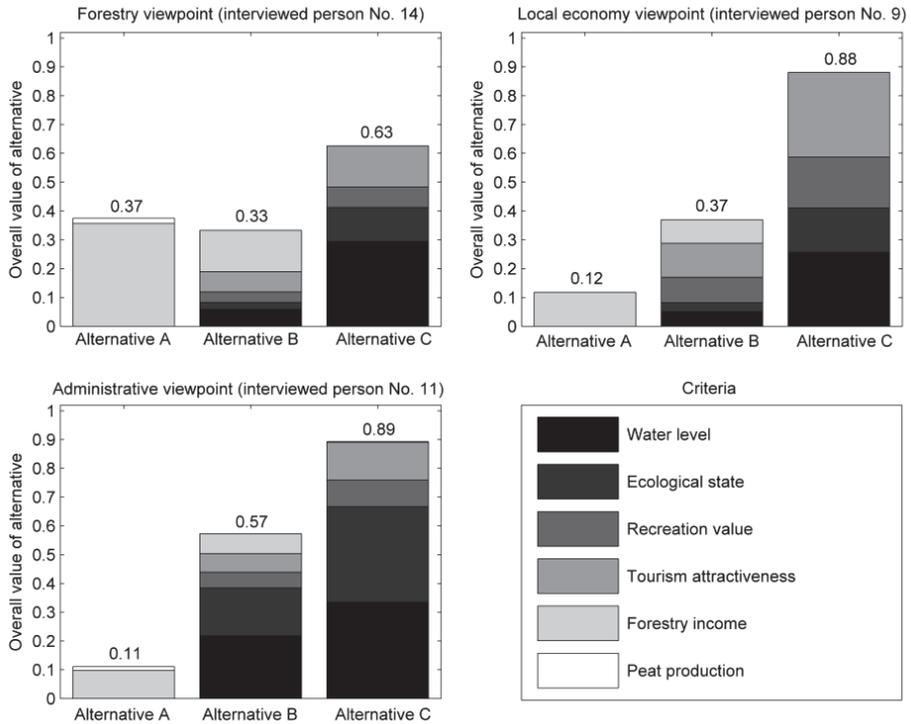


Fig. 22. Overall values of the forestry, local economy, and administrative perspectives.

Both the local economy and the administrative viewpoints (Fig. 22) emphasized more ecological and hydrological objectives. According to the local economy viewpoint, the water levels and the ecological status of existing water bodies should be kept in good condition, since tourism is the most important source of local income, jobs, and tax revenues. The attractiveness of the area (weighted as the most important criteria) also depends on the ecosystem services provided by the specific types of local esker ecosystems. Forestry was regarded as a locally important source of income and livelihood too, but the income loss caused by the proposed alternatives was regarded as tolerable if some compensation can be negotiated. The local economy viewpoint adopted the broadest perspective on sustainable development: ecological ‘health’ and ecosystem services were considered the major sources of human well-being, while keeping in mind the

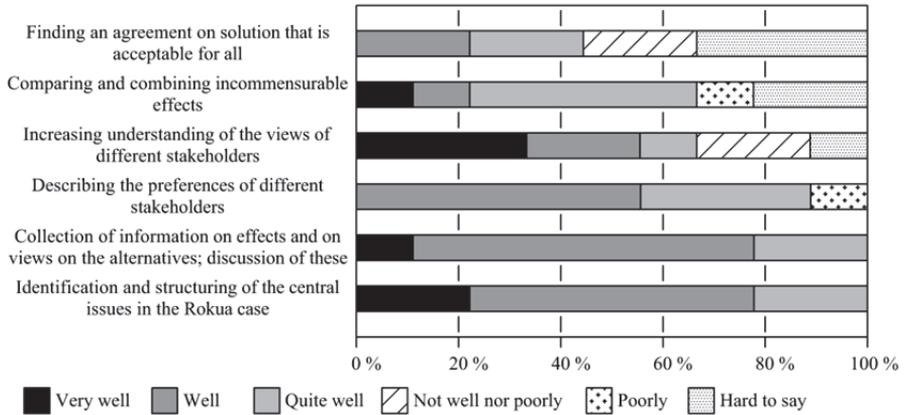
parallel economic effectiveness and social acceptance of the proposed policy actions.

