Management of water balance in mining areas - WaterSmart

Final Report

Kirsti Krogerus and Antti Pasanen (eds.)

Finnish Environment Institute

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ABSTRACT

Although mining companies have long been conscious of water related risks, they still face environmental management challenges. Several recent environmental incidents in Finnish mines have raised questions regarding mine site environmental and water management practices. This has increased public awareness of mining threats to the environment and resulted in stricter permits and longer permitting procedures. Water balance modelling aids in predictive water management and reduces risks caused by an excess or shortage of water at a mining site. In this study the primary objective was to exploit online water quantity and water quality measurements to better serve water balance management. The second objective was to develop and test mathematical models to calculate the water balance in mining operations. The third objective was to determine how monitoring and modelling tools can be integrated into the management system and process control.

According to the experience gained from monitoring water balances, the main recommendation is that the data should be stored in a database where it is easily available for water balance calculations. For real-time simulations, online measurements should be available from strategically defined positions in the mine site. Groundwater may also act as a source or sink with respect to mine site surface water, and therefore monitoring and investigations should be designed to account for the full water balance.

In Finland it is possible to calculate water balance for planning or for operative purposes by using the Watershed Simulation and Forecasting System (WSFS) developed at the Finnish Environment Institute (SYKE). This system covers every sub-basin (10-50 km^2) over the whole of Finland. WSFS automatically obtains the latest observations of temperature, precipitation, water level, discharge and other needed data provided by the Finnish Meteorological Institute (FMI), SYKE, as well as other sources. The system also uses these observations to follow-up on simulation and forecasting accuracy.

The water balance model was further developed to simulate and forecast the water balance at the Yara Siilinjärvi mine site. The WSFS-model was also extended with one-way coupling to the groundwater flow model. The model is operated via a web-based user interface and can produce water-balance forecasts automatically, if necessary, several times a day. The water balance and water flow in the area are simulated using real-time weather observations. The model enables forecasting water levels and planning discharges and pumping at the mine site. Possible uses of the model include preparation for spring floods by emptying ponds for storage of water from snow melt, estimation of the effect of heavy rainfall and calculating the required outflow from the mine site reservoir. Thus, overflows and dam-breaks can be avoided and consequently prevent the leakage of contaminated water. Furthermore, as the model can be modified to simulate changes at the mine site, it can also be beneficial during the mine site-planning process.

The water balance model is currently operational for Yara Siilinjärvi mine site and hydrological forecasts are produced on a daily basis. Water level, discharge and pumping data, essential for modelling the area, are provided by the mine operator and EHP-Tekniikka Ltd. The model uses meteorological observations and forecasts from FMI as inputs for the simulations and forecasts. In addition to the accurate

weather forecasts, the real time observations are a key factor in the accuracy of the model forecasts.

GoldSim is the most popular commercial simulation software solution chosen, not only by mines worldwide, but also in many other sectors. One of the main reasons for its extensive use is its versatility and the ability to expand the program as the needs of the mine require. As the mine project progresses, one of GoldSim's strongest assets is risk analysis at different phases during both the planning and execution of mine operations. The use of the GoldSim platform was tested during the project and some new features were developed.

The project has paid special attention to commercialization of the developed products and well thought out policies for possible joint bids.

TIIVISTELMÄ

Vaikka kaivosyritykset ovat jo pitkään olleet tietoisia vesien hallintaan liittyvistä riskeistä, ne kohtaavat edelleen ympäristön hallintaan liittyviä ongelmia. Vakavat kaivoksen ympäristöonnettomuudet Suomessa ovat nostaneet esiin kysymyksiä ympäristön ja vesimäärien hallinnasta. Ihmisten tietoisuus kaivosten ympäristöuhista on lisääntynyt. Muutos on nähtävissä myös esim. lupien tiukentumisena ja niiden käsittelyaikojen pidentymisenä. Vesitaseen mallintaminen helpottaa vesienhallinnan ennakointia ja vähentää liiallisen tai liian vähäisen veden kaivostoiminnalle aiheuttamia riskejä. Tässä tutkimuksessa selvitimme mahdollisuuksia hyödyntää jatkuvatoimisten veden määrän ja laadun mittauslaitteita siten, että mittaustulokset parhaiten palvelisivat vesitaseen hallintaa. Toisena tavoitteena oli kehittää ja testata matemaattisia malleja vesitaseen laskemiseksi kaivoksilla. Kolmantena tavoitteena oli selvittää miten seurantatulokset ja mallintamistyökalut voidaan integroida kaivosten hallintajärjestelmään ja prosessien valvontaan.

Saadun kokemuksen mukaan keskeisin suositus seurantatiedon hyödyntämiseksi on tallentaa tiedot järjestelmään, josta ne ovat helposti saatavilla taselaskelmia varten. Reaaliaikaisia mallilaskentoja varten tarvitaan jatkuvatoimisia mittauksia kaivosten tärkeimmistä havaintopaikoista. Pohjavedellä voi olla merkittävä vaikutus kaivoksen vesitaseeseen, joten myös pohjaveden monitorointia ja tutkimuksia tarvitaan kokonaisvesitaseen mallintamisessa.

Suomen vesitaseita on helppo laskea Suomen ympäristökeskuksessa (SYKE) kehitetyn vesitaseen simulointi ja ennustejärjestelmän (WSFS) avulla. Järjestelmä kattaa kaikki vesistöjen osa-alueet (koko 10–50 km^2) Suomessa. Järjestelmä saa automaattisesti uusimman tiedon lämpötila-, sademäärä-, vedenkorkeus ja virtaamahavainnoista sekä muun tarvittavan tiedon Suomen Ilmatieteen laitokselta (IL) ja SYKEltä ja osin muista lähteistä. Järjestelmä käyttää havaintoja myös simulointi- ja ennustetarkkuuden seuraamiseksi.

Vesitasemallia kehitettiin edelleen Yaran Siilinjärven kaivosalueen vesitaseen kuvaamiseksi ja ennustamiseksi. Lisäksi WSFS-mallia laajennettiin yhdistämällä pohjaveden virtausmalli siihen yksisuuntaisesti. Malli toimii web-käyttöliittymän kautta. Mallilla voidaan tuottaa vesitase-ennusteita automaattisesti tarvittaessa useita kertoja päivässä. Malli mahdollistaa vedenpinnan korkeuksien ennakoimisen ja virtaamien ja pumppausten suunnittelun kaivosalueella. Mallin yksi käyttötapa on varautua kevättulviin tyhjentämällä altaat lumen sulamisvesiä varten. Toinen tapa on arvioida rankkasateen vaikutuksia ja laskea tarvittava juoksutus kaivosalueen altaista. Näin ylivuodot ja patomurtumat voidaan välttää ja estää jäteveden juoksutus alueelta. Koska mallia voidaan muokata, sillä voidaan laskea kaivosalueelle suunniteltujen muutosten vaikutuksia, ja hyödyntää sitä kaivosalueella suunnittelun tukena.

Yaran Siilinjärven kaivosalueen vesitasemalli on tällä hetkellä operatiivinen ja hydrologiset ennusteet tuotetaan päiväkohtaisesti. Kaivostoiminnan harjoittaja ja EHP-Tekniikka Oy toimittavat alueelta mallinnuksen kannalta olennaiset vedenkorkeus-, virtaama- ja pumppaustiedot. Malli käyttää IL:n säähavaintoja ja -ennusteita vesitaselaskennan ja ennusteiden syöttötietona. Vesitaseeseen liittyvien havaintojen toimittaminen mahdollisimman reaaliaikaisesti on sääennusteiden tarkkuuden lisäksi keskeisin tekijä mallin ennustetarkkuuden kannalta.

GoldSim on maailmanlaajuisesti suosituin kaupallinen ohjelmisto kaivosalalla mutta myös monilla muilla aloilla. Yksi tärkeimmistä syistä sen laajamittaiseen

käyttöön on sen monipuolisuus ja mahdollisuus laajentaa laskentaa sen mukaan kuin kaivostoiminta edellyttää. Kaivostoiminnan edetessä ja laajetessa, GoldSim-ohjelmiston vahvuuksiin kuuluu riskianalyysi kaivostoiminnan eri vaiheiden aikana suunnittelusta toteutukseen asti. Hankkeen aikana testattiin GoldSim-alustan käyttöä ja joitakin uusia ominaisuuksia kehitettiin.

Projektissa on myös erityisesti selvitetty mahdollisuuksia kehitettyjen tuotteiden kaupallistamiseen ja mietitty käytäntöjä mahdollisten yhteisten tarjousten varalle.

SAMMANDRAG

Även om gruvbolagen länge har varit medvetna om vatten-relaterade risker, de fortfarande står inför problem med miljöledning. De allvarliga miljöolyckorna i gruvor i Finland hade en effekt på gruvindustrin genom att lyfta frågan om miljö- och vattenkontroll. Detta har ökat medvetandet om gruvornas miljöhot och resulterat i strängare miljötillstånd med långvariga processer. Modeller kan användas till att göra prognoser om vattenflöden och därmed kan risker som orsakas av överskott eller underskott av vattenflöden i gruvan reduceras. Det första målet i detta projekt var att utreda möjligheterna att använda apparatur för kontinuerliga mätningar av vattenmängden och -kvaliteten, så att resultaten bäst skulle passa för modellering av vattenbalansen. Det andra målet var att utveckla och testa matematiska modeller för beräkning av vattenbalansen i gruvor. Det tredje målet var att undersöka möjligheterna till en integrering av mätobservationer och modelleringsverktygen i gruvans övervakningssystem och processtyrning.

På basis av erhållna erfarenheter i projektet, rekommenderas speciellt att observationsdata skall lagras i ett sådant system, där det är lättillgängligt vid modelleringen. För simuleringar i realtid behövs on-line mätningar på de viktigaste uppföljningspunkterna på gruvområdet. Därtill är det viktigt att grundvattennivån observeras, eftersom grundvattennivån kan påverka gruvans vattenbalans.

Vattenbalanserna i Finland är enkla att beräkna med hjälp av simuleringsprogrammet "Watershed Simulation and Forecasting System (WSFS)" som utvecklats på Finlands miljöcentral (SYKE). Systemet täcker alla delområden (storlek 10-50 km²) av alla vattendrag i Finland. De senaste uppgifterna om temperaturer, regnmängder, vattennivåer och flödesobservationer samt annan behövlig information erhålls från Finlands meterologiska institut (IL) och SYKE samt delvis också från andra källor. Systemet använder dessa observationer för att följa upp noggrannheten i simuleringen och prognoserna.

Vattenbalansmodellen vidareutvecklades med data från Yaras gruvområde i Silinjärvi. Avsikten med modellen är att ge gruvdriftsidkaren ett förbättrat verktyg för hantering av vattenbalansen. Dessutom WSFS-modellen utvidgades med en ett-stegs-koppling till modellen för grundvattenflöden. Modellen fungerar genom en web-användningsanslutning. Med modellen kan prognoser om vattenbalansen göras vid behov flera gånger per dag. Modellen möjliggör en beräkning av vattennivån och en planering av pumpningar på gruvområdet. Ett av användningsområdena för modellen vara att ge beredskap för eventuella översvämningar på våren genom att i förtid tömma bassängerna för att ge plats för smältvatten. En annan möjlighet är att vid behov beräkna inverkan av störtregn och eventuellt tömma bassängerna på gruvområdet. Således kan överflöden och bassängläckor undvikas och man kan hindra ett utflöde av gruvvatten från området. Eftersom modellen kan modifieras, kan man beräkna inverkan av planerade förändringar och utnyttja dessa som stöd för planering och utveckling av gruvområdet.

Vattenbalansmodellen för Yaras gruvområdet i Siilinjärvi är nu i bruk och hydrologiska prognoser görs dagligen. Gruvdriftsidkaren och EHP-Tekniikka Oy samlar in väsentliga uppgifter om vattennivån, flödesmängder och pumpningar som behövs i modellen. Att dessa observationer insamlas möjligast nära realtid är, förutom noggrannheten i väderleksprognosen, den faktorn som mest bidrar till noggrannheten

i prognosen. Modellen använder som input data väderleksobservationer och prognoser från meterologiska institutet i Finland

GoldSim är globalt den mest använda kommersiella modellen som utnyttjas speciellt på gruvområden men också på många andra områden. En av de viktigaste orsakerna för dess utbredda användning är dess mångsidighet och möjlighet till flexibilitet för en utvidgning av beräkningarna enligt behov. Då gruvverksamheten utvidgas, är riskanalys i gruvdriftens olika skeden såväl i planering som i drift den starkaste egenskapen i GoldSim-programmet. GoldSim modellen testades under projektets gång och några nya egenskaper utvecklades.

I projektet har man också speciellt utrett möjligheten att göra de utvecklade produkterna kommersiellt tillgängliga och man har övervägt olika strategier för eventuella gemensamma offerter.

Nyckelord: vattenbalans, ytvatten, grundvatten, gruvdrift, prognoser, operationer, planläggning

This report aims to present mine water balance management possibilities developed through the WaterSmart project. Both surface and groundwater are included in the monitoring and balance calculations. The models can be utilized without a process control solution to create scenarios that indicate the effect of forecasted data on the amount of water at a mine site, but can also be connected to a mine site-specific process control solution.

The WaterSmart project is a part of the sustainable extractive industry program Green Mining by Tekes. The project was co-funded by Tekes - the Finnish Funding Agency for Technology and Innovation, Outotec Ltd, ÅF-Consult Ltd, EHP-Tekniikka Ltd, Boliden Kylylahti (former Kylylahti Copper Ltd), Yara Suomi Oy, Finnish Environment Institute (SYKE), VTT Technical Research Centre of Finland Ltd, and the Geological Survey of Finland (GTK). The project was coordinated by SYKE.

The steering group consisted of the following persons: Ilkka V. Kojo, Outotec Ltd, chairman; Laura Nevatalo, Outotec Research Center; Pasi Vahanne, ÅF-Consult Ltd; Jaakko Seppälä, EHP-Tekniikka Ltd; Kari Janhunen, Boliden Kylylahti; Toni Uusimäki, Yara Suomi Oy (until 31.3.2015); Jouni Torssonen Yara Suomi Oy (from 1.4.2015); Markku Maunula, SYKE; Risto Pietilä, GTK; Tommi Kauppila, GTK; Eemeli Hytönen, VTT; Auri Koivuhuhta, Kainuu ELY Centre and Tuomas Lehtinen, Tekes. The steering group has been actively supporting the work, and has been especially active in starting commercialization of the project results.

The report has been completed by a large team of experts from the research institutes SYKE, VTT and GTK. The authors are responsible for the content of their texts in corresponding sub-chapters.

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CONTENTS

1 Introduction

Mining operations can influence both the quantity and quality of water as mines are significant water users and producers of wastewater. The responsible use of water is becoming a critical business issue affecting the growth and profitability of mining companies. Although mining companies have long been conscious of water -related risks (Nguyen et al. 2014), they still, even in Finland, face environmental management problems (Välisalo et al. 2014). According to Törmä et al. (2015) the serious environmental accidents at the Talvivaara mine in north-eastern Finland led to the downfall of the mining company. Such incidents have had an effect on Finland's mining industry by increasing public awareness of possible environmental threats and have led to a stricter and longer permitting process. Particularly, the management of large quantities of water has become a public issue and affects both the social licence to operate and the profitability of the mines. Problems with excessive water at mining areas mainly emerge because mine sites' water balances have not been adequately assessed in the planning stage of the mines and the storage basin capacity is too small (Välisalo et al. 2014). According to Veijalainen (2012) impacts of climate change include seasonal changes in the discharge of natural waters in Finland which makes the anticipation of water balances in mines even more difficult. As a result, environmental permit regulations have been difficult to implement in practice because the permissions are based on inadequate or even false information. These difficulties indicate that a more consistent approach is required to help mining companies identify the risks and opportunities related to the management of water resources in all stages of mining.

This approach requires the water cycle of a mine site to be interconnected with the general hydrological water cycle. Therefore, reliable real-time data on the amounts of water are needed in Finland, in particular during water-rich seasons, during heavy rains, but also during harsh winters when water may become frozen and is not available for use. In areas of water stress, the challenge is the opposite; sustainable water resource management is required to enable significant reductions in water use (Buckley 2012). In addition to knowledge of hydrological conditions, controlling water balance in mining processes requires knowledge of the mining process unit operations, the ability to adjust process parameters to variable hydrological conditions, adaptation of suitable water management tools and systems, systematic monitoring of the amounts and quality of water, large enough capacity within the water management infrastructure to handle the variable water flows, good practices to assess the dispersion, mixing and dilution of mine water and pollutant loading to receiving water bodies, and the dewatering and separation of water from tailings and precipitates (Punkkinen et al. 2016).

Even though platforms for modelling water and mass balances at mines exist, and their use has increased, there are currently no comprehensive water balance models available that allow the stakeholders to sustainably manage mine-site water resources, carry out risk analyses, evaluate and predict potential environmental impacts, optimize site operations and support strategic planning of mine-site operations. For example, in the Finnish national report of Best Environmental Practices in Metal Ore Mining written by Kauppila et al. (2011) very little is said about managing water balances in mines, though the report draws on lessons learned in the field and international practices. Punkkinen et al. 2016 summarized the status of modelling mine water balances. Though spreadsheet-based programs are widely used in modelling, they are neither well-suited to simulate highly complex dynamics, nor very adaptable to different scenario inspections. Among the dynamic modelling software, the Simulink modelling environment supports fast development and analysis of time- and event-

driven models which makes it a useful tool when modelling mining related processes. A widely used software for dynamic modelling of complex systems is GoldSim, which provides the features and flexibility to simulate processes related to environmental applications. Therefore it is well-known to the mining industry.

The information needed for comprehensive water balance modelling is scattered, site-dependent, and is therefore difficult for authorities and mine operators to utilize. The main problem with the existing models is that the water cycle of a mine site is not thoroughly interconnected with the general hydrological water cycle. Although the scientific knowledge required for site-wide water balance modelling exists, the practical problem is that the required monitoring systems, application know-how, calculation models, as well as ICT tools required to transfer data, generate and visualize mine-site water balance have been scattered amongst various operators.

Selecting appropriate models is also difficult since the operating and environmental context of each mine site is different; water sources and water availability between mine sites vary, and catchment areas as well as ground water sources differ by geology, and topography, etc. Therefore, the practical ability to manage, forecast and control mine site-wide water balance is suboptimal.

The overall aim of the WaterSmart project was to improve the awareness of actual quantities of water and water balances in mine areas to provide the possibility to forecast water masses in the future. The goal was to promote the anticipation and management of water fluxes. The project focused on developing management systems for waters in mining areas with special consideration given to risk management.

The WaterSmart project has already published a report which identifies current and expected future needs for mine water management, describes water management procedures and decisions in different phases of a mine's life cycle, introduces good practices for water balance management, and presents selected case study examples (Punkkinen et al. 2016).

In this report we describe the constantly updated management system for water balance, including both natural waters and process waters, developed in the WaterSmart project. Online water quantity and water quality measurements were tested at case-study mines in order to understand their suitability to serve the primary objective of managing the water balance. Hydrogeological methods were tested in order to get better estimates for groundwater balances. Mathematical models were used to calculate water balance, as well as to test and develop the suitability of models for water balance calculations. Finally, it was determined how the monitoring and modelling tools can be integrated into the management system and process control.

2 Data collection and monitoring

2.1 Groundwater measurements

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When managing groundwater balance at a mine site the geological and hydraulic conditions and their distribution need to be known. The most important parameters are the level of phreatic surface and the hydraulic conductivity (K) of the geological medium. If known in several places, the direction of groundwater flow and velocity can be estimated. Groundwater level measurements are also used in many cases to calibrate the groundwater flow model.

The geology, the distribution of sediment types, as well as fractures and joints in bedrock affect groundwater flow. Therefore, these site specific conditions must be characterized prior to making assumptions regarding the water balance. In Finland studies of hydrogeological properties is in most cases confined to Quaternary sediments (*i.e.* the first meters or tens of meters of the subsurface). In many Finnish mines the sediments are less important for the management of the water balance than the water in secondary structures, such as fractures and joints in the bedrock.

The study of secondary structures in bedrock may entail a combination of traditional geological methods such as drilling, geophysical methods, and well hydraulics measurements.

The geophysical methods suitable for defining secondary structures in bedrock and their strike include VLF-R (Very Low Frequency with Resistivity), ERT (Electrical Resistivity Tomography), refraction seismics and gravimetric measurements. Aeromagnetic and DEM data are also useful in early stage interpretation of lineaments. In this study VLF-R, alongside a lineament study, were the main methods used to define bedrock fracture zones. Also, in some instances, GPR (Ground Penetrating Radar) can give information on fracture zones, sediment structure, and bedrock surface.

Drilling in fracture zones can be inclined or vertical. In the study of groundwater balances vertical drilling is favoured because the whole fracture zone is penetrated, in contrast to inclined drilling where the fracture zone is penetrated only partly. When performing vertical drilling, to ensure that drilling intersects the fracture zone, the location of the fracture zone must be known with high precision. Geophysical measurements are crucial in pinpointing target drilling locations.

The last stage of investigation prior to estimation of water balance and possible modelling is hydraulic measurements from the drill holes. Operating in vertical drill holes is much easier than in inclined drill holes. Further, when tests are conducted in vertical drill holes without packers, information on the whole fracture zone is obtained. The information received from hydraulic measurements can be used as parameter data for groundwater flow modelling.

2.1.1 Geological and geophysical studies

Geologic data pertinent to water balance studies were collected from the Yara Suomi Oy Mine Site in Siilinjärvi and the Boliden Kylylahti closed Mine Site in Luikonlahti. In these studies field data on bedrock surface, bedrock geology, Quaternary sediments, groundwater level, and hydrogeological parameters were utilized in groundwater flow models to describe interactions between groundwater and surface water in the respective catchments. At both sites slug tests were conducted from sediment and

bedrock groundwater observation wells as part of the WaterSmart project. At the Yara Siilinjärvi site data collection also included GPR, VLF-R and magnetic surveys, installation of two fracture zone observation wells by diamond core drilling, and groundwater monitoring across existing wells using HOBO dive data loggers. At the Boliden Luikonlahti site, these data were obtained from earlier work conducted as part of the Minera Project (Pasanen & Backnäs 2013).

The Yara Suomi Oy open pit phosphate mine and production plant is located near the town of Siilinjärvi in Eastern Finland (Fig 1). Mining started at the Siilinjärvi site in 1979 and currently about 9.2 Mt of ore is produced annually from the two open pits, Särkijärvi in the south, and Saarinen in the north-east. The mine is in the Precambrian Siilinjärvi carbonatite complex which consists primarily of phlogopite- and apatite-rich glimmerite, syenite, and carbonate-rich carbonatite. The apatite bearing host rocks comprise a steeply dipping lenticular body approximately 16 km long and up to 650 m in width, with a maximum depth of 1.5 km. The Precambrian bedrock is overlain by Quaternary deposits comprised of meltout till in the mining area, and fine silt and clay around the lakes south of the mining area. The topographic elevation

Figure 1. Siilinjärvi mine site overview map.

of the study area, as determined from LIDAR data, varies from 84.0 to 190.45 m a.s.l. (meters above sea level), with a mean elevation of 117.94 m a.s.l. Elevation generally decreases from north to south.

The Boliden Luikonlahti site is located near the town of Kaavi in Eastern Finland (Fig. 2). The site is a closed mine site with active processing plant and tailings storage facilities (Fig. 2). The mined ore is associated with Outokumpu assemblage rock types which contain elevated concentrations of Co, Cr, Cu, Ni and Zn. Typical for the area are serpentinite formations associated with skarns and carbonatites. The formation is surrounded by mica gneisses. The topography of the area is governed by hills and valleys. The hills consist mainly of bedrock and till formations and in the valleys small peat bogs occur on top of till and fine grained sediments. A small esker chain extends west of the area, but it is thought that its effect on water management is small.

Figure 2. Luikonlahti mine site overview map.

2.1.1.1 Methods

2.1.1.1.1 Ground Penetration Radar (GPR) method

Integration of GPR data with hydrogeological parameters provides increased understanding of groundwater occurrence, flow and interactions with surface water in the study area. GPR is a geophysical method that utilizes an electromagnetic pulse to the subsurface in combination with data from control wells to classify sediment distribution and to map the internal structure of sedimentary features. The amplitude and two-way travel time of electromagnetic pulses are measured in nanoseconds as they are reflected from boundaries in subsurface dielectric properties. Subsurface dielectric boundaries denote changes in water content, lithology, and material density (Hänninen 1991). GPR signal has the greatest depth in porous dry materials such as sand, in which signal can be resolved to about 50 m depth. Signal is attenuated in materials with high electrical conductivity, such as clays, or saline water bearing lithologies. The average signal depth during investigations is usually 20 to 30 m.

The GPR survey field investigation was conducted from 8 - 18 July, 2014 using the Malå - Ramac ProEx equipment and Rough Terrain Antenna (RTA) with 25 and 100 MHz centre frequencies. The 100 MHz antenna was determined to provide the best balance between penetration depth and vertical resolution, thus data from this antenna was used for interpolation of bedrock elevation. The 25 MHz antenna gives higher penetration depth, but the vertical resolution is much coarser. Global positioning system (GPS) was used for horizontal positioning throughout the field investigation. A GPS device with centimetre accuracy was used at the start of the study, while a normal handheld device with an accuracy of a few metres was used at the end. The change in accuracy of the positioning does not affect the reliability of the results. A LIDAR-based digital elevation model was used for the topography.

47 GPR survey lines totalling 41 km were carried out throughout the main geological deposits and mining activity areas at the Yara Siilinjärvi site, including tailings, gypsum pile areas, calcine pile areas, and rock/overburden dumping areas (Fig. 3). GPR data processing and interpretation were done using GeoDoctor (version 2.546) software. The data processing consists of filtering to enhance the signal to noise ratio, topographic correction to compensate for changes in surface elevation, and depth conversion. Data from drilled wells such as top-of-bedrock, descriptions of sediments, and groundwater level were used for the calibration and interpretation of the GPR data.

Bedrock surface elevation was interpolated from integrating GPR, drilled well, outcrop, and 1:20000 Quaternary sediment map and bedrock outcrop data. The initial interpolation was done using kriging with 5 m grid size across the study area in ArcMap (Version 10.1). This surface was calibrated with bedrock surface control points. Where the interpolated surface was shallower than the control points, the control points were used to define top-of-bedrock, and the bedrock surface was re-interpolated using the inverse distance weighting (IDW) method in the ArcMap program.

The thickness of Quaternary deposits was calculated as the difference in the LIDAR topographic map (re-gridded from 2 m to 5 m grid size) and the interpolated bedrock surface map. Quaternary sediment type and distribution was interpolated by integrating data from drilled wells, soil samples, outcrops, and the 1:20000 Quaternary geologic map sheet numbers 333 11 and 3333 12 (Huttunen 2000, 2002).

The survey is fully described in Luoma et al. (2016).
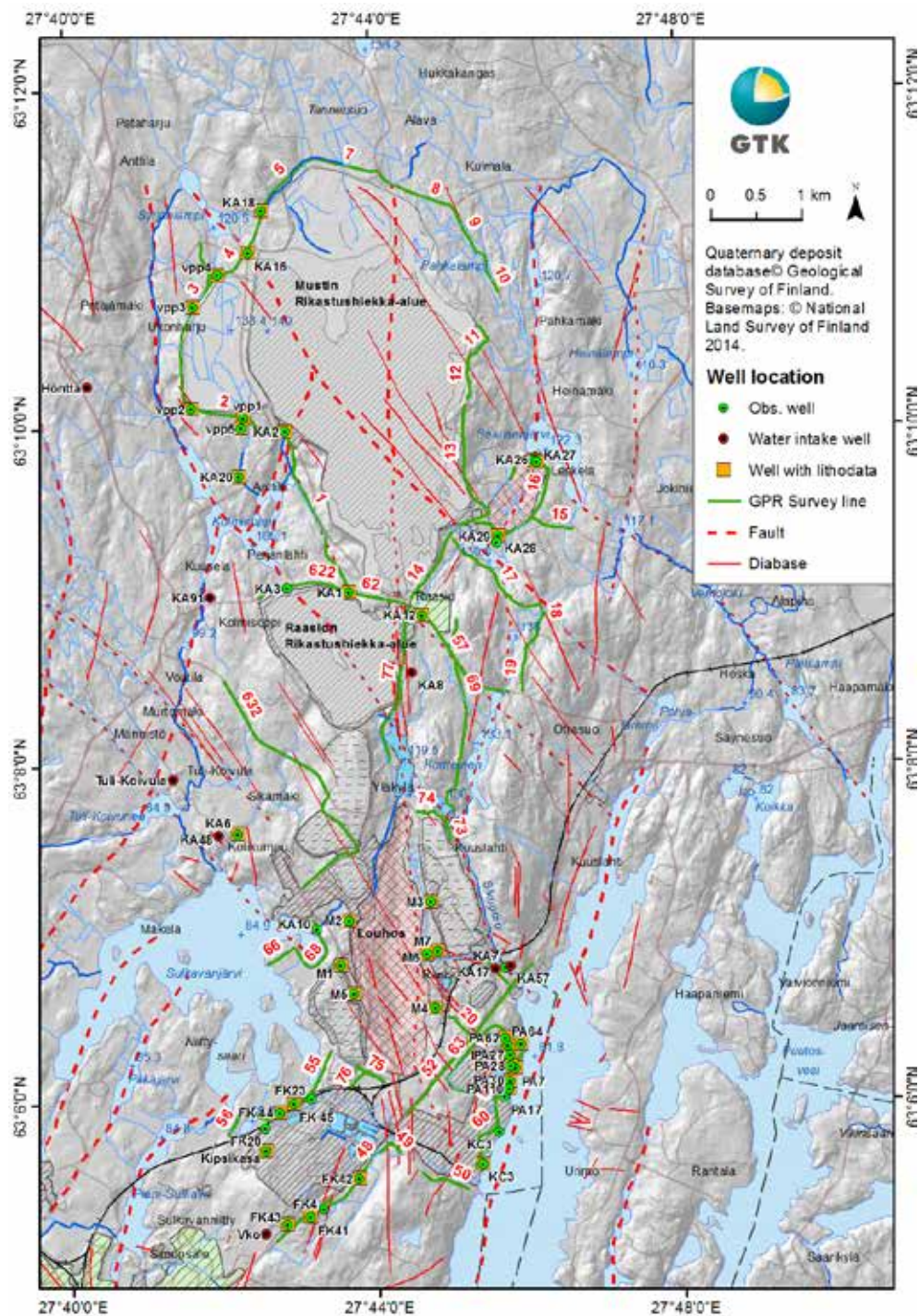
Figure 3. Overview map of Siilinjärvi Mine area showing well locations and GPR survey lines collected from 8-18, July, 2014.

2.1.1.1.2 Very Low Frequency with Resistivity (VLF-R) method

VLF-R measurements were collected to map fracture zones at the Yara Siilinjärvi site. The VLF-R method is an electromagnetic planewave method very suitable to mapping fracture zones in resistive environments. In the WaterSmart project a total of 8 profiles (38 km) were measured.

The interpretation of measured profiles is performed using inverse modelling for apparent resistivity and phase to show the thickness of soft sediments and bedrock topography (Fig. 4). Bedrock fracture zones are interpreted from the low points in the
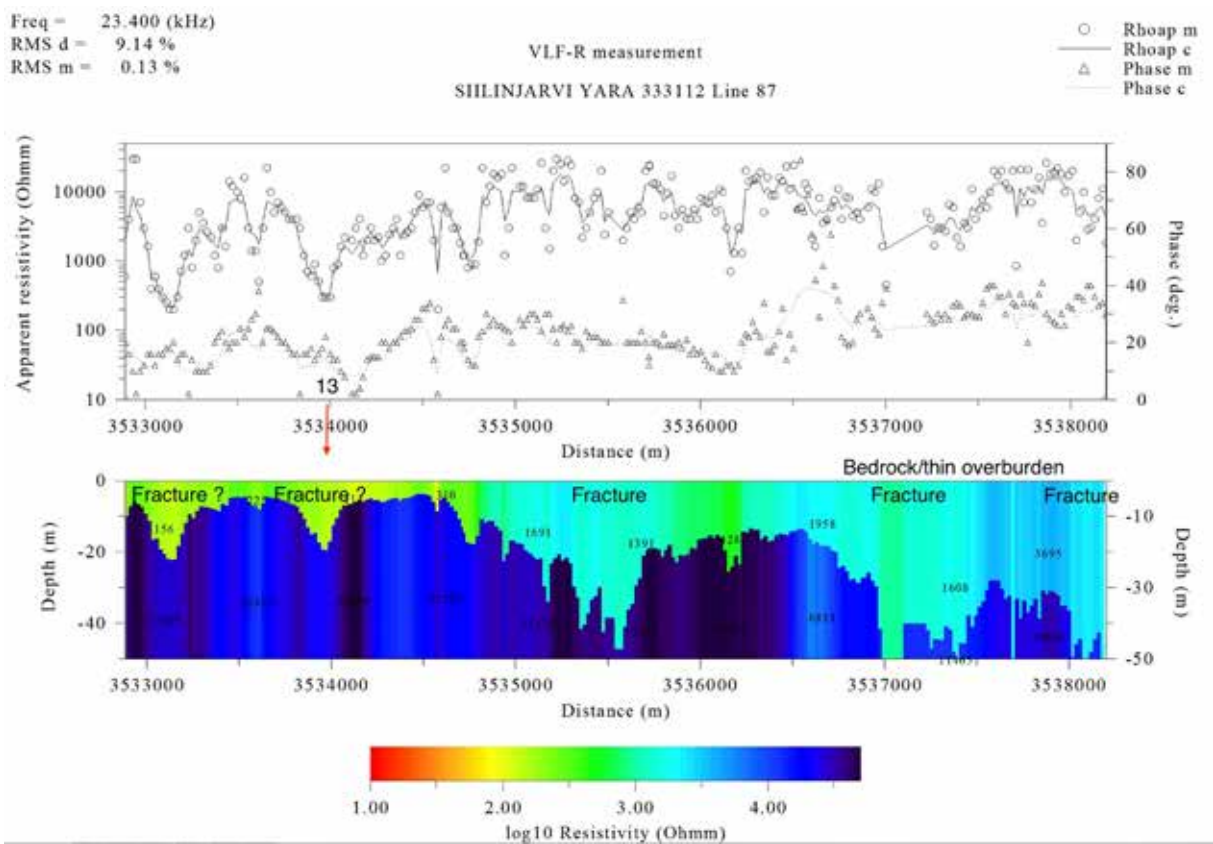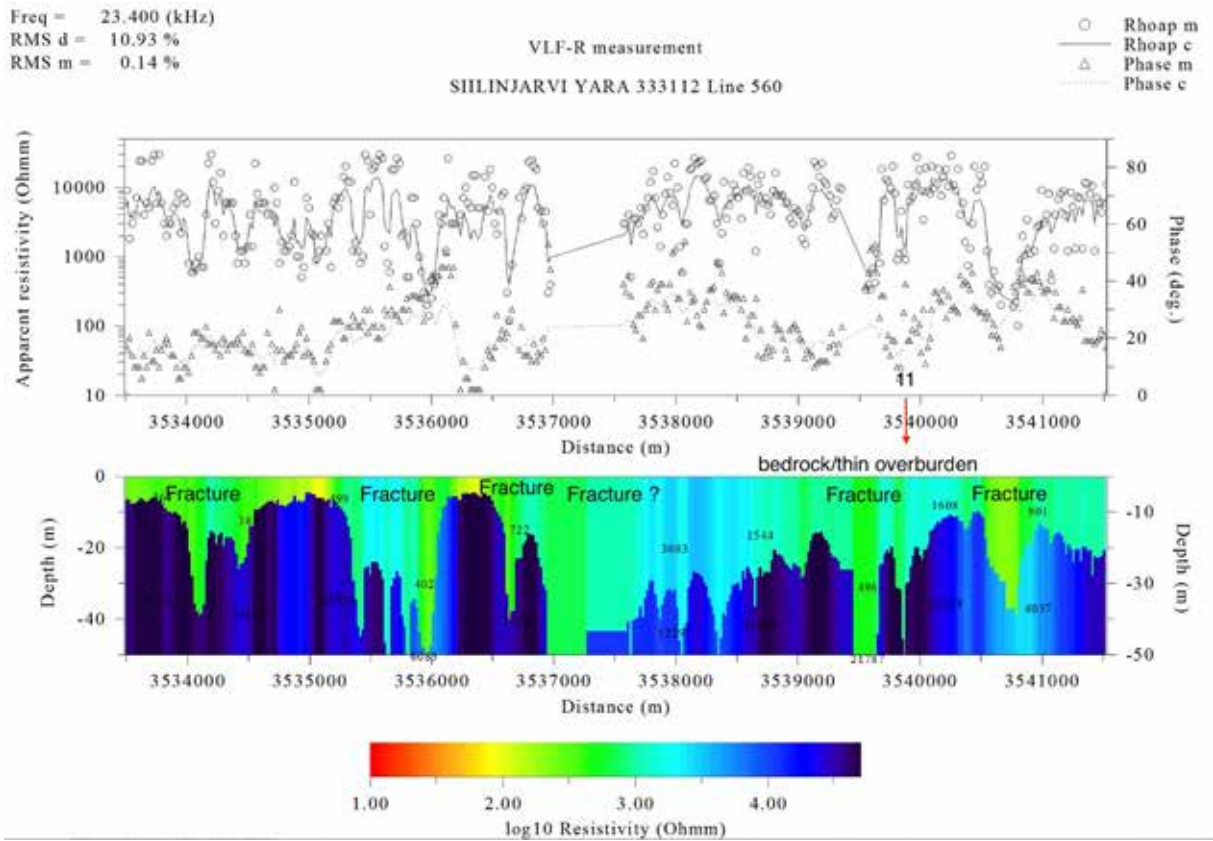
Figure 4. Interpretation examples of VLF-R-measurements from Yara Siilinjärvi Apatite mine, lines 560 and 87.

bedrock surface which have been eroded by glacial ice. Interpretation of the locations of the fracture zones based on VLF-R measurements are presented in Fig. 5. To verify the interpretations other geological and geophysical data are always needed.

The results received matched very well with other data and mapped fracture zones. Also, some new possible fracture zones were detected but have not been verified.
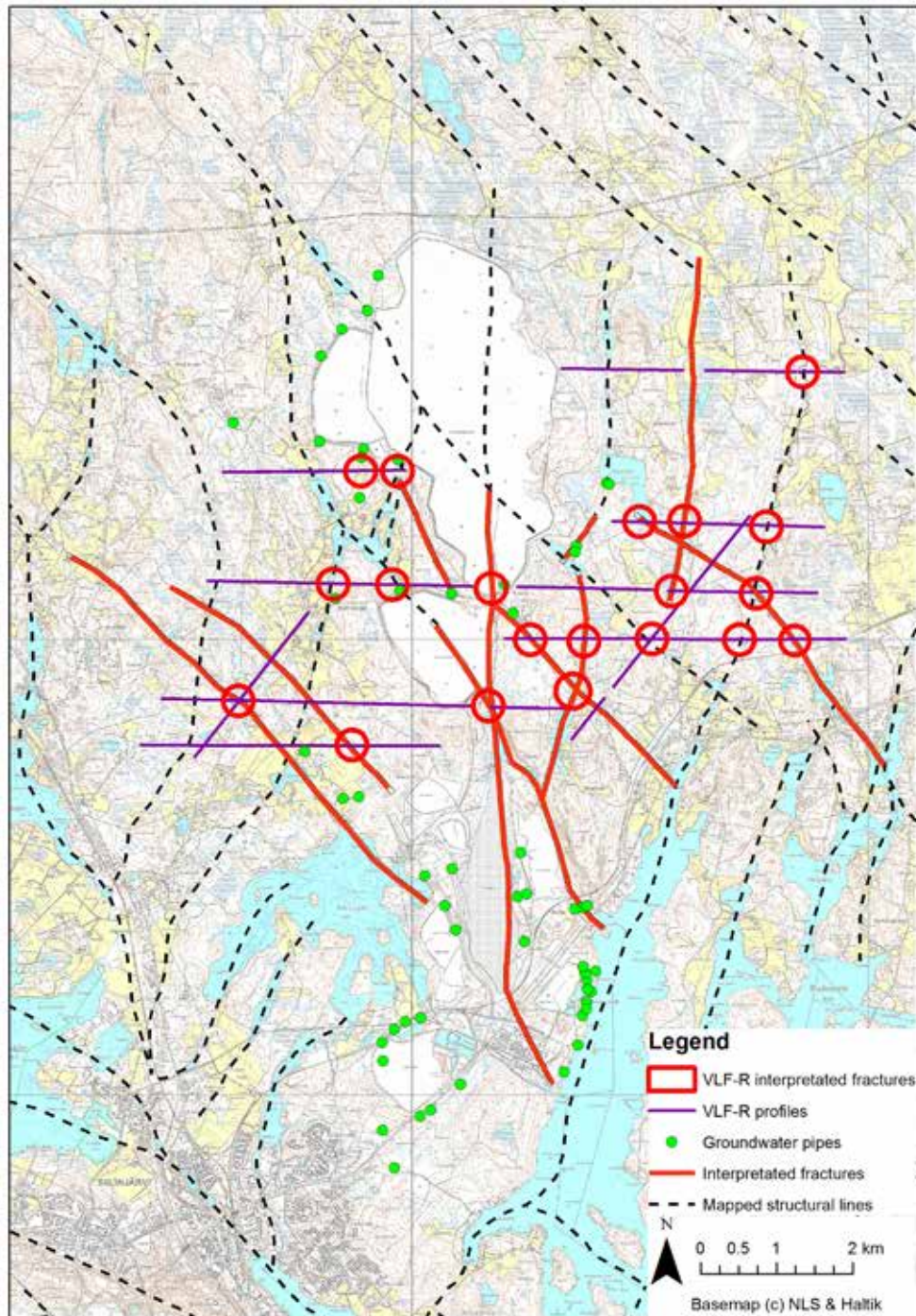
Figure 5. VLF-R profiles structure lines (dash and thick red, [DIGI-KP 2015]), interpreted fracture zones from VLF-R measurements (red circles) and GPR lines blue. Base map. © Geological survey of Finland.

2.1.1.2 Interpolation of quaternary deposits and top of bedrock

At the Siilinjärvi site the GPR survey was successful across most transects. However reflection was obscured beneath gypsum and calcine piles. Example GPR profiles are provided in Fig. 6 (line 73) and Fig. 7 (line 56) to illustrate the difference in successful and obscured GPR transect data. The location of the lines is shown in Fig. 3. The poor resolution beneath the gypsum pile is attributed in-part to Quaternary sediments dominated by clay, as identified from well log observations. Additionally, GPR resolution was likely impacted by high salinity waters in the sediments of both the calcine and gypsum piles, which exhibited electrical conductivity values of 1040 mS m^{-1} and 428 mS m^{-1}, respectively. Due to poor resolution beneath the calcine and
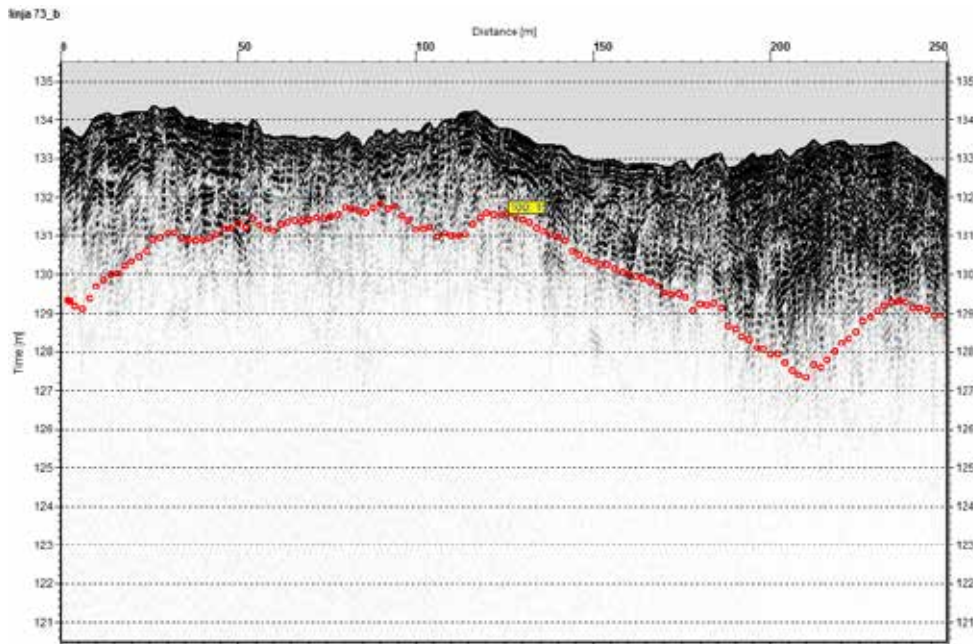
Figure 6. GPR profile along survey line 73, southeast of Sikopuron Allas artificial lake. Red dots represent interpreted bedrock surface. The location of the line is shown in Figure 4.