The administrative perspective (Fig. 22) placed more emphasis on the ecological and hydrological criteria than the other two points of view. The overall value of Alternative B was rated higher among the representatives of this group than the other groups. The administrators believed that positive impacts on the groundwater level and the ecological status of lakes and springs can also be achieved by expanding the boundaries of the groundwater protection area. This assessment was based on the guideline stating that in the groundwater area, every proposed land use activity should be obliged to apply for a license from the regional environmental or forestry administration. In that way, forestry practices (especially ditches) can be banned in critical groundwater discharge areas.

5.3.4 Evaluation of the approach

At the closing workshop, the members of the participating stakeholder groups were asked to evaluate both the suitability of the approach applied for this case and the practical implementation of the process, including their understanding of the process and the results. In general, the stakeholders were quite satisfied with the application of the MCDA approach. The mean grade awarded in the overall evaluation of the success of the approach was 8.3 (on a scale from 4 to 10). The approach was considered most suitable for the identification and structuring of the central issues of the problem, for increasing understanding among the different stakeholder groups, and for the collection of information (Fig. 23). In the meeting discussions, the stakeholders appreciated the method's ability to collect information from different sources, while at the same time revealing differing views on the importance of different land use practices and the overall objectives of the stakeholders. There was agreement that this was the most significant benefit of the MCDA method.

Suitability of the decision analytical approach for meeting the following objectives



Implementation of the decision analytical approach in practice

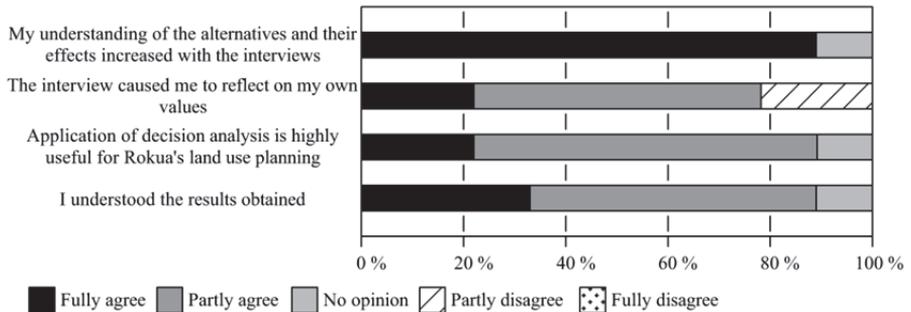


Fig. 23. Results of the feedback questionnaire among the participants of the MCDA process.

All participating stakeholders considered the MCDA process necessary as a starting point and as a basis for further negotiation about the land use in the area. Most of the stakeholder representatives also considered the MCDA process highly useful for Rokua's land use planning (Fig. 23). In their feedback evaluations, most of the interviewees considered personal learning to have occurred during the process. To the analysts, it was obvious that the participating stakeholders had learned more about Rokua's groundwater system itself, about how land use and climate change might affect the system, and about the different stakeholders' preferences. Computer-aided interviews helped the participants see how their

preferences affected the desirability and ranking of the alternatives. Nevertheless, the participants considered weighting to be a challenging task.

The MCDA process having ended, learning success was now evident and many results (facts, issues, viewpoints) uncovered during the process will be usable in decision making in the Rokua area. Nevertheless, important gaps still exist, for example the hydrological modeling was still at a preliminary stage.

5.3.5 Findings from the decision analysis process

The MCDA process in the Rokua case was successful in finding a way towards sustainable land use in the esker aquifer area in three major respects.