Figure 7. GPR profile along survey line 56, north of the gypsum pile. The location of the line is shown in Figure 3.

gypsum piles bedrock surface elevations were determined from well and outcrop data only.

Bedrock surface elevations in the mine area (excluding tailings, rock piles and quarry areas) vary between +56.64 and +190.45 m above sea level (a.s.l.), with a mean elevation of +111.64 m a.s.l. Bedrock elevation decreases from north 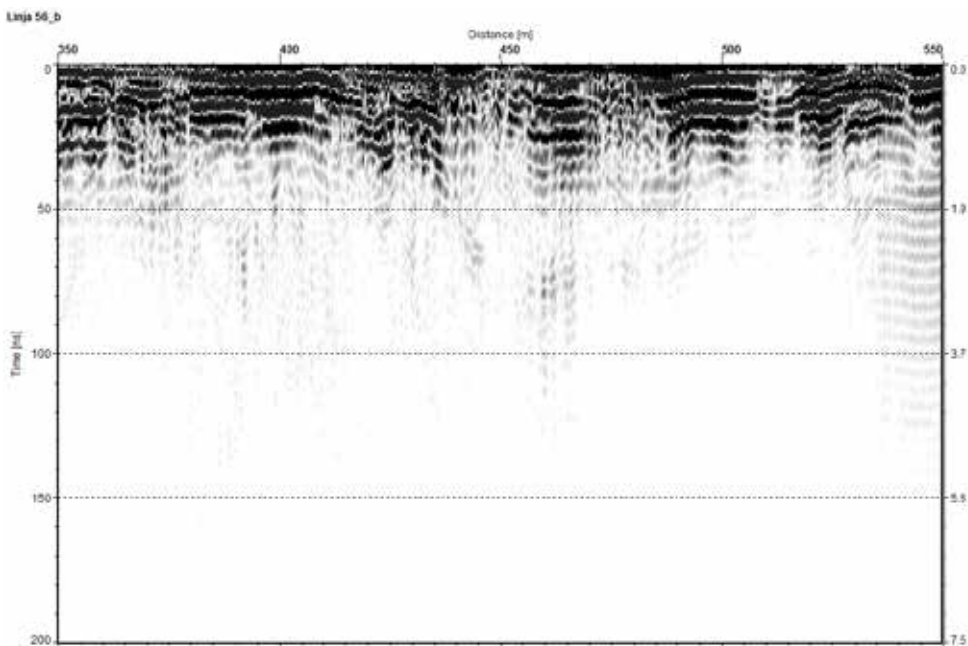to south, following topographic elevation. The bedrock surface creates a sharp contact with the overlying Quaternary sediment and in most places bedrock outcrops exhibit fracturing. Fractures observed in open pit walls and interpreted from geophysical data are generally oriented at 311°, 0°, and 18°, and indicate a relatively broad, deep fracture zone oriented from NW to SE (Fig. 5). Fractures in this direction approximately align with the most common direction of Quaternary continental ice movement, which has likely resulted in exaggerated surface expression due to glacial scouring (Puustinen, 1971). Many of the lakes in Finland, especially eastern Finland, align with this direction.

The thickness of Quaternary sediments across the study site varies from 1.05 to 17.7 m, with a mean thickness of 2.3 m. Approximately 60% of the study site's total surface area is comprised of till, ranging from fine grained to basal melt out till. 13.8% of the study site surface area is covered in surface water (i.e. streams, rivers, and lakes) and 11.1% is exposed bedrock. 8.3% of the study site surface area is comprised of fine grained sediments such as silts, clays, and peat, which are distributed along watercourse areas, in valleys close to lakes, and often overlie fine grained till. Such deposits have relatively low hydraulic conductivity (0.001 to 0.61 m d^{-1}), and subsequently correspond to low surface water infiltration rates. The occurrence of such sediments across the site can be observed in coincidence with areas where rainwater remains in puddles on the ground surface for days following a rain event. Fine grained sediment deposits vary in thickness from < 1 m to 17.8 m, with a mean thickness of 1.70 m, and the thickest clay deposit is south of Lake Sulkavanjärvi. The remaining 6.8% of the study site surface area was undefined, and includes mine construction and development areas.

At the Boliden Luikonlahti site surface topography was defined from LIDAR data from the National Land Survey of Finland, while the bedrock surface profile was interpreted from drilling and geophysical data collected as part of the Minera project (Pasanen & Backnäs 2013).

2.1.2 Groundwater monitoring and hydraulic testing

Hydraulic testing consists of a set of methods to determine the hydraulic properties of the geological media near the well or at the ground surface. In the wells a short or long time change in a stable groundwater system is induced and the effects are measured. The main parameter received from the single well test, which was the main approach in this study, is the hydraulic conductivity which then can be used to calculate several other parameters. The hydraulic conductivity alongside with groundwater level monitoring gives a basis for groundwater flow modelling.

The slug test is a fast field technique to determine localized hydraulic conductivity values. The method involves the instantaneous injection or withdrawal of a volume of water into or from a well and monitoring how it recovers from the sudden change in head to the initial static conditions. The K-values around the well can then be obtained by analysing the change of water levels over time. In this study the slug test was done using the rising-head test by removing the slug (using a solid PVC tube) quickly from the well, while groundwater level and the recovery time were recorded until the head returned to the initial water level. The K-values were then calculated using the AqTestSolver 4.5 program with the Bouwer & Rice (1976) method.

Slug tests were conducted in 19 wells at the Boliden Luikonlahti site in the spring of 2014 (Fig. 8) and in 35 wells at the Yara Siilinjärvi site in the summer of 2014 (Fig. 9). Tests were conducted in both sediment- and bedrock groundwater observation wells.

At the Luikonlahti site the objective of hydraulic testing was to produce hydraulic conductivity data for the groundwater flow model. The slug tests were conducted according to the Butler (1998) protocol. The wells were tested for physical condition to identify wells with open screens, which were subsequently used for hydraulic testing. Hydraulic test results from the observation wells in sediments are shown in Table 1 in Appendix. There are also four bedrock groundwater observation wells in the Luikonlahti area. In addition to slug tests, single well pumping tests were performed to approximate transmissivity (T) alongside hydraulic conductivity (K). The results are shown in Table 2 of the Appendix.
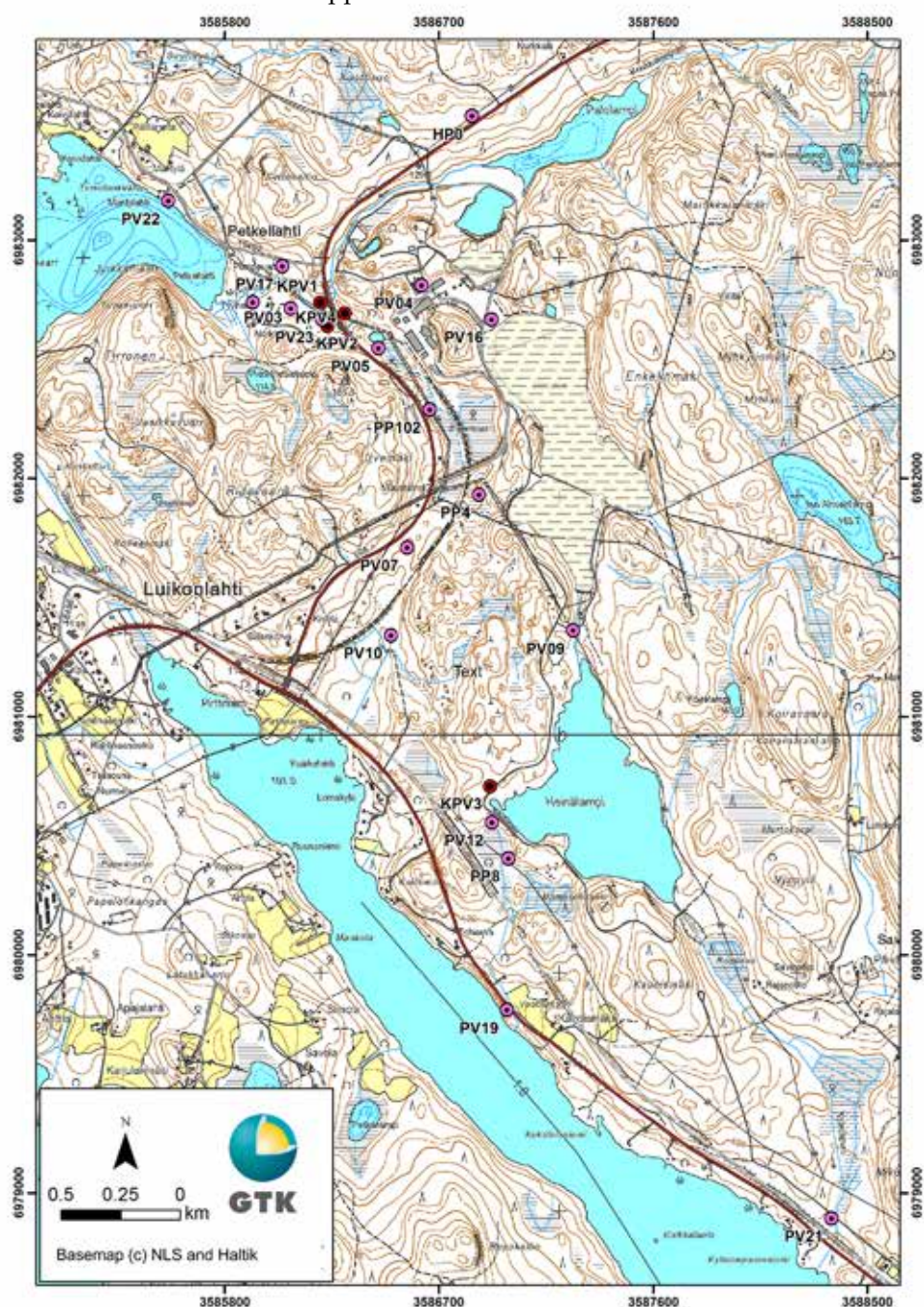

Figure 8. Luikonlahti study site. Pink circles show the location of the slug tests in sediment wells and red circles the slug tests and single well pumping tests in bedrock wells.
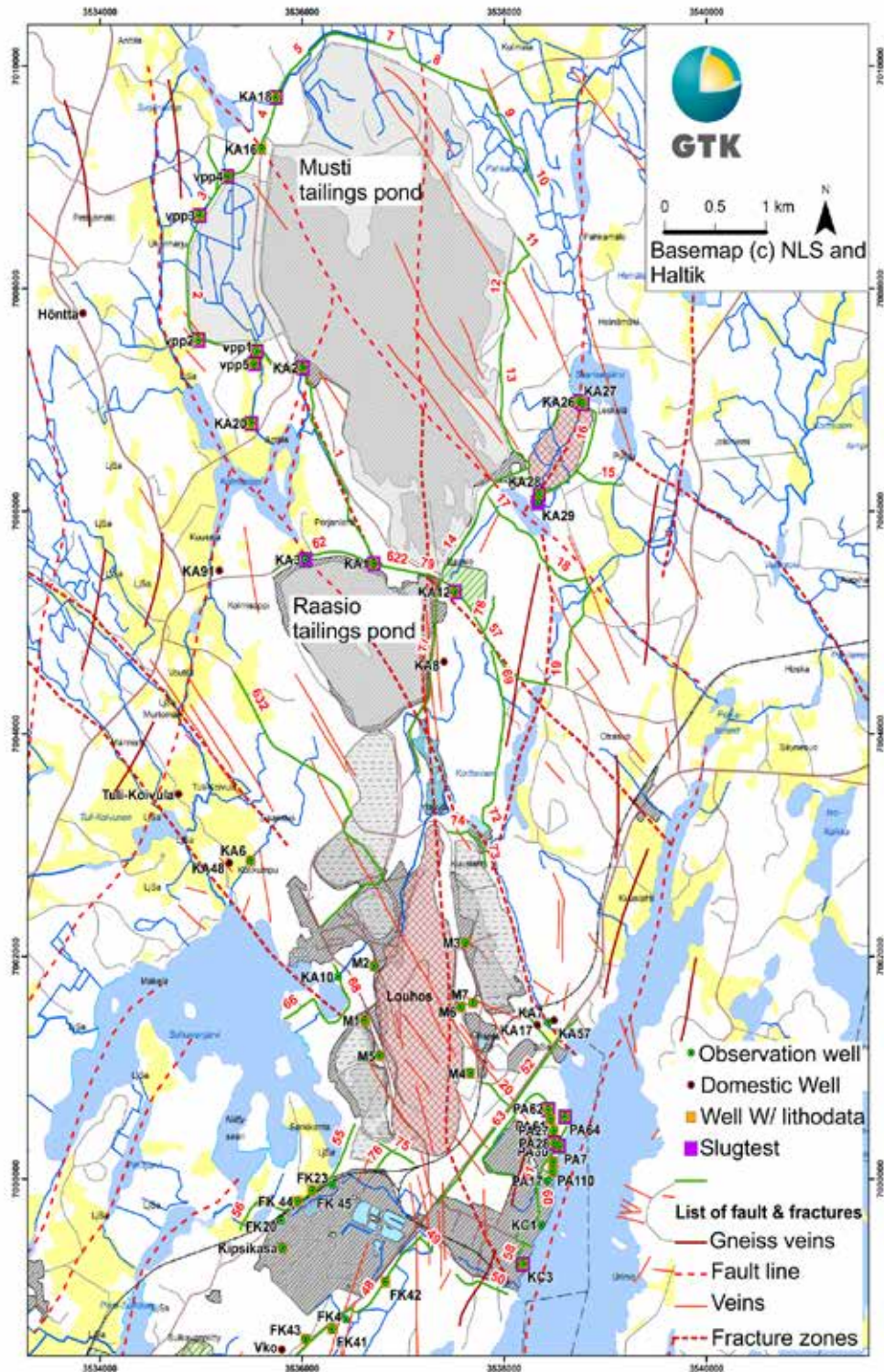
Figure 9. Locations of observation wells, domestic wells and slug test sites at the Siilinjärvi site. The lineament structures in bedrock are used in the groundwater flow modelling.

At the Yara Siilinjärvi site 64 wells were tested for physical condition and 35 were selected for hydraulic testing (Fig. 9). The results of the tests are shown in Table 3 of the Appendix.

In addition to tests in existing wells, two vertical bedrock wells were cored at the Siilinjärvi site. These corings were made to verify the geophysical interpretation of the fracture zones. Electrical conductivity profiling was also performed on both cored wells. In the Sikopuro1 well the electrical conductivity is similar to the Sikopuro water pond next to the well, but the conductivity decreases at 30 m depth, suggesting percolation from the pond to the top of the well and natural groundwater at the bottom (Fig. 10). In the Musti_länsi well the electrical conductivity is similar to that of the adjacent small creek throughout the depth of the well. The creek collects the effluent from the tailings storage facility and it was unclear whether the water in this well reflects percolation from the creek or from the tailings storage facility (Fig. 11).

The groundwater level varies according to the season, but is also affected by mining processes. Groundwater level monitoring provides one of the most important parameters for calculating the water balance and groundwater flow modelling. In this study monitoring was performed at the Yara Siilinjärvi site from July 2014 to November 2015.

At the Yara Siilinjärvi site HOBO U20L divers were installed in 25 observation wells to monitor changes in groundwater level. The wells were selected to cover the whole mining district and hydrogeologically different areas. Measurements were collected every 30 minutes. The divers measure the total pressure and, therefore, a barometer was installed above the groundwater level in a well central to the mine area. The barometric data was subtracted from the total pressure to receive the hydrostatic pressure. The divers were installed as deep as their pressure rating allowed to avoid
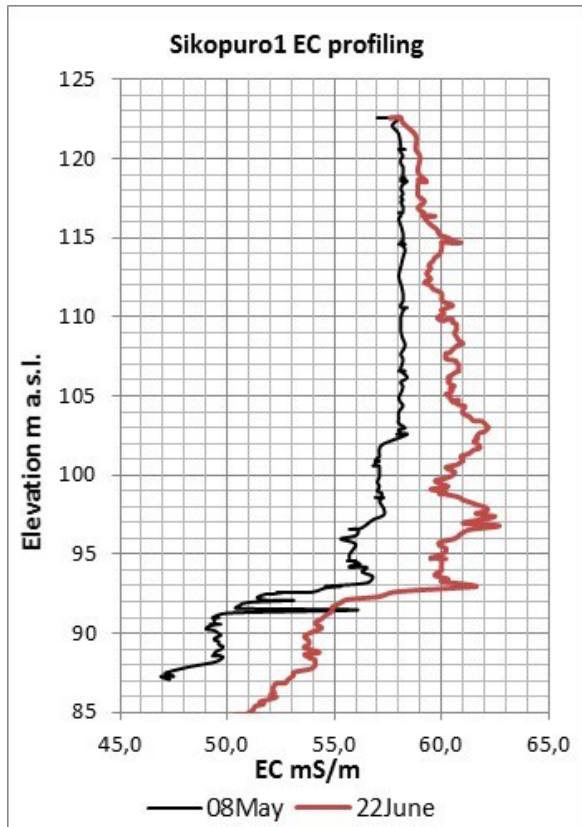
Figure 10. Electrical conductivity logs of groundwater from Sikopuro1 coring.
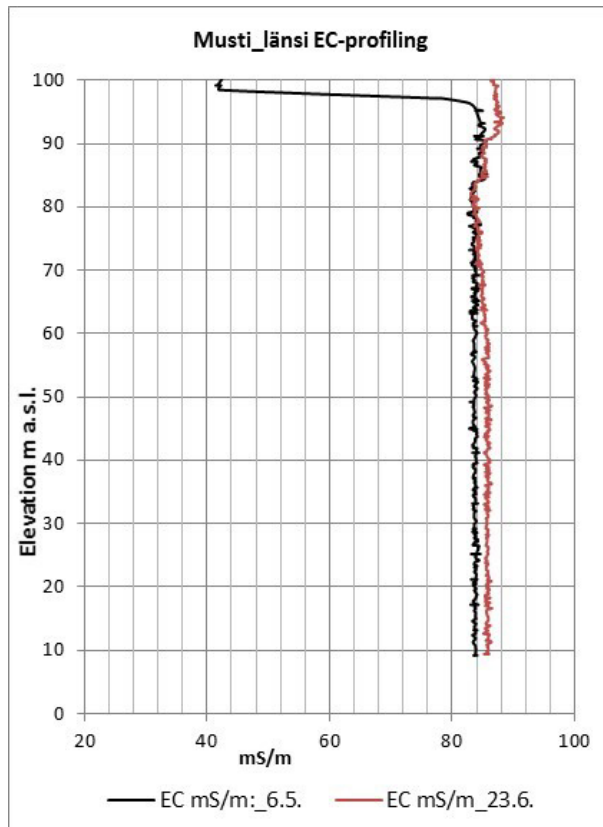
Figure 11. Electrical conductivity logs of groundwater from Musti_länsi coring.

exposure during periods of groundwater surface decline. The divers remained submerged in most wells, but close to the open pit, where fast and large changes in groundwater surface were detected, the divers were exposed above the water numerous times.

The monitoring results show hydrogeologically different districts in the site. Fig. 12 and Fig. 13 illustrate hydrograph differences in the context of the site conceptual model for the open pit and tailings areas, respectively. Some wells are located in areas where normal seasonal variation is the dominant factor driving the change in the groundwater surface (see Fig. 12, hydrograph KA10 and Fig. 13, hydrograph KA18). In an open pit and tailings area (see Fig. 13, hydrograph VPP1) normal seasonal variation in the groundwater surface becomes obscured by fluctuations that are interpreted to reflect mining processes. In two wells close to the open pit (M1 and M6) the variation in groundwater level is large and abrupt (see Fig. 12, hydrograph M6). The variation was plotted against the blasting schedule at the open pit, but no correlation was evident. The reason for this may be that the blasting affects the groundwater surface only when it happens close to the well, but the source for these large variations remains undefined.
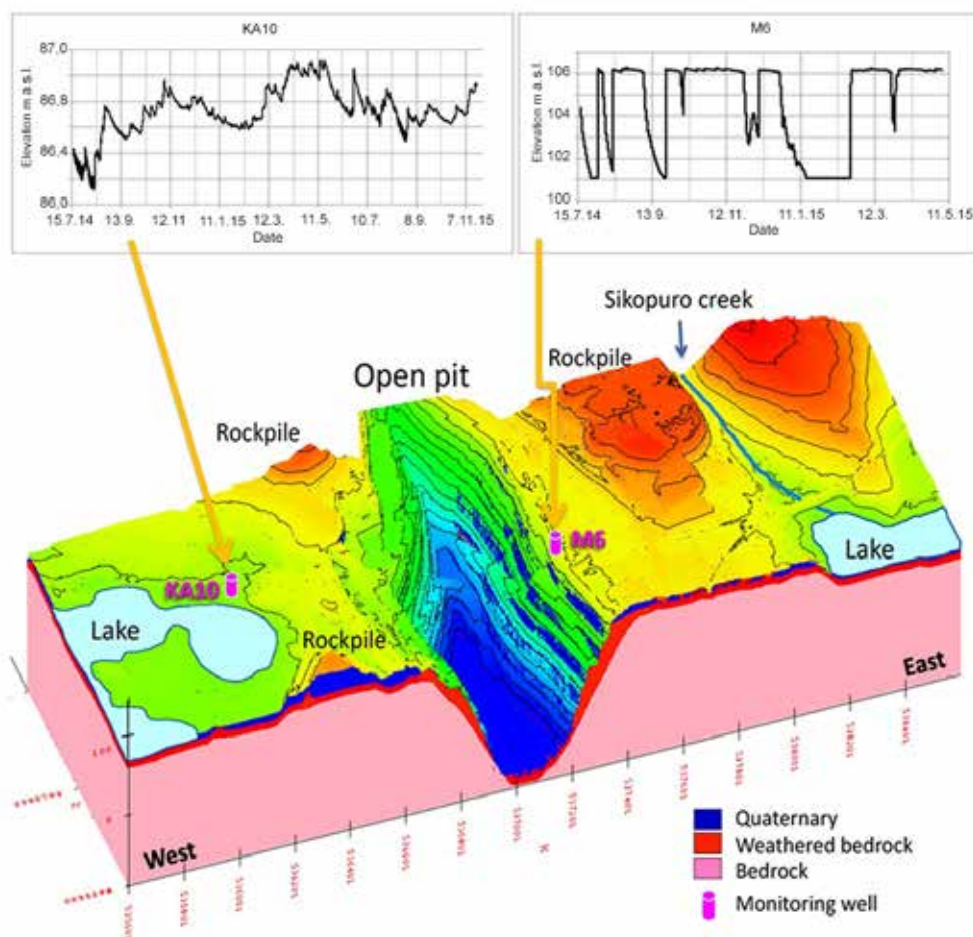
Figure 12. Location and graphs of water level in KA10 and M6 observation wells. The basemap show the geological model used in defining the geometry in ModFlow modelling at the Särkijärvi open pit area.
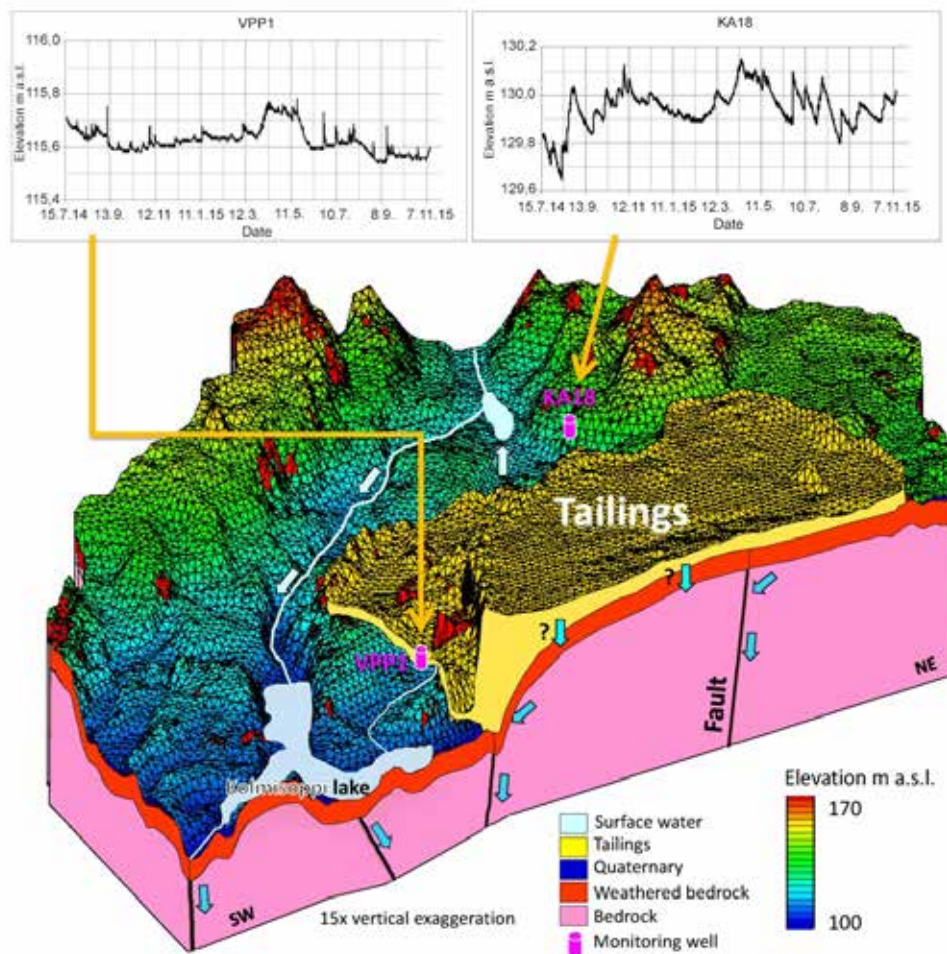
Figure 13. Location and graphs of water level in VPP1 and KA18 observation wells. The basemap show the geometry of the ModFlow model at Musti tailings pond area.

2.2 Surface water monitoring

Kirsti Krogerus, Tiia Vento

The Boliden Luikonlahti site is situated in the headwaters of the Vuoksi River basin. Surface waters from Luikonlahti tailings storage flow either northwest to Myllypuro stream on to the Petkellahti bay in Lake Retunen, or south to stream Kylmäpuro and on to the Luikonlahti bay. The waters from the tailings area discharge mainly to the stream Kylmäpuro.

The Yara Siilinjärvi site is situated at the headwaters of a drainage basin, too. Surface waters leaving the site flow in three different directions. Most of the mine site drainage flows to Kuuslahti Bay. Water from the western side of the tailings pond flows through Lake Kolmisoppi to Lake Siilinjärvi. Water from the eastern side of the tailings pond flows through Lake Saarinen to the Pajulahti Bay. These three waterways meet at Lake Juurusvesi.

Surface water monitoring data are obtained from both Yara Suomi Oy and from the automatic measurement stations of EHP-Tekniikka LTd, which were installed as part of this project. The mine operator monitors the mine-site water levels of most of the lakes and ponds, as well as the amount of water pumped in the process. Monitoring is required in order to be aware of the water quantities, regulate the storage ponds, and to make sure the environmental permits are fulfilled. The available data is catalogued in Table 4 in the appendix.

Online-measuring equipment for monitoring water level and discharge was installed in July, 2014 and used to supplement the measurements conducted by Boliden at the Luikonlahti site and by Yara at the Siilinjärvi site through the end of the project (Fig. 14 and Fig. 15) (Seppälä et al. 2016). There were altogether eight on line measuring stations, four at each site. The discharge was measured automatically based on water level from a V-notch weir, except in two places were the measurement was conducted from a pipe by ultrasonic technique.

Data were automatically sent to a data service (Pilvipalvelu) from where they could be accessed and transferred for processing. The data records were exploited in the calibration and operation of the water balance model at the Yara Siilinjärvi mine. Surface water data compiled from the Yara Siilinjärvi site included hourly water level values [m] for the Musti, Vesiallas, Raasio and Jaakonlampi ponds. Information about the pumped water quantity [m3/s] was available from the enrichment plant to Musti (approximately 50 % water and 50 % gangue), from Vesiallas to Raasio, from Jaakonlampi both to Sikopuro and back to the internal cycle, and from the open mine pit to Itäallas pond. Open pit pumping was measured as a cumulative monthly total. Seepage was also measured from Musti and Vesiallas with a small V-notch weir about once a month.

The snow densities and snow pack heights were measured at 11 locations in the mining area using a snow scale. The locations were selected such that they represent both forested and open-area snow accumulation, while still being easily accessible. Snow pack measurements were conducted twice during the winter of 2015, the latter around the time of the highest SWE values. The measurements were conducted by GTK field personnel who received the equipment and adequate training from the North Savo ELY Centre.

Weather data is not always measured at a mine site, and therefore either a measurement station should be installed or the data from the nearest weather station should be used.
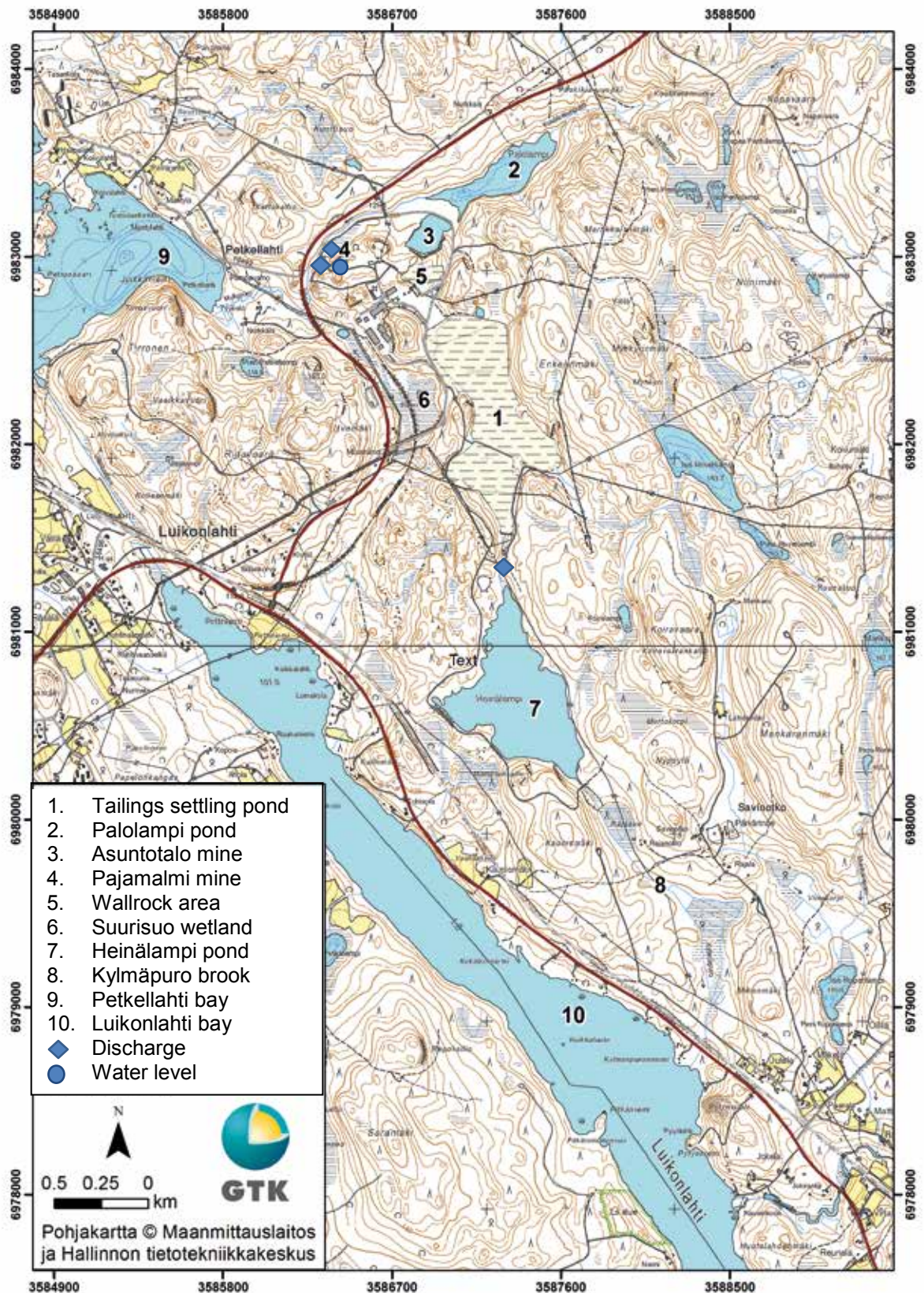
Figure 14. The position of on line measurements at Luikonlahti processing plant.

Legend:

1. Tailings settling pond
2. Palolampi pond
3. Asuntotalo mine
4. Pajamalmi mine
5. Wallrock area
6. Suurisuo wetland
7. Heinälampi pond
8. Kylmäpuro brook
9. Petkellahti bay
10. Luikonlahti bay
◆ Discharge
● Water level

0.5 0.25 0 km

Pohjakartta © Maanmittauslaitos
ja Hallinnon tietotekniikkakeskus
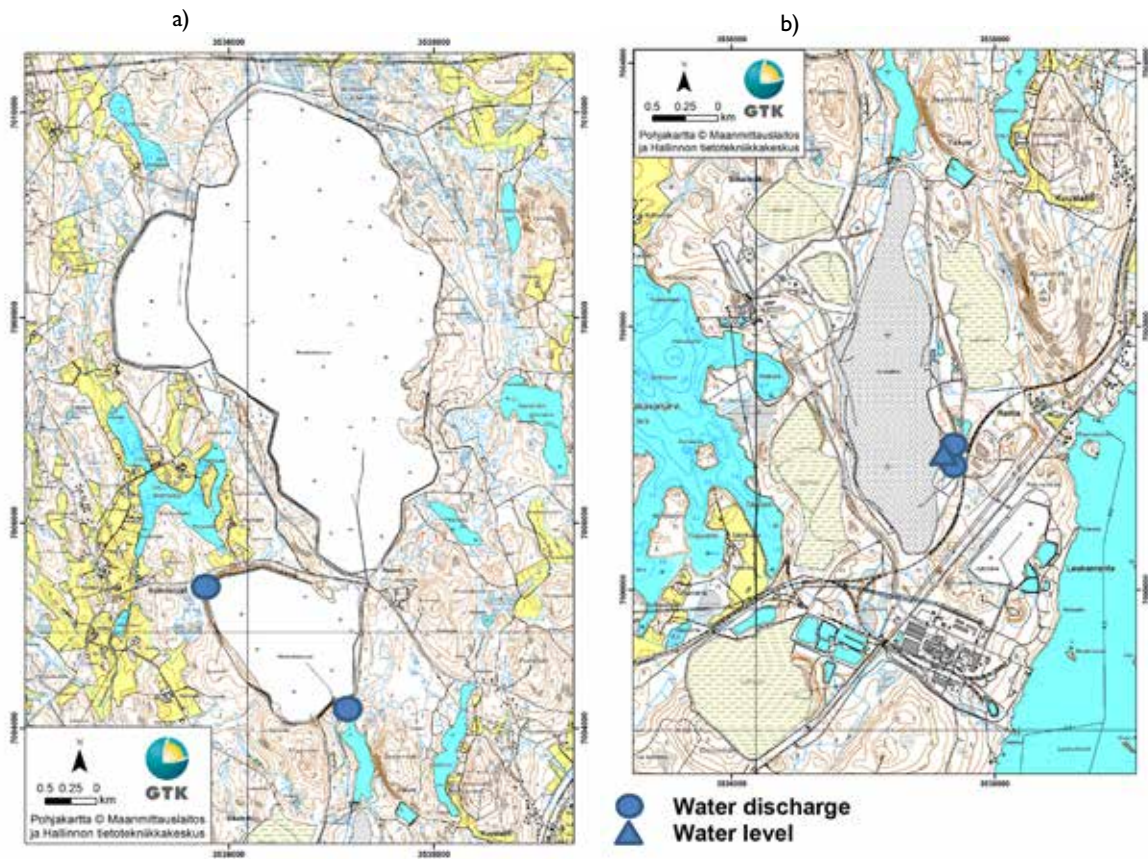
Figure 15. The position of online measurements at Siilinjärvi mine site, a) Northern part, b) Southern part.

2.3 Proposal for improvements in measurements

Kirsti Krogerus, Antti Pasanen, Arto Pullinen

2.3.1 Groundwater measurements

The geophysical and geological methods used in the study of groundwater management are well known and major improvements are not expected soon. However, some minor improvements that could provide new insights to the study of aquifers are already in testing.

Direct measurement of hydraulic conductivity of an aquifer is possible with the MRS (Magnetic Resonance Sounding) method. This could compliment hydraulic testing in areas and cases where drilling is impossible or too expensive. The method is limited to areas where the electrical conductivity of the ground is low.

Indirect measurements are currently mostly done in 2D, or in the best cases 2.5D, whereas 3D measurements would provide much more information relevant to improving groundwater system understanding. Aerogeophysical 3D methods are already available and would be extremely valuable for covering large areas. One of these methods is SkyTEM. Land based 3D measurements are always more difficult to perform than airborne methods. Even though the time, effort and money spent is higher than in 2D, it is always worth considering. The 3D-ERT method is currently in testing. Measurements can already be performed with commercial equipment but the inversion modelling is still under development.

In the literature tens of hydraulic measurement methods and their variations can be found. The methodologies and analytical methods for calculating the hydraulic parameters are well known, but improvements can be made by testing these methodologies under local conditions to select the most suitable for each mine. Bedrock fractures, while largely not considered in water resource studies, can have a huge effect on a mine's water balance. To advance bedrock groundwater studies at mine sites reference studies need to be conducted and the industry and the authorities would need training.

Groundwater monitoring equipment is commercially available and the prices are getting lower. On-line monitoring connected with water balance modelling provides the biggest advantage. Through sufficiently dense monitoring, large and abrupt groundwater level changes close to the open pit were identified. This could not have been identified through periodic manual monitoring alone. The implications of these changes and the causes behind them still require further investigation.

2.3.2 Online monitoring of surface waters

Modern continuous water quantity, and level measurement solutions are reliable, and the measurements can be produced all year round. A prerequisite, however, is that the measurements are carried out correctly, using the most appropriate methods and equipment. Moreover, a skilled person must evaluate the measurement data with a critical eye. The suggestions below are discussed in Seppälä et al. (2016).

When purchasing online measurement equipment, it is necessary to use a professional designer who is familiar with online-measurement solutions. Still the provider should visit the mine site with the operator. The design of automatic continuous measurement stations should be based on a thorough consideration of site-specific data needs (maximum and minimum discharges, water levels, etc.). It is recommended that all the available monitoring data be analysed before installing new monitoring posts.

Freeze-up of sensors or measuring weirs is a significant problem during winter time. The best way to avoid this is by using recorder wells for the year-round flow measurements.

The power supply of the equipment, in particular in the winter, requires attention, and in the north this is especially important. Therefore, the station should be equipped with an energy source with greater capacity, or alternatively the measurement intervals and the frequency of result transmission must be reduced during the winter season. If there are barriers causing shade in front of the solar panels, the size of the panel or battery capacity must be increased. Alternatively, obstacles, such as shady tree cover can be removed.

Continuous monitoring equipment always requires follow-up after installation to verify functionality and regular maintenance. Maintenance needs can vary significantly depending on the quality of the water to be measured and the instrumentation. In addition, the condition of the equipment should be remotely monitored and, if necessary, additional maintenance visits should be made. As a general rule, automatic cleaning technology integrated into the sensor should be used in order to keep the sensors clean.

It is important that the personnel of the mine notify those who are in charge of the monitoring program of any changes which might have an effect on data quality. Changes may affect the measuring results and the need for maintenance of the equipment.

The hydrological data measured at the mine site should be stored in a database where it is easily available for water balance calculations. For real-time simulations, online measurements should be available from the most important positions on the mine sites.

3 Tools and development of water balance modelling

3.1 Groundwater flow models

Kimmo Hentinen, Clayton Larkins, Antti Pasanen

Groundwater modelling is somewhat underutilized in Finland and many other mining regions in the world with respect to mine water balances and water management considerations. Groundwater balances are often seen as a subject that do not need prior investigation, but which can be dealt with after the mine has been opened. After the mine opens, however, incorrect scaling of water control measures can result in substantial monetary losses. The simplified geological strata in Finland consists mainly of hard bedrock (Archean and Proterozoic) overlain by soft sediments consisting mainly of Pleistocene and Holocene glacial, sub-glacial and biogenic deposits. Groundwater studies and monitoring are usually conducted in soft sediments. Hard bedrock is often omitted from groundwater studies due to a lack of understanding of the hydrogeological conditions and methods to study them effectively.

The quarries in Finnish mines, both open cast and underground, are made in hard bedrock. Therefore, with regard to mine water management, the study of water in bedrock is extremely important. The groundwater in soft sediment, in many cases, has a low hydraulic conductivity, but can still be important in the water balance. In quarries the effect of soft sediment groundwater can be dealt with through technical solutions which divert the flow.

Hard bedrock can exhibit a large range of hydraulic properties. For example, the hydraulic conductivity can be almost insignificant in intact bedrock, while in fracture zones it can be very high, depending of the amount of fracturing. The flow is channelized in the fracture zones, but also separate joints and faults can act as significant routes for groundwater to the quarry. Groundwater can also interact with the surface water balance in other parts of the mining area through upwelling and sinking, while waste piles can change flow routes and directions.

Groundwater flow modelling coupled with surface water modelling allows for the whole mine site water balance to be modelled. The modelled results should be used to guide the design of mine site water balance control measures.

As part of the WaterSmart project the Yara Siilinjärvi and Boliden Luikonlahti sites were studied and modelled for groundwater flow to estimate the respective groundwater balances. At both mines the work concentrated on developing the groundwater flow models in hard bedrock, but the finished models also included soft sediments.

3.1.1 Modelling at Yara Suomi Oy, Siilinjärvi mine

Prior to the WaterSmart study the Yara Siilinjärvi site water balance had not been modelled. The objective of WaterSmart modelling was to develop a simple groundwater flow and water balance model for the mine area, with particular emphasis on the discharge of groundwater to the open pit, and impacts of mine expansion and dewatering on local water resources. Two separate modelling approaches were used. To evaluate water balance and discharge to the mine area modelling was conducted using The Finnish Environmental Institute's (SYKE) Hydrological Watershed Simulation and Forecasting System (WSFS) in combination with a 3D groundwater model developed in FEFLOW. Details on this approach are given in

Hentinen (2016). To characterize potential impacts of mine expansion and dewatering on local water resources the three-dimensional, finite-difference groundwater flow software, MODFLOW and the LAK package were utilized. Details on this approach are given in Luoma (2016).

3.1.1.1 Data

Data inputs for the FEFLOW model were from geophysical measurements conducted as part of the WaterSmart project, drill hole data provided by Yara Suomi Oy, surficial bedrock observations by GTK and the National Land Survey, water body depths provided by the National Land survey, and site-specific hydrogeologic properties derived from the literature. Geophysical data was used to interpolate bedrock surface and fracture zones, and generally aligned with data collected from the open pit by Yara Suomi Oy. The Yara Suomi Oy drill holes were used to measure groundwater levels, and from select drill holes, conduct slug tests. Watershed areas were defined by the Finnish Environmental Institute (SYKE).

For the MODFLOW model, percolation input data for groundwater recharge were received from SYKE, initial K-values were received from slug-tests performed as part of the WaterSmart project, as well as simulation results from Hentinen (2016). The final K-values were determined from model calibration. Bedrock fracture location and orientation data were utilized from the WaterSmart geophysical studies.