First, it opened up a discussion about possible land use management options in a conflicting situation with a considerable amount of mistrust between the different stakeholders. Stakeholder meetings, as well as structured and transparent methods of analysis, enabled the discussion and consideration of other points of view, and especially reflection on the participants' own preferences in this context. The participants' understanding and preferences evolved during the process as they assessed their previous knowledge about new scientific and socio-economic information and reflected on their preferences in the context of new knowledge and specific options. When the participants had an opportunity to view their attribute weights and the effects of these on the desirability of the alternatives, this interactive and iterative approach improved the participants' trust in the method and promoted the transparency of the whole process – as has been observed in earlier DAI studies (Marttunen & Hämäläinen 2008). At the beginning of the process, the stakeholders' comments and arguments in defense of their prior point of view and the interests of their stakeholder group were observed to be more rigid than at later stakeholder meetings.

Second, the analysis revealed that the stakeholders actually agreed on many crucial issues. The most important issue is that some active measures be implemented in the esker area in order to prevent a possible further decline in groundwater levels. The analysis was effective in opening a dialogue and negotiations. However, the stakeholders still disagreed with each other about the measures and the effects of the alternatives. A critical issue for the social acceptance of the management option in the Rokua case is the nature of measures conducted (restoration efforts and/or expansion of groundwater area), where they are implemented, and the compensation tools (monetary, land exchange, or

something else) available for forest owners who will lose part of their income if the forest area they own is groundwater-protected and/or restored.

Third, the MCDA process informed decision-makers about the possible alternatives in land use management in the Rokua esker area. This MCDA work can be seen as a first step in the process of building up a sustainable land use plan. It opened the way for a new process by showing an overall picture of the problem and decision contexts, as well as the different views of the stakeholders (agreements and disagreements), and identified the critical issues (e.g., new research needed) in furthering the process.

The common purpose of MCDA methods is to evaluate and choose among alternatives, based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision making. However, in many planning processes the ranking of the alternatives may be less important than other process outputs, such as the identification of knowledge gaps, improved and shared understanding about the situation, and revelations on the diversity of different views. The modeling results (Paper II) changed the estimation of water levels in future. For example, climate change might mask part of the water level decline or the uncertainty of expensive restoration, in which case the alternatives studied in the MCDA would need to be re-estimated. Still, while the MCDA process may not lead to a specific action plan, it can provide a basis for better cooperation.

6 Conclusions and future recommendations

This thesis combined hydrological and socio-economic research in a case study of the Rokua esker aquifer to update the concepts of groundwater management. The research concentrated on forestry drainage of peatlands in the esker surroundings and on the effects on aquifer water levels. This combined approach can also be applied to other conflicts concerning groundwater and groundwater-dependent ecosystems.

Objective of the first paper was to determine how groundwater discharges from an esker aquifer and interacts with a drained peatland. In the second paper groundwater modeling was used as a tool to study management options for esker aquifers and related land uses. Third paper analyzed the potential of interactive multicriteria decision analysis for facilitating stakeholder involvement and learning in groundwater management.

According to the results obtained for the Rokua area, forestry ditches within groundwater discharge areas can change the groundwater discharge patterns and therefore could have an impact on aquifer groundwater level and dependent ecosystems such as kettle lakes. Groundwater can discharge into a forestry ditch either by seepage, if the ditch has been dug through the peat layer, or by preferential flow through the peat matrix in areas where the peat layer is thicker than the depth of the ditch. This is important information for groundwater protection planning, as low hydraulic conductivity of the peat matrix does not necessarily prevent contact between peatland ditches and the underlying aquifer.

Modeling of the esker aquifer-peatland system clarified the groundwater management options. Climate and land use can have a significant impact on the esker groundwater and related ecosystems such as groundwater-dependent lakes. Peatland drainage in the esker surroundings can have similar impacts to groundwater abstraction and droughts. Thus forestry drainage should be properly accounted for in groundwater management and conservation of Finnish esker aquifers. Based on model simulations, drainage restoration by filling ditches could restore the aquifer groundwater as long as it decreases the hydraulic conductivity of the ditch bed by blocking preferential flows and seepage. Restoring the ditches by simply using dams to lower the hydraulic gradient between aquifer and ditches does not appear to be an effective method to influence aquifer conditions.