3.1.1.2 Conceptual model

The area modelled at the Yara Siilinjärvi site is bound by lakes, streams and wetlands on all sides (Fig. 16). The model vertical profile is from +187.5 to -100 m a.s.l. (15 m below the maximum depth of the open pit). The model is divided into two stratigraphic units; an upper soil unit and lower bedrock unit. Fractures shown in Fig. 16 are modelled as vertical fracture planes, extending from the bedrock surface to the bottom of the model.

To provide a comprehensive assessment of water balance both groundwater and surface water balances must be understood. The SYKE WSFS model was used to provide data on surface water balance, and groundwater recharge resulting from percolation. Percolation data from the WSFS model was incorporated into a 3D groundwater model created in FEFLOW via a one-way coupling to facilitate groundwater flow direction and flux modelling.

3.1.1.3 Numerical Model

The final Yara Siilinjärvi site FEFLOW model is an unconfined quasi-steady state model. Calibration was performed as a steady state and integrated into a transient model in which properties and parameters were not time-dependant. This approach was selected to account for poor model convergence observed in steady state simulations believed to result from the occurrence of very thin soil layers throughout the site.

The Siilinjärvi FEFLOW model area was approximately 6.5 x 14.7 km^2, with a depth profile ranging from +187 to -100 m a.s.l. The soil layer of the model was defined to have a minimum thickness of 0.5 m. Where bedrock outcrops, the upper model layer was assigned bedrock properties. Boundary conditions were defined by linear interpolation across the site from fixed hydraulic head at surface water bodies. Where interpolated hydraulic head exceeds ground surface, it was corrected to match elevation. Extrapolation of this hydraulic head was generally consistent with average groundwater level observations from drill holes. Rivers, streams and the open pit were defined as seepage faces (points from which water can be removed from the model) when hydraulic head exceeded elevation. Otherwise, no flow through the top or bottom of the model was assumed to occur beyond these defined boundary conditions.
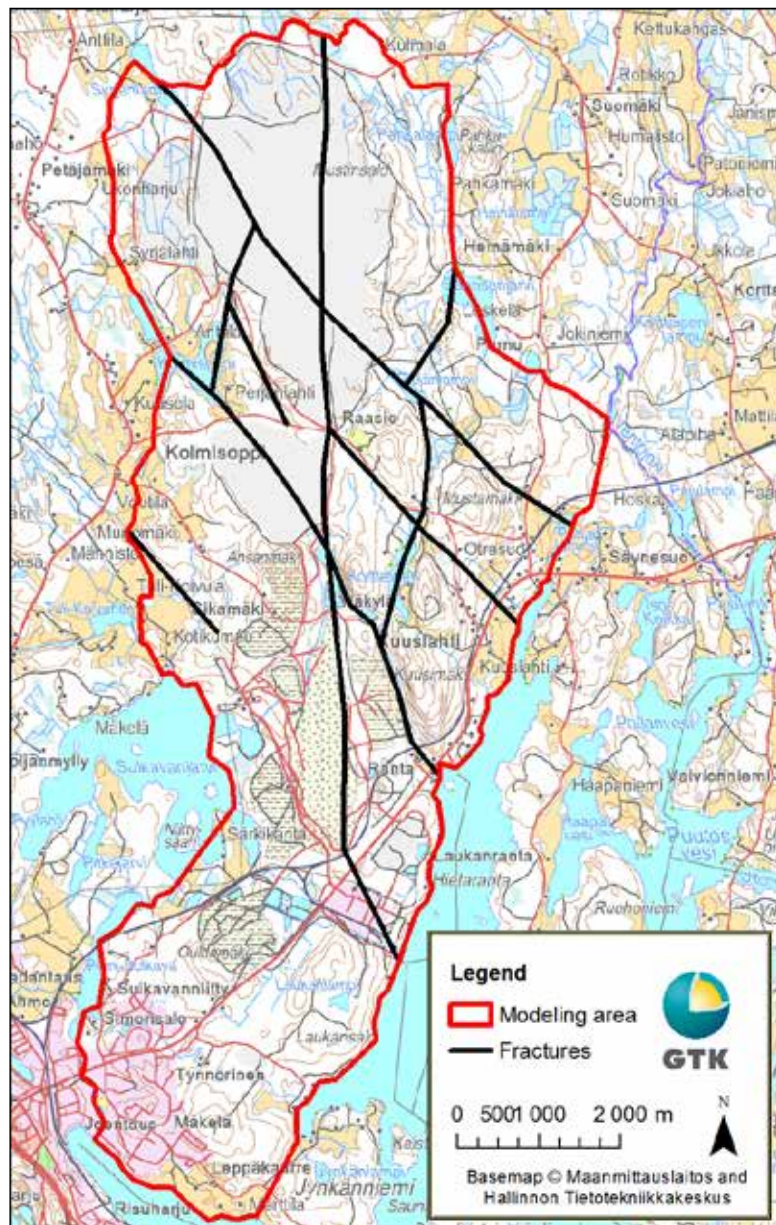
Figure 16. Siilinjärvi mine site modelling area and fracture lines.

The finite element mesh of the model is refined around fractures and the open pit. Fracture lines were defined as discrete 2D vertical high conductivity faces reaching from the bedrock surface to the bottom of the model, through which flow was defined according to Darcy's law. Fractures were divided into three groups; N-S, SE-NW, and Other N-S, as shown in Fig. 17. The hydraulic properties of each fracture group were initially set equal, and subsequently adjusted during model calibration. Hydraulic conductivity values across the soil element of the first layer were interpolated from on-site slug test results and refined during calibration. Recharge from precipitation to soil was estimated from a ten year average across each drainage basin determined using the WSFS model. Recharge was assumed to be 0 where bedrock meets the ground surface.

For the MODFLOW model the groundwater domain area was located in the subwatershed around the Särkijärvi open pit. The model boundaries are defined as 1) a no-flow boundary along the groundwater divide in bedrock in the northwest, east and
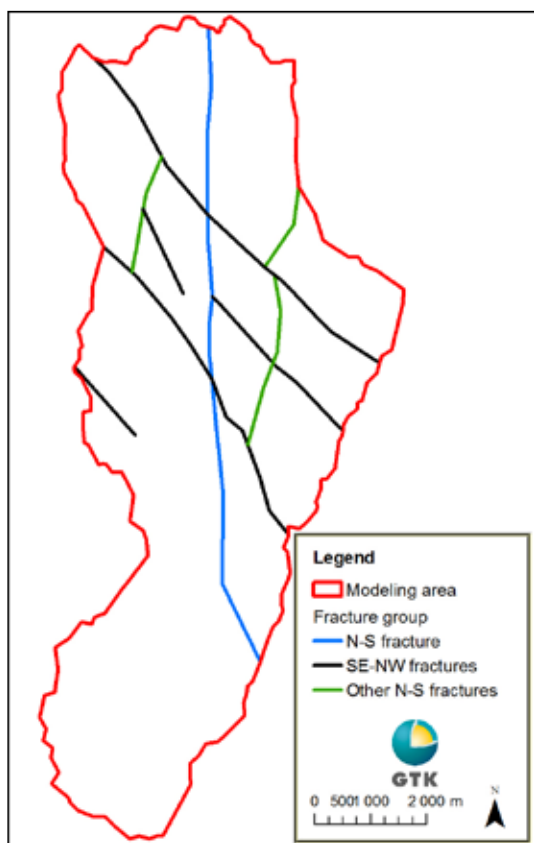
Figure 17. Fracture groups of the Siilinjärvi model.

south of the study area; 2) the constant head boundary along the lake shore lines in the west and southeast; and 3) the drains for all creeks and ditches in the model domain.

The model was divided into 5 layers, extending from +125 m a.s.l. to -120 m a.s.l., which covers the simulation of flow from the ground surface through the bottom of the present day open pit mine. The model domain consists of a thin overburden of Quaternary deposit and highly fractured, weathered bedrock. Thus, the first layer consists of overburden and fractured bedrock. The thickness of the first layer varied from the ground surface down to 50 m a.s.l. To prevent model convergence problems, layers 2 to 5 were horizontally divided from the bottom of layer 1 down to the bottom layer of the model domain. LiDAR survey data were used to define the topographic data of layer 1.

3.1.1.4 Calibration and Simulation

The Siilinjärvi model was calibrated with FEPEST, a PEST code integrated in FEFLOW. Model results were calibrated to the average observed groundwater levels measured from drill holes. Horizontal distribution of soil hydraulic conductivities were assigned based on a site soil raster map. As part of calibration, hydraulic conductivity in the z-direction was defined as 75% of that determined for the x-direction in order to account for reduced vertical conductivity related to the downward pressure of overburden. Based on the calibration, hydraulic conductivities across fractures were 0.74 m d^{-1}, 1.14 m d^{-1}, and 35.8 m d^{-1} in the N-S, SE-NW and Other N-S fracture systems, respectively. Projected soil conductivities did not always align with literature values, and constraining conductivities in both soil and bedrock layers resulted in unrealistic hydraulic head distributions. Therefore, proposed conductivity distributions in both soil and bedrock should be considered only indicative.

Flow rates in and out of the transient model are presented in table 5 in Appendix. Total flow rate into the model was greater than that out of the model due to storage

properties in the top model layer. Flow rates for the model surface, bedrock surface, and the bottom of the model are shown in Fig. 18.

In the MODFLOW and LAK Package simulation, the MODFLOW groundwater flow simulation under pre-open pit conditions was constructed and calibrated. Then, the open pit polygon area, which is defined as a lake, was added into the model domain using the LAK Package. The pumping rate for dewatering the excavation was assigned and adjusted using trial and error until the lake stage reached the target level at the bottom of the excavation pit. At the same time groundwater levels surrounding the open pit area were calibrated with the water levels from the monitoring wells and surface water levels (creeks and lake shoreline) in the modelling area. The water
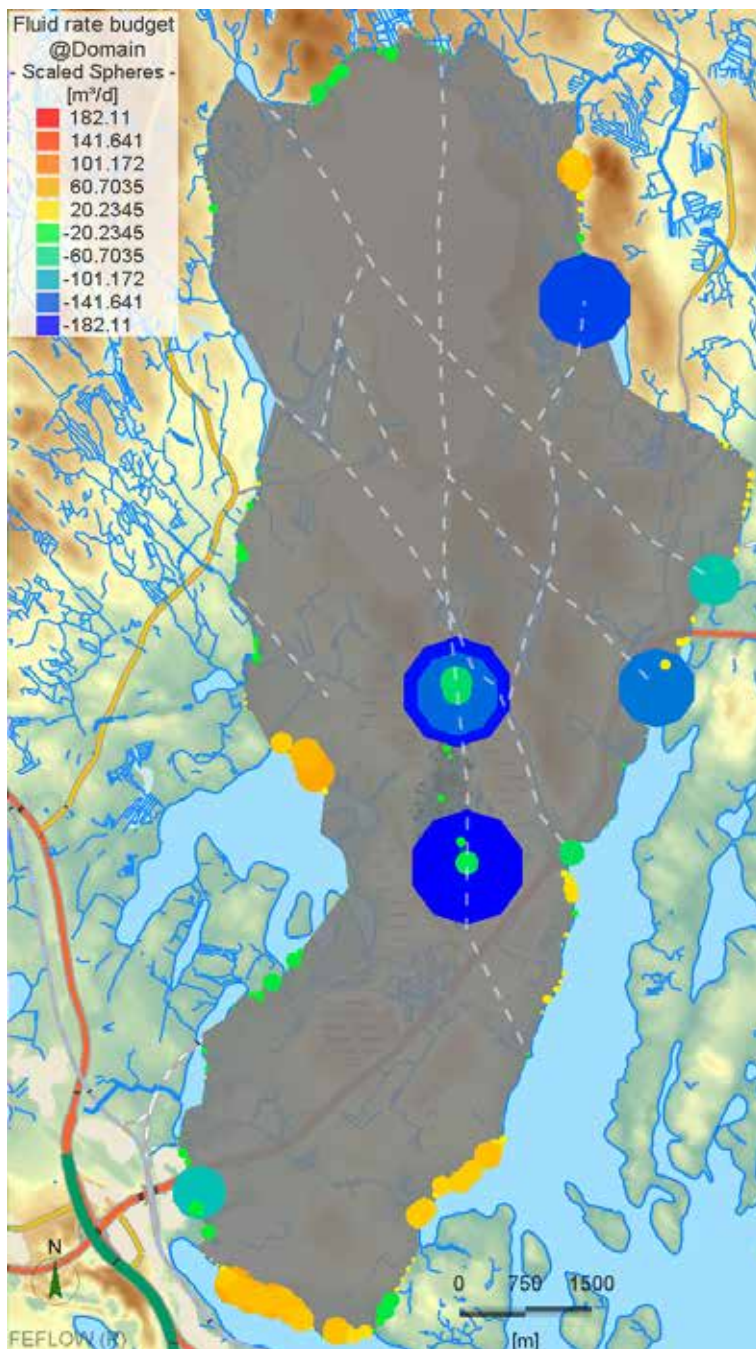
Figure 18. Modelled flow rates in and out of the Siilinjärvi model area by layer. Fractures in dashed lines. a) top of the Siilinjärvi site model. b) top of the bedrock. c) bottom of the model.

budget, a function of inflow and outflow resulting from head differences between the aquifer and the lake, was then calculated (Fig. 19). More details from the study are found in Luoma (2016).

3.1.1.5 Groundwater Surface Water Model Coupling

The water balance at the Yara Siilinjärvi site was modelled by coupling the WSFS, used to model surface water and part of the groundwater balance, with a 3D groundwater site model created in FEFLOW (see 3.2.1.3). The 10 year average for groundwater recharge for each basin within the Yara Siilinjärvi site was used to forecast percolation using the WSFS model. Percolation data was input to the FEFLOW model via a one-way coupling. Technical details on how the models were coupled are provided in Hentinen (2016). The percolation forecast was then used to model groundwater levels and fluxes in FEFLOW. The results of a preliminary 1 year simulation suggest that the coupled model responds correctly to changes in percolation.
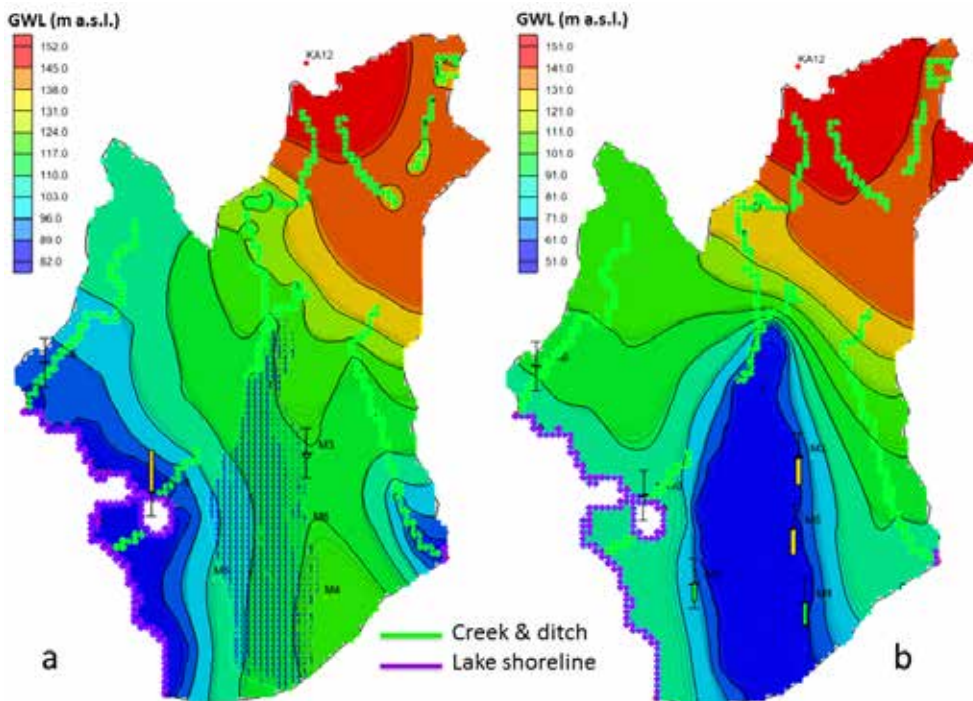
Figure 19. Simulated groundwater levels (GWL, m a.s.l.) before the open pit mine operation (a), and during the open pit mine at current situation, where the lowest level for open pit is approximately at -110 m a.s.l. (dark blue area) (b). In (a) the simulated groundwater level was calibrated with observed groundwater levels from wells around the open pit mine (KA6, KA10, M3 and KA12), which assumed to have no influence from the mine dewatering. In (b) simulated groundwater level during mine dewatering at current condition is represented with the pumping rate approximately 1200 m³/d, similar results with FeFlow modelling (Hentinen 2016) was observed.

3.1.2 Modelling at Boliden Kylylahti Oy, Luikonlahti closed multi-metal mine

Groundwater flow modelling at the Boliden Luikonlahti site was based on an earlier groundwater flow model produced as part of the MINERA project (Pasanen & Backnäs 2013). The enhanced modelling of the Luikonlahti site is described fully in Hentinen (2016).The objective of the modelling was to build a simple groundwater model and to study the groundwater balance in the area. The geological model was constructed in GSI3D (currently Subsurface viewer) as a 10 layer model and simplified to three layers for the flow model. The flow model was built and executed using the FEFLOW 6.1 software.

3.1.2.1 Data
The data used in the modelling consisted of airborne laser scanning data for accurate ground surface elevation, geophysical measurements (electrical resistivity tomography, refraction seismic, ground penetrating radar, self-potential measurement and Terra-TEM) and drill core records for bedrock topography and fracture zone locations, as well as the properties and internal structure of the soft sediments. Landscape analysis was also used in the interpretation alongside other methods. The initial values for hydraulic conductivities were defined from the literature (Airaksinen 1978, Mälkki 1999) and hydraulic slug tests from drill holes. Specific yield, storage and percolation were defined from literature review (Airaksinen 1978, Mälkki 1999, Mustonen 1986). The percolation was estimed from average precipitation for a 10 year period obtained from the Finnish Meteorological Institute. Groundwater levels were observed in 34 observation wells and used to define boundary conditions, as well as for model calibration.

3.1.2.2 Conceptual model
The horizontal modelling domain is presented in Fig. 20, and covers the whole mining area, including the water runoff routes. The area used is the same as in the MINERA project (Pasanen & Backnäs 2013). In the vertical direction the model extends from 0 m a.s.l. to ground surface. It is divided into two units: bedrock and soft sediments. Soft sediments in the modelling area are relatively shallow and considered as one unit, but horizontal variability in the hydraulic properties of soft sediments is taken into account. While characterization methods provided good information on fracture zone distribution, the spatial coverage of bedrock observation wells was not sufficient to provide hydraulic characteristics of the fracture zones across the modelling area. Subsequently, the fracture zones are modelled as vertical high conductivity zones extending from the bottom of the model to the bedrock surface using discrete elements in FEFLOW(r).

3.1.2.3 Numerical model
The model used at the Boliden Luikonlahti site is mathematically an unconfined groundwater system. The final model is quasi steady-state such that while the model is transient, the parameters are time-independent. This approach was selected to facilitate simulation convergence. Difficulties in convergence were encountered during steady-state simulations, which were attributed to very low soil thickness in multiple locations.

The modelling domain is 4.2 km x 5.7 km x 100 m (E-W x N-S x top-bottom) and vertically the model is numerically divided to two layers, bedrock and soil. In areas where bedrock outcrops at ground surface the first layer is assigned properties of the bedrock layer. In addition to the two layer model, the interpreted fractures are modelled as FEFLOW(r)'s Discrete Features. The mesh for the model was redefined
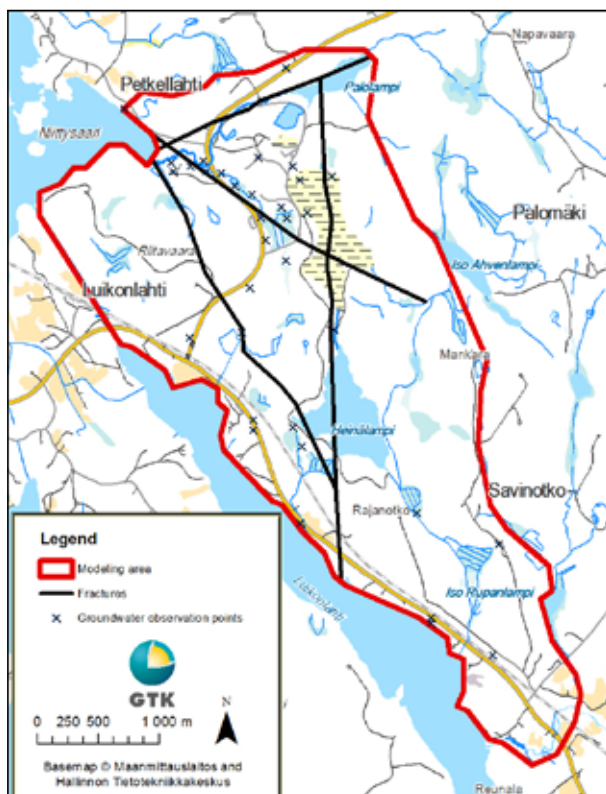
Figure 20. Luikonlahti mine site modelling area and fracture lines.

close to the fracture lines to model the fractures more accurately. 2D high hydraulic conductivity faces are defined inside the bedrock layer from the fracture lines.

Boundary conditions along the western side of the model area were set based on the elevation of the water bodies in and next to the modelling area. Eastern and southern boundaries were set 1 m below ground level, and a no flow boundary condition was assumed along the northern boundary (Fig. 21). Also at the bottom of the model a no flow boundary condition was set. The main streams and rivers at the top of the model are modelled as drains.

The material properties are assigned separately for bedrock and soil. The hydraulic conductivity distribution is assigned by interpolating the slug test results, except for sand areas where a hydraulic conductivity of 15 m d^{-1} is used. The recharge to groundwater from precipitation is assumed to be 13% (Mustonen 1986). The fracture properties were modelled using Darcy's law, for which the width of the fractures were interpreted from the geophysical measurements (Pasanen & Backnäs 2013). Fracture hydraulic conductivity values were based on previous studies and set to 30 m d^{-1} for north-south oriented fractures and 300 m d^{-1} for other fractures. Fracture hydraulic conductivities were adjusted during model calibration.

3.1.2.4 Calibration and simulations

The model was calibrated using the FEPEST, a PEST-code integrated in FEFLOW. A pilot point method using 58 fixed points was applied to calibrate the modelled hydraulic head values to observed values by adjusting material hydraulic conductivity parameters. A 10 year simulation was performed by using the calibrated quasi steady-state model. Total modelled input is slightly greater than modelled output from the area due to transient storage conditions in the top layer of the model (Table 6 in Appendix). Modelled flow rates are depicted in Figure 22 for the top of the model, top of bedrock, and from the bottom of the model.
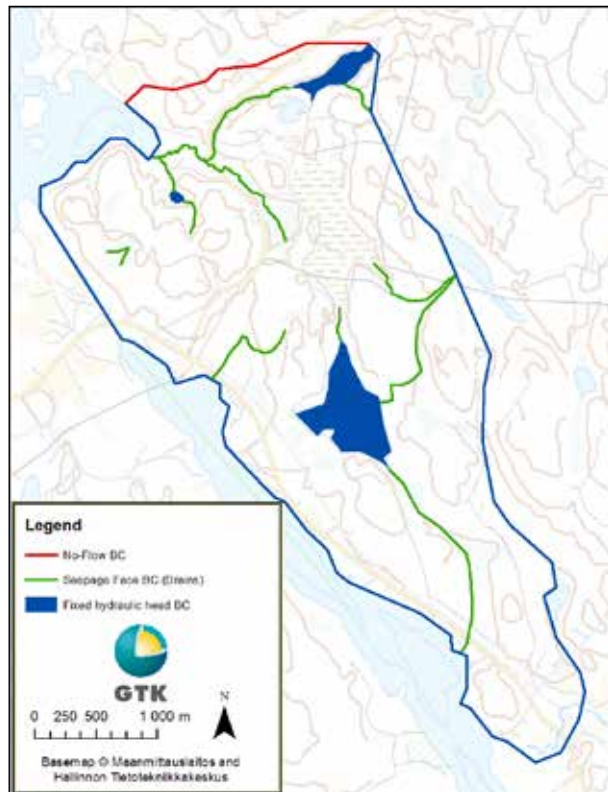
Figure 21. Luikonlahti model boundary conditions.

3.1.3 Proposal for improvements in groundwater flow modelling

Numerical complexity in both Siilinjärvi and Luikonlahti models is attributed primarily to variability in soil thickness across these sites. At both sites soil is sporadically very shallow and in some locations, absent entirely. The variability in soil depth combined with the distinct difference in hydraulic conductivity between bedrock and soil complicates models that provide consideration for these materials separately. An additional source of uncertainty in model inputs at both sites is the hydraulic properties of fracture zones. While increased data collection regarding bedrock fracture systems will likely improve the accuracy of model simulations, it is not likely to be cost effective to collect sufficient data to significantly improve the uncertainty introduced by the influence of shallow soils.

The current model approach does not provide results sufficiently accurate to facilitate two-way coupling between surface and groundwater models. Accordingly, alternative modelling approaches should be considered. Because surface water likely has a greater influence on site-wide water balance than groundwater in areas with high precipitation and multiple water bodies, the SYKE WSFS model provides a good option for water balance modelling.
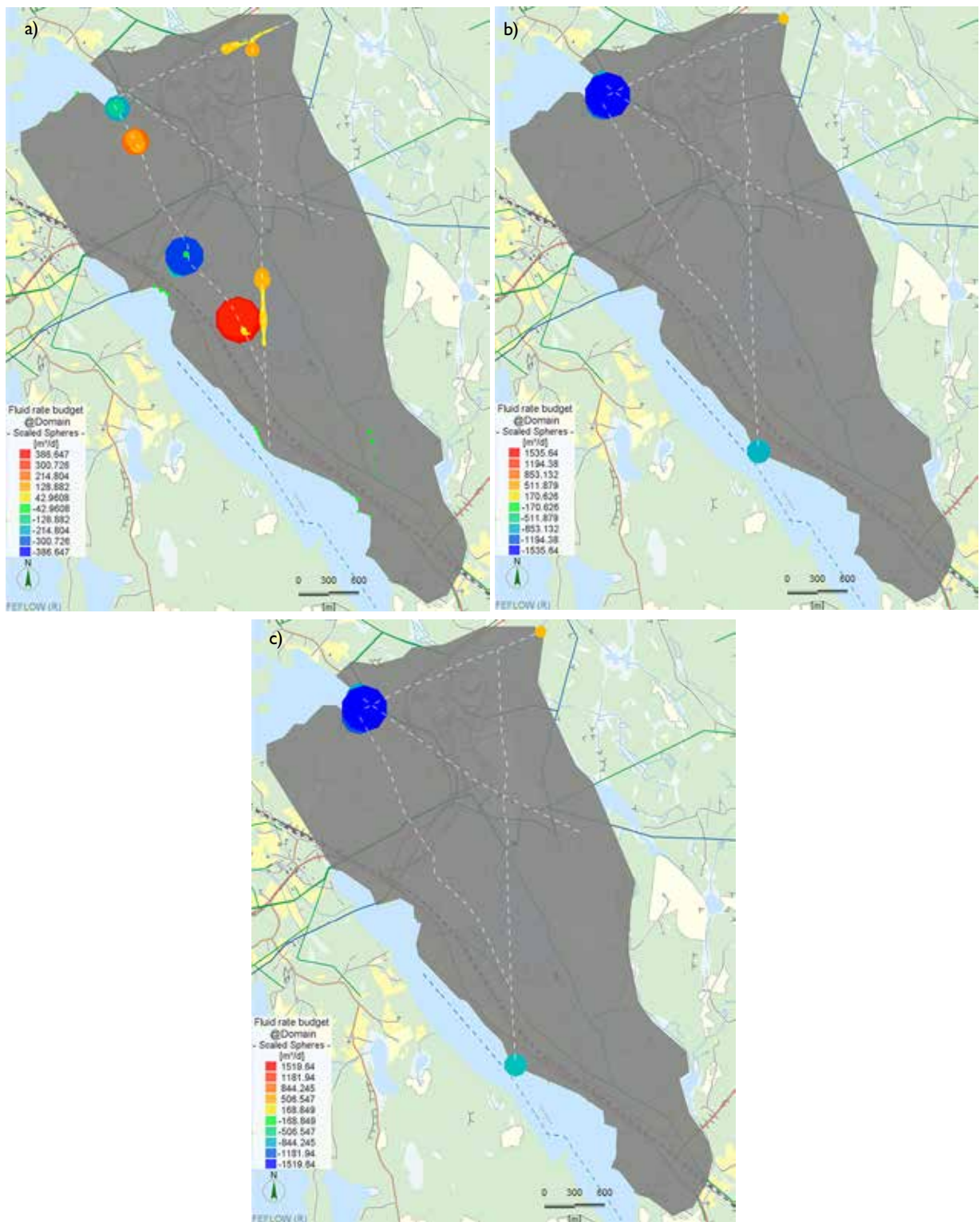
Figure 22. Flow rates in and out of the Luikonlahti model by layer. Fractures in dashed line, a) top of model, b) top of bedrock and c) bottom of the Luikonlahti model.

3.2 Water balance model for Yara Siilinjärvi mine site

Vesa Kolhinen, Tiia Vento, Juho Jakkila, Markus Huttunen, Marie Korppoo, Bertel Vehviläinen

3.2.1 Description of the hydrological simulation model

The Watershed Simulation and Forecasting System (WSFS) developed in the Finnish Environment Institute (SYKE) monitors and forecasts the water levels and discharge of lakes and rivers in real-time. The WSFS is the main tool in national flood forecasting, and it has been used for operational water quality modelling as well as climate change research (Vehviläinen 1992, 1994, 2000, Veijalainen 2012). A number of hydrological variables such as areal precipitation, evaporation, runoff, soil moisture, groundwater storage, and snow pack, etc. are simulated for all catchments in Finland. A wide range of hydrological and meteorological observations are utilized in the operation of the model system. The WSFS was modified to simulate and forecast water balances – both natural and industrial – at the Yara Siilinjärvi site. This section introduces the key ideas of the WSFS and the hydrological model and then explains the modifications for the mining environment.

3.2.1.1 Data
The data was retrieved from the mine management system by the mine operator about once a month and sent to SYKE in excel format (Table 4 in the appendix). The hourly data was processed into daily average values, checked for quality, and then integrated into the modelling system. No real-time data – needed for the automatic update procedure of the WSFS – was available by the operator. However, the continuous measurement data from the in situ devices installed by this project were automatically retrieved and processed into the modelling system.

3.2.1.2 The hydrological model
The hydrological model of the WSFS is a conceptual semi-distributed hydrological rainfall-runoff model. The WSFS was developed in SYKE in the 1980s (Vehviläinen 1992, 1994, 2000). The hydrological model simulates the following components of the hydrological cycle: snow accumulation and melt, infiltration, soil moisture, evapotranspiration and two components of flow – sub-surface flow and base flow (Fig. 23). Daily temperature, precipitation and potential evaporation values are needed as model inputs. Snow accumulation and melt are simulated by a degree-day approach, which assumes that below a threshold air temperature precipitation accumulates as snow. Snow accumulation and melt are simulated separately for open and forested areas.

The soil water is stored in three storages – soil moisture storage, upper water storage and groundwater storage. Two components of flow with different delays in response are formed from the last two storages. Water balance for all three storages is calculated for each time step (1 day). Snowmelt or rainfall infiltrate and increase the soil moisture and the upper water storages. The division of flow into soil moisture storage and upper water storage depends on the relative soil moisture. Soil moisture storage is filled by snowmelt or precipitation and emptied by evapotranspiration and infiltration to the upper water storage, which produces sub-surface flow and percolation to the groundwater.

The daily actual evapotranspiration is simulated by an empirical formula depending on potential evaporation and soil moisture storage. Class-A pan observations are used as potential evaporation in calculations of the actual evapotranspiration. If observations are not available, potential evaporation is calculated by an empirical formula depending on temperature and precipitation.
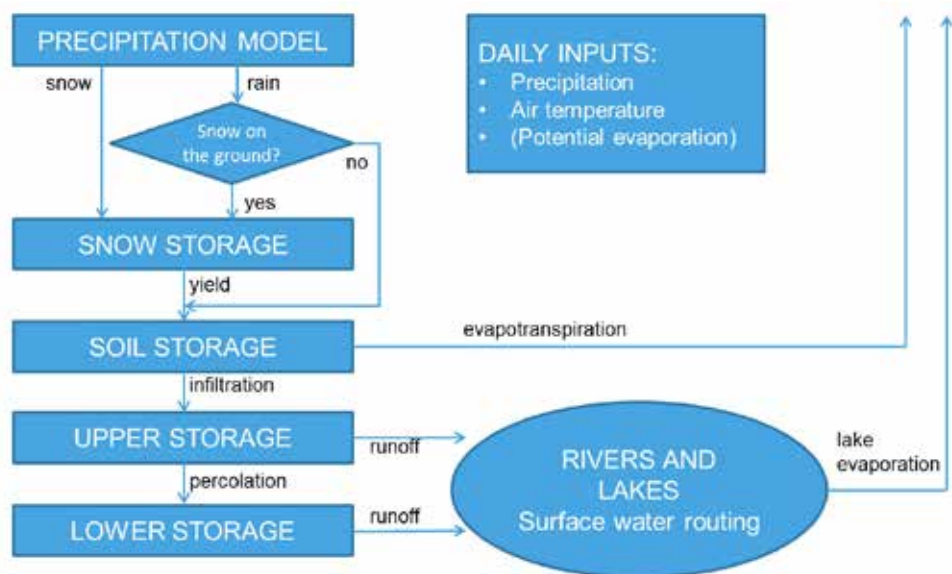
Figure 23. Schematic presentation of the WSFS hydrological model.

A water balance is calculated for each water storage. Components of the flow are dependent on the amount of water stored in upper and groundwater storages and the calibrated response coefficients. Percolation depends on the water amount in the upper storage and the calibrated percolation coefficient.

Data records of air temperature and precipitation are used as model inputs. Real-time meteorological forecasts from FMI and the European Centre for Medium-Range Weather Forecasts (ECMWF) are applied to provide daily hydrological forecasts throughout Finland. Weather radar observations can produce a precipitation forecast for the next three hours as it can track areas of rain approaching the simulated area. The weather radar accumulation data is illustrated in Fig. 24. Furthermore, weather data from the last 50 years is used to produce a long-term climatological forecast. These observations and weather forecasts are received, read and assimilated automatically into the system. The WSFS also includes a correction model which corrects model inputs (precipitation and temperature) in order to get hydrological quantities (discharge and water level) to better fit the hydrological observations. As temperature and precipitation observations might not be representative for large areas, this method corrects the model state in order to ensure the best possible initial condition for the model on the forecast day. All these data and forecast retrieval systems, as well as the correction model, are fully automatic.

3.2.1.3 Development of Siilinjärvi mine water balance model

The Siilinjärvi model is a modified version of the WSFS. All hydrological process models that simulate the water balance are the same as in the nationwide operational model. Most of the data assimilation routines are also the same. The most crucial part in building the model is the watershed description, i.e. determining the water basins and water flow directions (Fig. 25). This was established by using elevation data, public maps and the expertise of hydrologists in SYKE and local mine personnel. The division into basins was made for the mining area as well as some of the immediate mine surroundings. GIS information consisting of basin areas and locations, outlets, streams, lakes and ponds was derived with the help of a Finnish watershed database available to SYKE. The meteorological data, such as temperature, precipitation and snow depth are available via FMI from the meteorological measurement stations located nearby. On-site snow depth and density measurements conducted during the

24 hour precipitation sum (mm) UTC 201602231200.
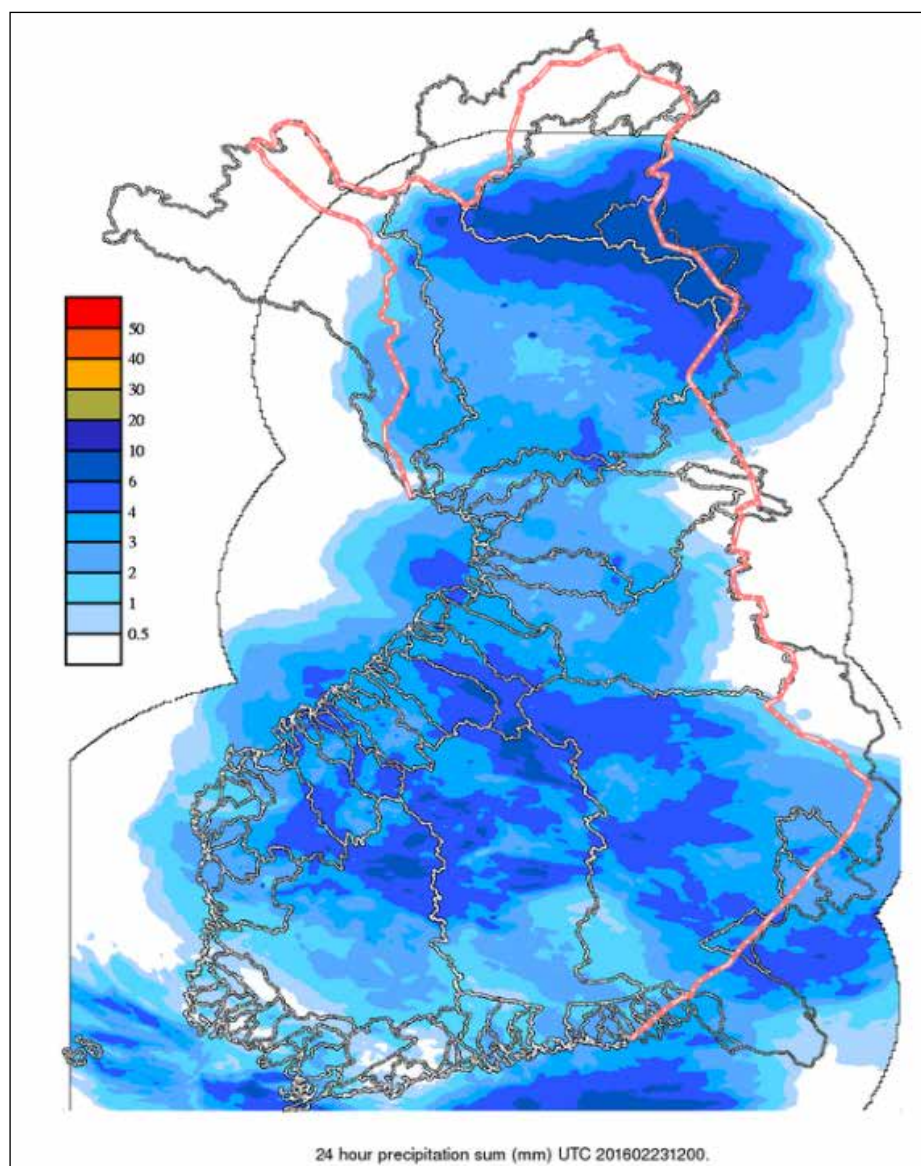
Figure 24. Precipitation sum of 24 hour weather radar observations.

project by SYKE and GTK were included in the model. The mine-site hydrological observations, described further in Section 2.2 were also exploited.

The Yara Siilinjärvi site was divided into 28 sub-catchments, most of which contain one lake or pond (Fig. 25). The hydrological model describes water balance and flow in the area for each pond. The main ponds of interest are the Musti tailings pond, as well as the Vesiallas, Raasio and Jaakonlampi ponds. The water balance of the open mining pit, and Itäallas (east pool) into which water is pumped from the open pit, are also included in the model.

The hydrological model uses daily meteorological observations and forecasts to simulate precipitation (either liquid or solid), evaporation and percolation to the groundwater. The runoff model describes the water flow from the ground area into lakes, and the discharge model describes the water flow from one lake to another.

Operation of the model is explained later in the section "The operating system of WSFS" (see chapter 4.1). Simulated results are available both as figures and numerical data. All the above-mentioned variables are obtained for each pond and they are presented in figures, as shown in Fig. 26. Numerical data can also be exported into