The Rokua area could experience less severe dry periods in the future. Under these conditions, extensive drainage restoration by filling in ditches in the entire

groundwater protection zone appears to be too ambitious, uncertain, and expensive a measure relative to the potential benefits. A smaller, subcatchment-scale pilot test of ditch filling would increase knowledge on the effectiveness of this peatland restoration method. Additionally, it would be interesting to apply the groundwater modeling approach used for Rokua (recharge area 92 km²) to a smaller aquifer, with e.g. recharge area less than 5 km², as the impacts of peatland ditches for a smaller aquifer might differ with scale. The used modelling approach should be appropriately versatile for different scales and situations.

If new drainage or reopening of ditches is planned in a peatland area where a risk of groundwater discharge can be expected, for example in the close vicinity of a groundwater protection area, a simple piezometer measurement could be conducted beforehand to define the hydrological conditions. A piezometer with a screen beneath the peat (Fig. 24) could measure the pressure level in the aquifer. If the pressure level is above the planned ditch level, there is an immediate risk of groundwater discharge.

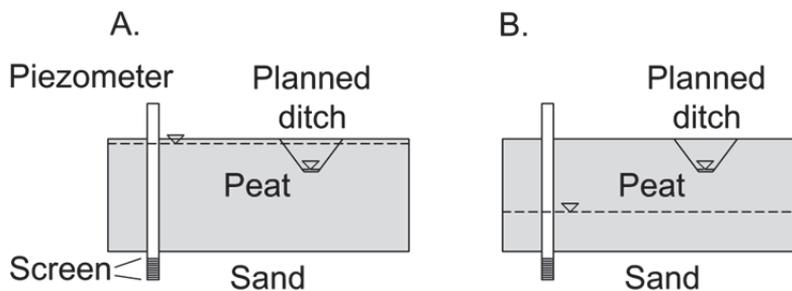


Fig. 24. Concept of piezometer measurement for defining the risk of groundwater discharge to a planned new ditch or reopening of an old ditch. A) Groundwater pressure below peat higher than planned peat bottom; risk for groundwater discharge. B) pressure level lower than planned peat bottom; ditch probably does not cause groundwater discharge.

The decision analysis framework used in this thesis revealed positive impacts of participatory analysis in supporting groundwater management. Although the hydrological study results were still preliminary during the Rokua case MCDA, the method had immediate impacts. It opened the conflicting situation between stakeholders in the Rokua groundwater area and started a discussion on a sustainable and acceptable land use plan for the area. Based on the feedback from the analysis, the main advantage of the process was the learning of the

participants. Groundwater issues can be fairly abstract. This is the case especially in the Rokua study where the ditch-aquifer interaction can be difficult to understand. The MCDA process helped with this learning process and therefore eased the discussion on the Rokua land use plan as the stakeholders came to understand the subject. When the hydrological modeling results of the Rokua study were made available (Paper II), the discussion on how the groundwater management plan should be updated was fairly calm. This was probably due to the conflicting situation being already dealt with and the discussion already opened. This emphasizes the importance of using participatory analyses from the start of management projects.

The Rokua case study showed why these participatory methods should be introduced as a more regular part of groundwater management. For example, these methods could easily be integrated as part of water abstraction planning for cities. Participatory analysis improves learning and interactive discussion whereby all sides are heard and viewpoints taken into account. As stakeholders and administrators learn to understand the issue at hand, the results of hydrological studies, and each other's viewpoints, the risk of management issues culminating in mistrust or even litigation can be reduced or avoided.

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Original publications

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- II Rossi PM, Ala-aho P, Doherty J & Kløve B (2014) Impact of peatland drainage and restoration on esker groundwater resources: modeling future scenarios for management. *Hydrogeology Journal*. DOI 10.1007/s10040-014-1127-z.
- III Karjalainen TP, Rossi PM, Ala-aho P, Eskelinen R, Reinikainen K, Kløve B, Pulido-Velazquez M & Yang H (2013) A decision analysis framework for stakeholder involvement and learning in groundwater management. *Hydrology and Earth System Sciences* 17: 5141–5153.

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ISBN 978-952-62-0477-2 (Paperback)

ISBN 978-952-62-0478-9 (PDF)

ISSN 0355-3213 (Print)

ISSN 1796-2226 (Online)