other systems. For example the numerical values of simulated percolation were provided to GTK to be used as an input to their groundwater model (Fig. 27) (see chapter 3.1.1.5).
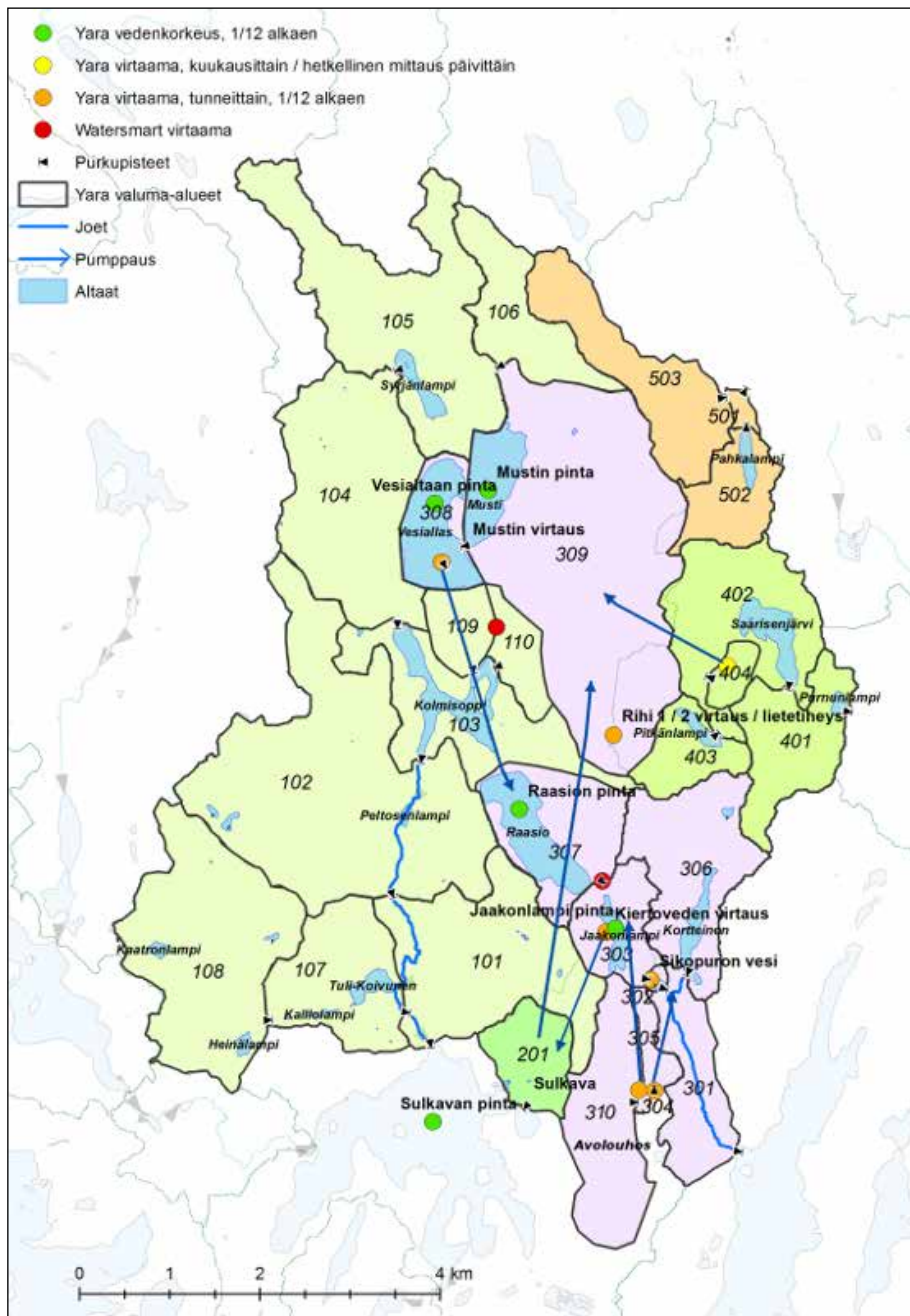
Figure 25. Water basin areas and monitoring places in Yara Siilinjärvi site. Most important areas of interest are Musti tailing area (309), Vesiallas (308), Raasio pond (307) and Jaakonlampi (303). Water from mining area is pumped through Itäallas (304). Open pit (Avolouhos) (310) was also modelled to estimate pumping needs. Pumping lines are marked with blue arrows.
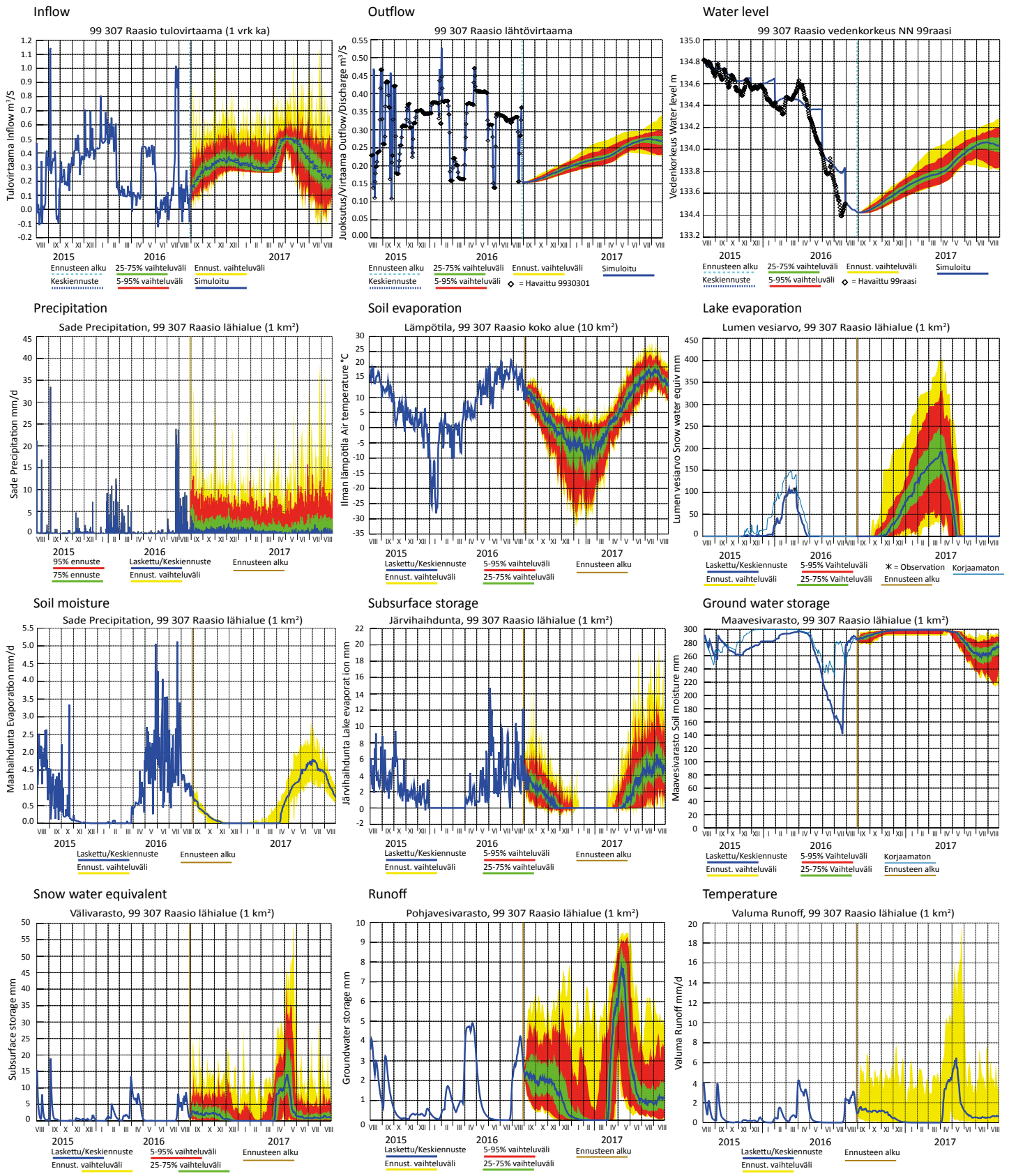
Figure 26. Set of images produced for each area (pond). Images are (top row): outflow, inflow, water level, (second row) precipitation, soil evaporation, lake evaporation, (third row) soil moisture, subsurface storage, ground water storage, (bottom row) snow water equivalent, runoff, temperature.
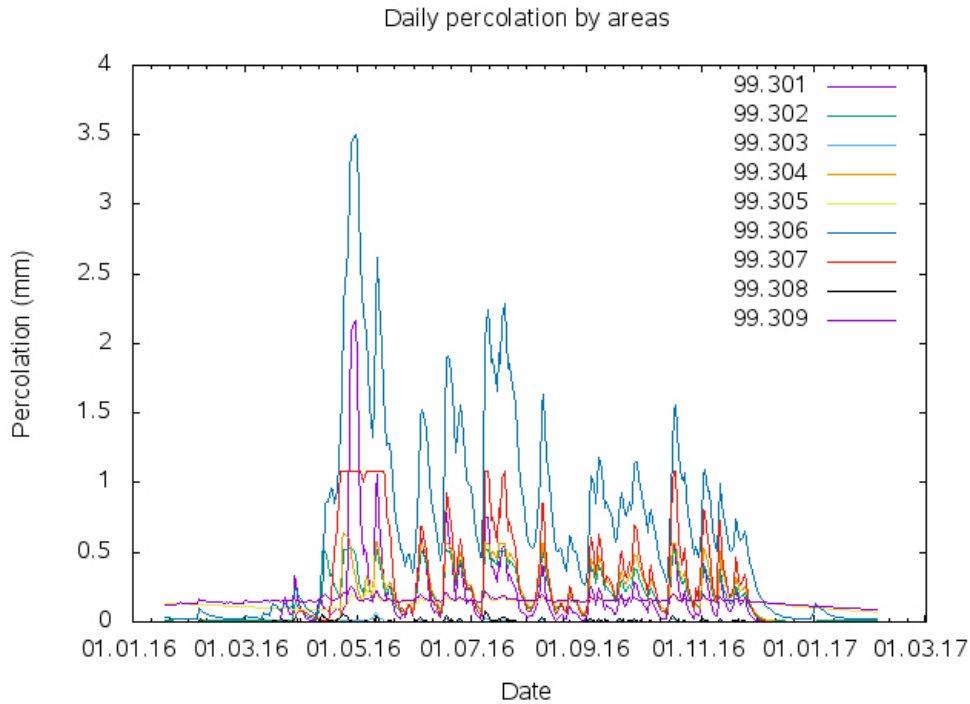
Figure 27. Simulated daily percolation by area (see map in Figure 3) for selected basins. Simulated percolation is used as an input for GTK ground moisture model.

3.2.2 Extensions of the model

Several additional sub models are available for the WSFS mine-site model. A two-layer soil moisture model, which provides a better description for soil moisture and percolation, was included in the Yara Siilinjärvi area. A transport model of substances is currently used in the WSFS model for all of Finland, but is not implemented at the Yara Siilinjärvi site. Moreover, a high temporal resolution model which uses a one-hour time step in the simulation (compared to the one-day time step currently used) is being tested in other areas, but is not yet implemented here either.

3.2.2.1 Two-layer distributed soil moisture model
A two-layer soil moisture model (Jakkila et al. 2014) is used in the Yara Siilinjärvi site model to obtain a better areal resolution for simulation of soil moisture and percolation to the groundwater storage. In the two-layer model, soil is divided into surface (10 cm) and sub-surface (80 cm) layers. The model requires spatial distribution of the soil properties, specifically soil porosity and field capacity, in both layers from the mine site. The data was obtained from the Finnish Soil Database (Lilja et al. 2009) and the distribution of soils is shown in Fig. 28. The benefits of the two-layer model compared to the original HBV-based model are the more detailed areal variation of the soil moisture, percolation, and evaporation. In addition, the possible soil moisture observations from the mine site could easily be compared with the simulation of the two layer model.

The result of the surface and sub-surface soil moisture simulation and forecast are shown in Fig. 29. During the winter soil moisture is typically close to saturation, when the ground is frozen. In the summer the surface layer soil moisture may decrease to half of the saturation moisture content since most water evaporation occurs from the surface layer. The sub-surface layer responds more slowly to precipitation events and dry periods. The simulation of precipitation and runoff in Fig. 30 shows how the soil moisture affects the runoff peaks. In summertime the soil is dry, as large precipitation

events cause smaller runoff peaks than in autumn or winter when the soil is close to saturation. As can be seen in Fig. 31, which shows the differences in soil moisture by soil type, soil moisture is highest in areas covered by soils with large water retention capacity.

3.2.2.2 Transport of substances in and from the mining area

In estimating the effects of metals in the watershed downstream from a mining site, it is essential to simulate the transport and fate of metals in the network of rivers and lakes. VEMALA is an operational, national-scale hydrological model for Finnish watersheds (Huttunen et al., 2016). It is further developed from WSFS model, and it simulates the hydrological cycle together with nutrient processes (total nitrogen, total phosphorus and total organic carbon (TOC)), leaching and transport on land, and in rivers and lakes. VEMALA can also simulate the travel of inert metals through the river/lake network of Finland. It was utilized following the Talvivaara gypsum sedimentary pond leakage in November 2012 both for retrospective and prognostic assessment purposes.

VEMALA can provide the BLM (Biotic Ligand Model) with an estimate of the dissolved metals concentrations (zinc, nickel and copper) in the watershed downstream from a mining site in order to understand the impact of a leak on the environment and the extent of the affected area. This will first be tested in an ongoing project: Multiple lines of evidence in assessing ecotoxicological and human health risks of mine effluents and public perception - MINEVIEW led by the University of Jyväskylä (https://www.jyu.fi/bioenv/en/divisions/ymp/research/mineview). In addition, the BLM model requires pH, dissolved organic carbon (DOC) and calcium in order to simulate the bio-available proportions of zinc, nickel and copper in the water. The main processes affecting the transport of heavy metals should also be modelled, i.e. assimilation by algae, precipitation/dissolution, and sedimentation/re-suspension,
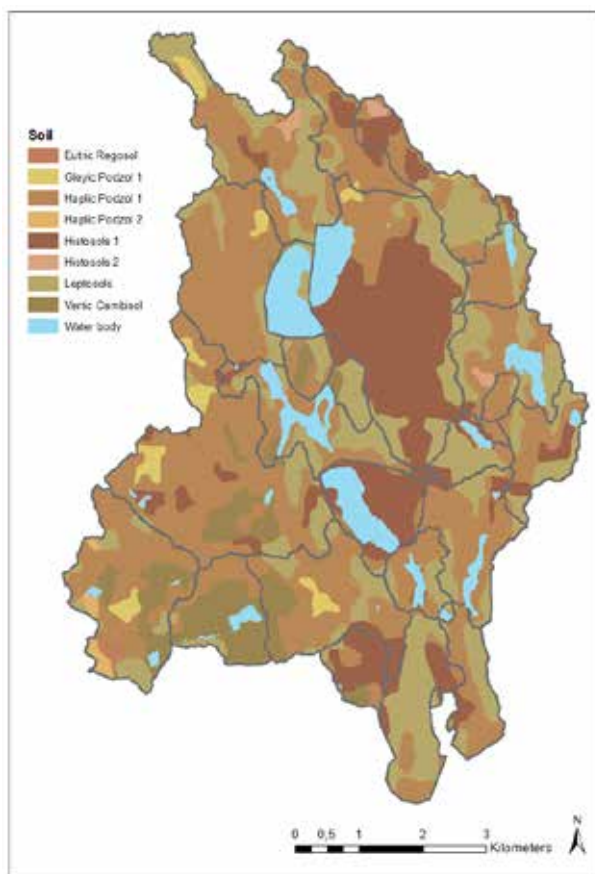
Figure 28. Distribution of soils in Siilinjärvi mining area. The area is characterized by till (Podzols) and rock soils (Leptosols).

depending on the metal and the state of the environment (pH, temperature, and wind, etc.). The VEMALA model will be tested on two mine sites (Pyhäsälmi and Talvivaara) over the course of the project. The simulation of pH, based on the concentrations of TOC, calcium, magnesium, sodium, potassium and sulphate (Kortelainen et al., 1989), was successfully added to the VEMALA model in December 2015 for the purpose of the MINEVIEW project.
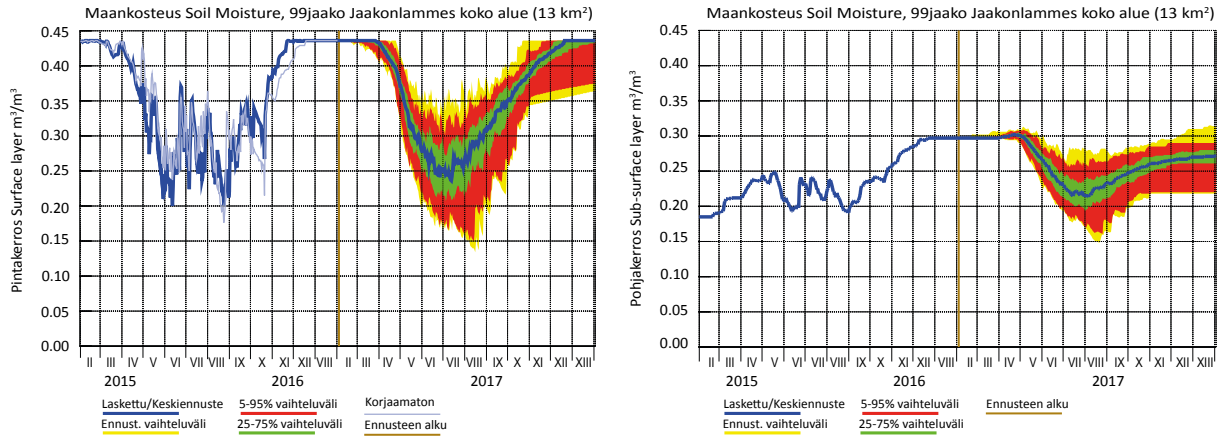
Figure 29. Mean soil moisture content from 7/2015 to 11/2016 as simulated by the two-layer model for the area upstream of Jaakonlampi. Variation of the upper layer soil moisture content (on the left) is much larger than that of the lower soil layer.
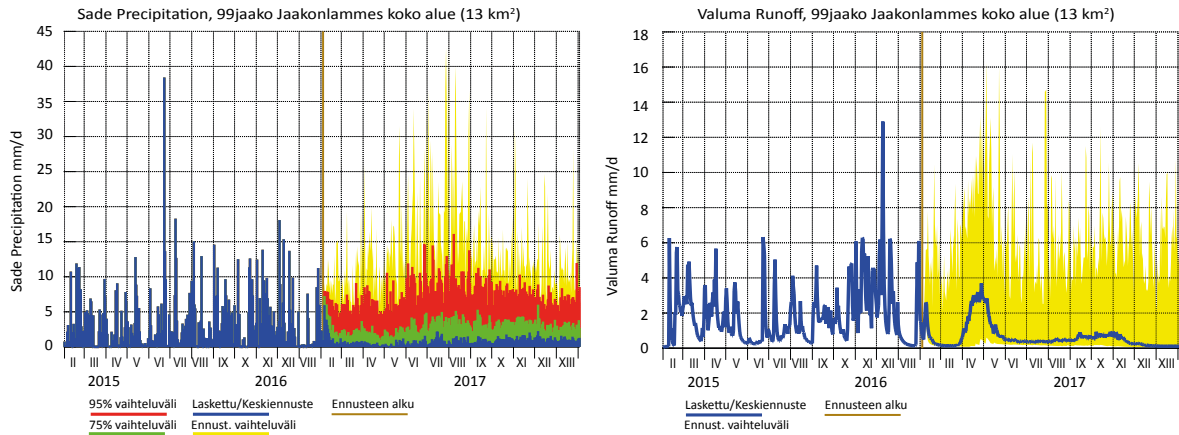
Figure 30. The areal mean precipitation (on the left) and runoff (on the right) simulation and forecast in the Yara mine site by the two-layer model.
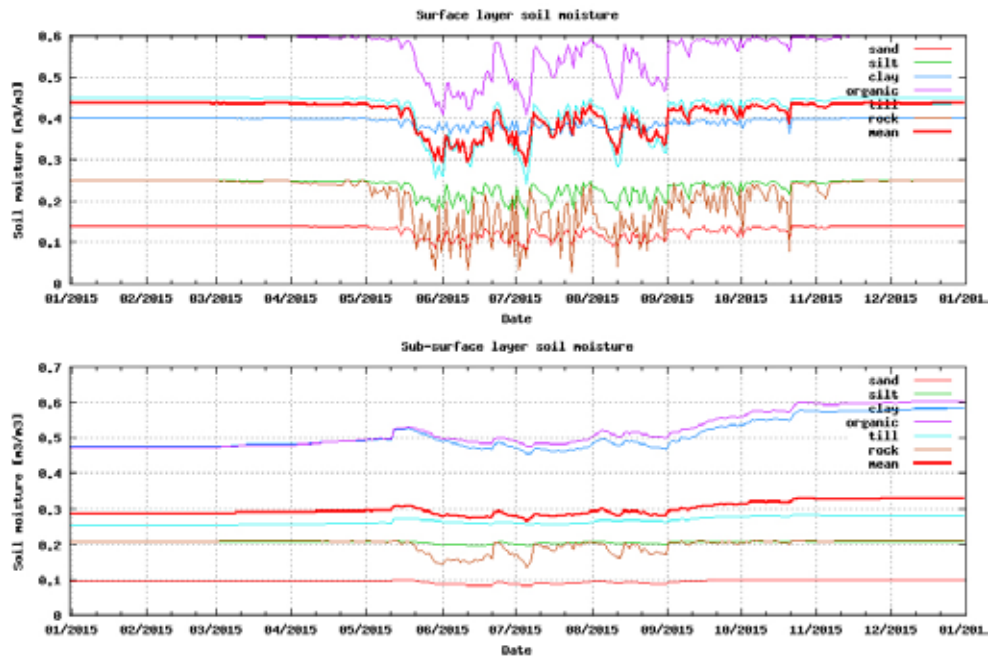
Figure 31. Soil moisture content in different soils in the surface and the sub-surface layer.

3.2.4 Proposal for improvement in water balance modelling

The WSFS model is operative at the Siilinjärvi site and can be used to forecast, for example, needs for pumping and managing ponds. It works relatively well for the Musti tailings area and Vesiallas pond, as well as for the natural state lake Kolmisoppi. However, some difficulties were met when simulating the Raasio and Jaakonlampi ponds. Observations of discharge (pumping) into and from both ponds exist, but if they are used as such, the water levels of the ponds tend to rise or fall too rapidly. It is therefore suspected that they are incorrect or possibly scaled incorrectly. According to GTK, it is possible that there are some ruptures in the bedrock south of the Musti and Vesiallas ponds leading to some increased infiltration, but it is unlikely that it can cause such an effect on water level. As the model can be operated without direct discharge observations using the regulation schedule (as done in the forecast period), or using a combination of observations and regulation schedule to limit drastic changes in water level, one is still able to obtain sufficiently reasonable results for the Raasio and Jaakonlampi ponds. Questionable discharge observations should be examined, however, and corrected if necessary.

In general, the reliability of measured data needs to be checked at the first phase of application into the water balance model. Continuous measurement data should automatically be retrieved and processed into the modelling system, or in the case of manual samples, at least automatically processed and then integrated into the modelling system.

Water quality parameters like heavy metals and sulphate can be connected to the hydrological model. This option is especially useful for extending the water balance model application to calculate the dispersion and impact of the waste waters in recipient bodies.

4 Management and control of mine site water

4.1 The operating system of WSFS

Vesa Kolhinen, Bertel Vehviläinen

The WSFS is operated via a web-based interface. Forecasts and observations are automatically updated, and the resulting images can be viewed for each area and for three different time periods (one month, three months, and one year). Old forecast images are saved and these are also available from the interface. The interface can be accessed from any computer which has a certificate issued by SYKE, and installed on a browser.

The forecast points are accessed by clicking the target on the front-page map of the user interface shown in Fig. 32. As an example, Fig. 33 shows the lake water level and discharge simulation for *Vesiallas*.

Figure 32. User interface is web based and can be used from any computer that has access to computing server. Clickable map used to navigate into different areas and to view their forecasts, some of which are also shown on right. On the left panel there is a menu, where regulation schedules and discharge forecasts, observations etc. can be accessed.

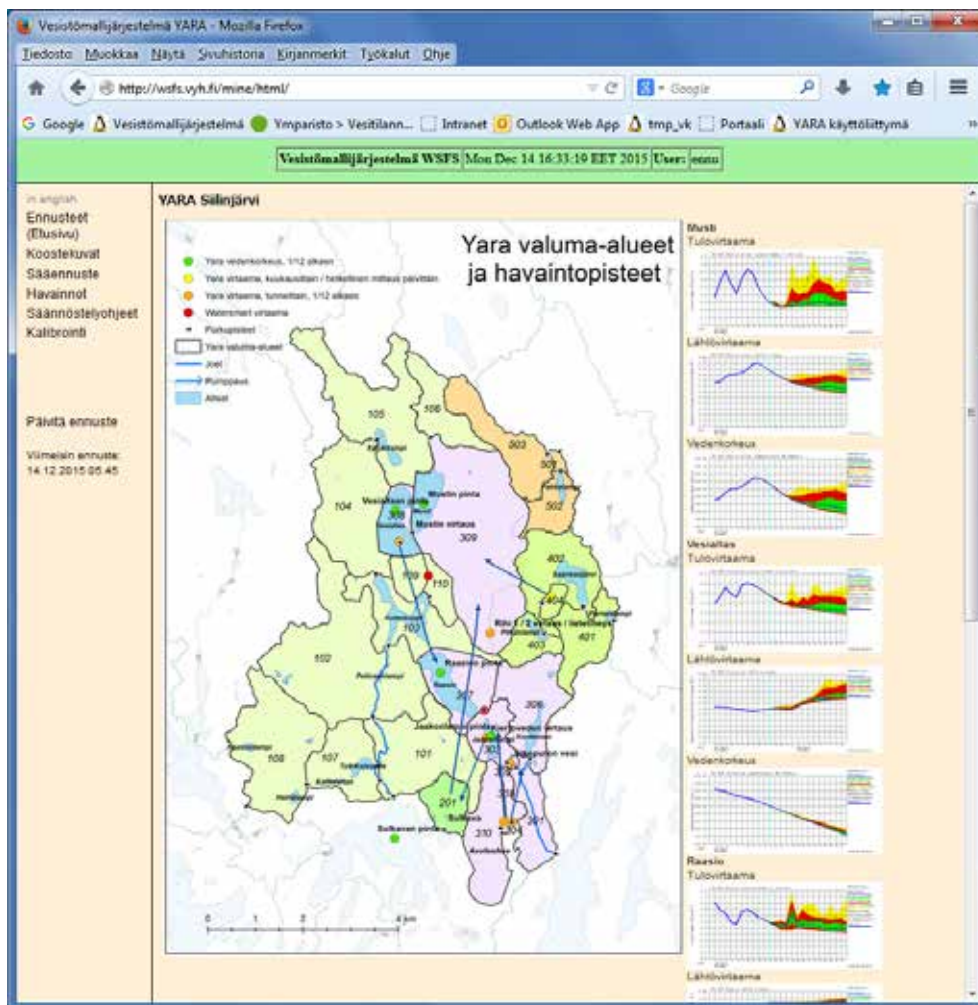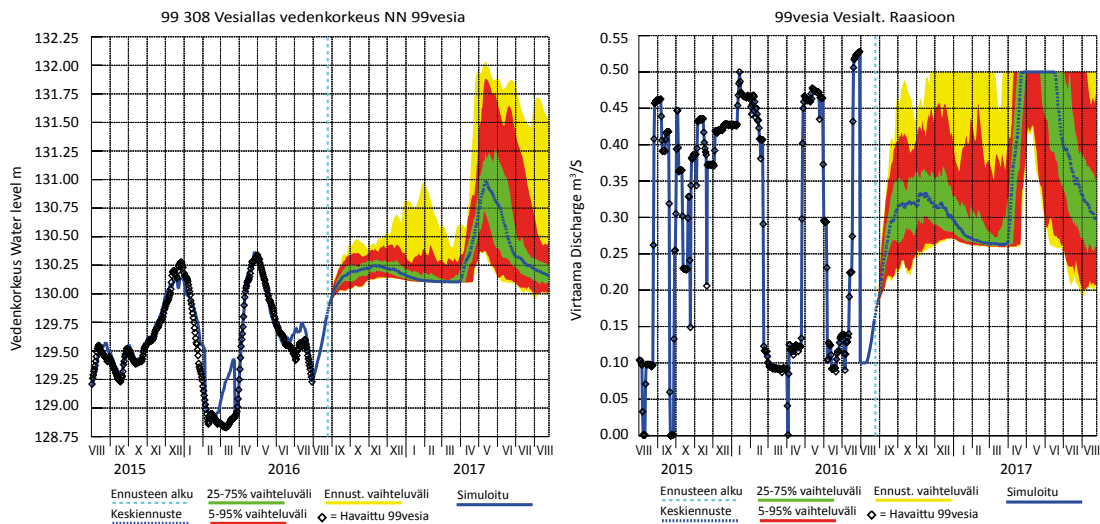**Figure 33.** Water level (on the left) and pumping (on the right) of Vesiallas illustrated in a one year image. Vertical blue line indicates the simulation date and beginning of the forecast period.

The model automatically calculates the inflow for each pond. The outflow of a pond then determines the change in lake water level. The observed discharge is used for the simulation period, but in the forecast period some speculative information is needed about the discharge. This is put in the model using discharge forecasts and regulation schedules. The model first uses the discharge forecast if it has been entered into the system by the model operator, and uses the regulation schedule when the discharge forecasts end. Both can be directly modified from the user interface shown in Fig. 34. Above the regulation schedule for Vesiallas pond is shown where are relations between the discharge (on the top) and water level (in the table) in different periods (on the left). New rows and columns can be added to the table. The image at the bottom of the web page shows this relation graphically. The regulation schedule is used to set an estimated outflow through the year.

Below in Fig. 34 is the discharge forecast for Vesiallas. This is used to directly set the outflow of a pond to the desired value, usually for a short forecasting period. These values are usually entered when mining operators know what the outflow from the pond will be in order to provide realistic forecasts, but they can also be used to simulate different outflow scenarios.

Direct observations (of discharge, and water level, etc.) can also be entered into the system using the interface. This is practical when new observations need to be entered more frequently than once a day, or when automatically entered observations are faulty. Fig. 35 shows an observations sheet for Jaakonlampi pond. The values on the right (in column "*Register I*") have been read automatically by the system (currently they are sent to SYKE by email and stored on the server), and values on the left (in column "*Saved data*") have been entered manually using the interface. All the observations will be taken into account in the next forecast run. If necessary, the forecast can be started immediately from the user interface by clicking the "*Update forecast*" ("*Päivitä ennuste*") button on the menu.

From the perspective of the model user, the operation of the model is based on setting the best possible approximation for the pond outflows. In the Siilinjärvi case, one of the ponds is somewhat special – the open mine pit. It was also included in the model in order to estimate the need for pumping to keep it empty of water. The model has a small 2 hectare pond based on information obtained from Yara Suomi Oy, on the bottom of the pit, and it attempts to keep the water level in the pond at zero by increasing outflow if necessary. Pumping is kept under the maximum values

Vesiallas säännöstelyohje

[Palauta alkuarvot] [Talleta taulukko]

		Juoksutus					~~ Lisää sarake
		0.00	0.20	0.30	0.40	2.00	
kk	pp	Vedenkorkeus					
1	1	128.70	128.90	129.05	129.25	129.60	-999.99
2	1	127.70	127.90	128.15	128.35	-999.99	-999.99
3	1	126.80	127.00	127.15	127.30	-999.99	-999.99
4	1	126.80	127.00	127.15	127.30	-999.99	-999.99
6	1	127.95	128.10	128.25	128.40	-999.99	-999.99
10	8	129.20	129.35	129.40	129.55	-999.99	-999.99
11	1	129.30	129.40	129.50	129.60	-999.99	-999.99
12	1	129.30	129.40	129.50	129.60	-999.99	-999.99
		Lisää rivi					
		-999.99	-999.99	-999.99	-999.99	-999.99	

[Kopioi taulukko varmuuskopioksi] [Palauta viimeisin varmuuskopio]

Taulukon täyttöohje

Kuva säännöstelyohjeen juoksutuksista

Vesiallas säännöstelyohje

Q= 0.00
Q= 0.20
Q= 0.30
Q= 0.40
Q= 2.00

Vedenkorkeus m

I II III IV V VI VII VIII IX X XI XII

21-Dec-2015 15:35:50
Filename=/ine/juoksuohje1450704950
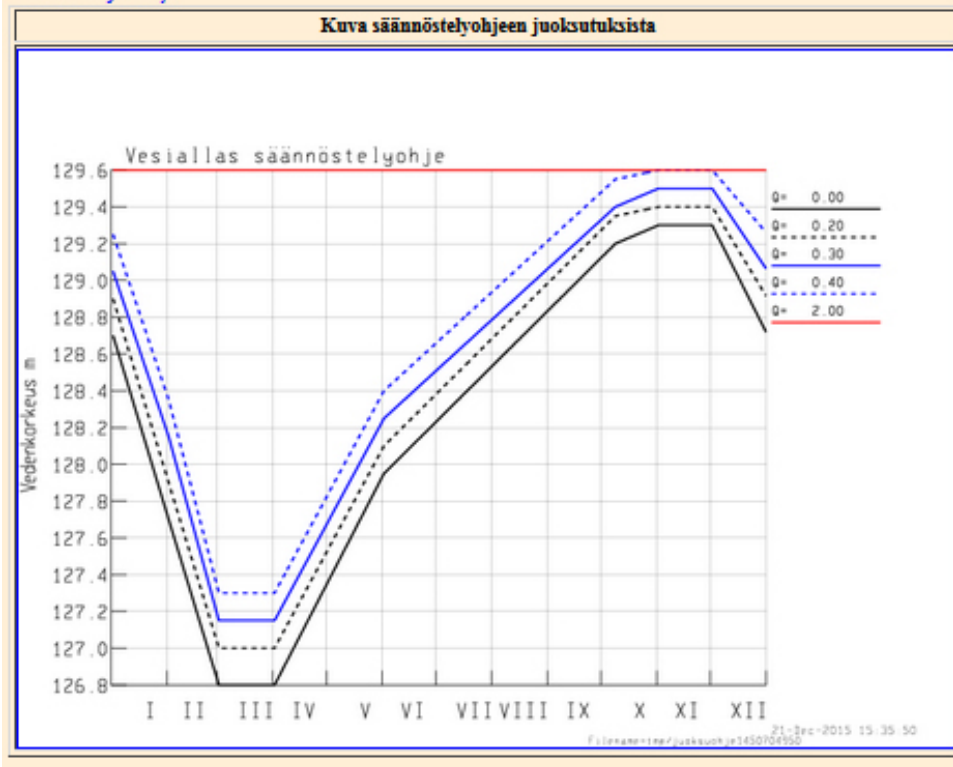
Figure 34. (Above) Regulation schedule for Vesiallas. Relation between water level and discharge can be set for different periods over the whole year. (Below) Discharge forecast for Vesiallas. Daily averages for pumping from Vesiallas have been entered using the interface.

in english

Ennusteet
(Etusivu)
Koostekuvat
Sääennuste
Havainnot
Säännöstelyohjeet
Kalibrointi

Päivitä ennuste

Viimeisin ennuste:
15.12.2015 05.55

Jaakonlampi_kiertoon virtaama %l/s%

Year	Month	Day	Data	Period	
2015	11	5	204.10	1 days	Save
2015	11	4		1 days	Remove
2015	11	5		1 days	Mark as missing

Show last: 20 values Show

yyyy	mm	dd	Saved data	Register I 99kiert.q????	Register II
2015	11	4	204.10		
2015	11	3	204.30		
2015	11	2	204.30		
2015	11	1	204.55		
2015	10	31	204.50		
2015	10	30		204.72	
2015	10	29		214.11	
2015	10	28		205.88	
2015	10	27		197.85	
2015	10	26		196.55	
2015	10	25		212.56	
2015	10	24		228.12	
2015	10	23		217.67	
2015	10	22		204.60	
2015	10	21		214.99	
2015	10	20		216.37	
2015	10	19		214.03	
2015	10	18		211.14	
2015	10	17		211.88	
2015	10	16		227.81	

Figure 35. Discharge observation sheet for Jaakonlampi. Observations on the right column are obtained from Yara (semi-)automatically, those on the left ("Saved data") have been entered using the inteface.

obtained from Yara Suomi Oy, restricted to a maximum 0.2 m³ s⁻¹ in the code, but it can be modified using the regulation schedule as well, and currently the maximum pumping capacity is 0.1 m³ s⁻¹. In the Figure 36, the water level (on the left) and pumping (on the right) are shown. Notice the rise in the water level as maximum pumping capacity is reached in May 2015. Different climate change scenarios can be added to the system to evaluate the pumping needs in the future (see chapter 3.2.3 "Extensions of the model").

The Yara Siilinjärvi WSFS forecast system is currently run on SYKE's computing server, but it can be moved into other systems as well. If the WSFS system is moved from SYKE to another location under different operators, the delivery of weather observations and forecasts, as well as the right to use them, must be negotiated with FMI.

Although the model can be almost completely operated using the web interface, some lower level settings, such as changing weights of errors for the correction model and calibration require system level access. Forecasts are normally run automatically at a given time, but they can also be run manually from the user interface.
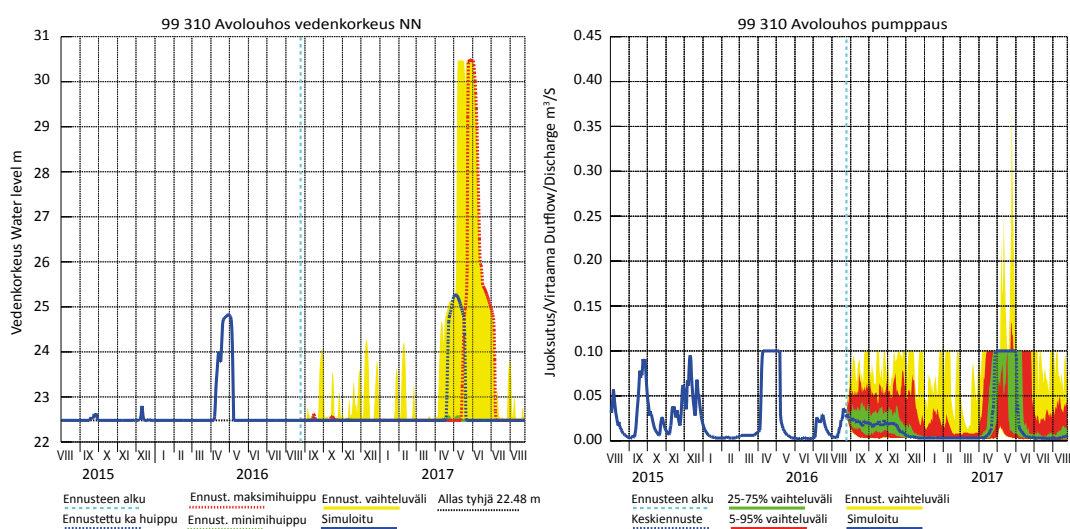
Figure 36. Water level (on the left) and pumping (on the right) of the open pit. Vertical blue line indicates simulation date, blue curve median forecast, and band coloured areas show forecast with different probabilities. Model attempts to keep the pit empty. When pumping needs exceeds the maximum pumping capacity, water level begins to rise, as seen in the figures. Pumping capacity is restricted to 0.1 m³ s⁻¹.

4.2 The use of GoldSim

Ulla-Maija Mroueh, Juhani Korkealaakso

Another potential approach is to construct the site-wide water balance modelling system using the GoldSim modelling platform. GoldSim is simulation software for dynamic modelling of complex systems. Internationally it is commonly used for mine water balance studies, but it is also suitable for other water balance modelling purposes.

The flexibility of the modelling platform allows site-specific definition of the boundaries of the system. Depending on the needs of the mine, the water-balance model can be site-wide or include a specific sub-unit, such as tailings facilities. The system is updatable and it will evolve continuously when the there is more data available. It can also be developed stage by stage along with different mine phases or starting from a specific unit. It includes Monte Carlo simulation for analysis of uncertainties.

The modelling platform allows dynamic integration of spreadsheet models, several other file formats and data streams, including:
- Tools for groundwater and surface water modelling, for simulation of different hydrochemical processes, and process modelling
- On-line monitoring data, on-site and laboratory analysis data, weather data
- Free exe-player viewer is available for customers. The user interfaces can be tailored custom specific.

The modelling system can be used for several purposes, such as:
- Prediction of future behaviour and potential risks, and for identifying which factors have the greatest influence
- Operative management of the mine
- Creating different water management reports for authorities, mine personnel and other stakeholders.

Further details regarding GoldSim application in the WaterSmart project are given by Punkkinen et al. (2016).

5 Commercialisation of the results

Kirsti Krogerus, Ulla-Maija Mroueh, Antti Pasanen, Bertel Vehviläinen, Kaisa Turunen

The commercialisation of the WaterSmart project's results was planned in cooperation with the research institutions and companies that participated in the project.

The real-time monitoring of groundwater level, flow and quality service includes hydrogeological investigation, geological and groundwater flow modelling and installation of monitoring stations. To avoid several overlapping systems, if possible the groundwater monitoring system and models should be integrated with the already existing systems. The geological and groundwater flow models are made with commercial software but need to be tailored for each site. Furthermore they are made for the site before actual online monitoring, but can be updated during mining operations as the hydrological circumstances may change. Building a geological model may require subcontractors (e.g. geophysical investigations, drilling for groundwater wells) and local expertise.

Flow modelling is based on real-time measurements which require sensors and their maintenance. Groundwater level and quality is monitored online from groundwater wells by maintained devices. Since measuring devices are portable and can be tailored for any scale, they can rather easily be set up at the site, but the amount and location of measuring stations, as well as the measured parameters are site specific. The devices are adequately located in accordance to groundwater flow, tailings ponds etc. to be as representative as possible and function as an early warning system in case of a leak or other disturbance in water management systems. Since the groundwater system is influenced by the entire hydrological system in the area (e.g. dewatering of the mine, surface water level fluctuations, construction and excavation), the groundwater monitoring system is combined with the surface water and weather monitoring systems. The data from the system will be delivered as reports which are further linked to the water balance model of SYKE.

In the WaterSmart project, the online monitoring systems have not yet been integrated to groundwater models since they need further developing before commercialization. Furthermore, the interface needs to be built up between the measurements and the models.

The water balance system (WSFS) can aid in planning the dimensions of dams, pumping stations and reservoirs, as well as in the review of different structural options. Furthermore, the system provides estimates of changes in a mine area's water balance caused by climate change. The WSFS system gives added value for the customer (e.g. a mining company or a consultant), in particular in cases of managing extreme situations, planning assessment, climate change assessment, dam safety issues, and services related to monitoring.

The water balance model and service by SYKE, tailored for mine sites includes:
- Hydrological data
- Weather service (FMI)
- Real-time simulation and forecast of water balance and up-keeping of the model
- Operative service (up-keeping of the simulation system and real-time data transfer, analysis of results and reports)
- A map-based user interface, which includes reservoir management, weather observations and forecasts, basin inflow, water level and drainage forecasts, simulating snow water equivalent, soil moisture and percolation and changes in groundwater storage
- Simulated groundwater input as percolation, which can be entered into hydraulic groundwater models (such as operated by GTK)
- Automatic warnings for mine personnel (such as water level and outflow capacity alerts, as well as heavy rain and flood alerts)

One of the potential approaches is to construct the site-wide water balance modelling system using existing, commercially available water balance simulation tools. In the WaterSmart project general skills were developed for calculations using GoldSim modelling platform. GoldSim was chosen because it is suitable for dynamic modelling of complex systems, and as such commonly used for mine water balance studies internationally.

The water balance management system from GoldSim consists of simulation software and additional modules which will be dynamically integrated to the platform. The cases can vary from construction, implementation and regular updating of a site-wide water balance management system, to modelling of specific sub-units such as tailings facilities. In practice, the system has to always be tailored based on case specific needs. The work carried out in the project forms a basis for the development of mine specific water balance models and systems and integration of further modules to the system. The next stage of commercialization could be a larger scale piloting case in collaboration with the mine and other actors involved in water balance management. The actors can include service providers and consulting companies involved in planning and operational services of mines, providers of on-line monitoring technologies and monitoring services, as well as actors competent in specific modelling tools. To develop a real-time water management system the on-line monitoring systems also need further development.

Water and mass balance models are important decision support tools for mine operators and regulators. They are needed for planning and operative management of the mine activities, as well as for prediction of future behaviour and potential risks.

6 Conclusions

Kirsti Krogerus, Antti Pasanen

For the WaterSmart project the objective was first to exploit online water quantity and quality measurements to better serve water balance management. The second objective was to develop and test mathematical models to calculate the water balance in mining operations. The third objective was to determine how monitoring and modelling tools can be integrated into the management system and process control. These objectives were pursued at two mine sites in Finland.

Methodologies to study groundwater properties exist, but have not been piloted at a large scale in Finland. Measurement techniques for hydraulic properties at the Yara and Luikonlahti sites included slug tests, electrical profiling and several types of pumping tests. The slug tests were conducted both in sediment and bedrock groundwater observation pipes and drillholes, whereas the other tests were done in bedrock. Additionally, an off-line groundwater level monitoring network as well as an on-line surface water monitoring network were built at the Yara site. The following conclusions can be drawn from the pilot studies and their results:

- Hydraulic measurements of groundwater provide crucial input data for groundwater flow modelling
- The scale (both spatial and temporal) of both groundwater and surface water monitoring networks must be sufficient to estimate groundwater and surface water balances in the mining area.
- On-line monitoring provides temporal resolution that can also reveal odd groundwater behaviour that would not be evident through manual monitoring.

A hydrological water balance model based on the WSFS model was developed for the Yara Siilinjärvi site to simulate and forecast water balance. The resulting model is operational and fully automatic. It produces water balance, level and discharge forecasts for each pond and discharge point in the area.

- The model is operated using a web-based user interface. It can be controlled by modifying the outflow and water level for each pond.
- The observed discharge and water levels, as well as snow observations can be entered manually via the interface, or they can be received automatically.
- Real-time weather observations and forecasts are received and used automatically to produce up-to-date forecasts.
- The groundwater model uses percolation from the water balance model as input for the groundwater simulation.
- The water balance model can also be connected to the process simulation and management system of the mine.
- It is possible to modify the model in order to simulate changes in the area. These can include, e.g. changing the size or number of ponds and basins for site planning, or temperature and precipitation for worst-case or climate change scenarios.
- The system provides information for regulating ponds and basins in the mining area.

One of the potential approaches is to construct the site-wide water balance modelling system using existing, commercially available water balance simulation tools such as the GoldSim modelling platform. The GoldSim platform can be used to couple models similar to those developed in this project.

The commercialisation of the results was planned in cooperation with the research institutions and companies that participated in the project. The products include real-time monitoring service for groundwater level, flow and quality, as well as the water balance system (WSFS) for surface waters which can be connected with groundwater models. The WSFS system can be used independently but also be connected to process control systems and management systems such as GoldSim.

The WaterSmart project combined online measurements and mathematical models with predictive process control solutions. The project developed a constantly updated management system for water balance.

- The water balance model allows mining operators to prepare for changes in water quantities, to prepare for floods, and to ensure the adequacy of the water supply.
- The modelling of groundwater and surface water balances prior to mine construction may lead to considerable monetary savings through a properly designed water management infrastructure.

The project demonstrated the need for coupling online surface water and groundwater quality and quantity measurements with water balance modelling. To prevent leakage of harmful substances to the environment requires early warning of unusual weather conditions to proactively adjust mine processes and water management. In addition, the effect of the changes in process will have on water management can be investigated in advance. During the planning stage at mine sites the modelling of combined water management and process scenarios could lead to substantial economical savings and better environmental protection through better design criteria, recirculation and reduced use of water.

Water balance modelling is currently seldom used in mining operations in both Finland and other parts of the world. It is expected that the authorities will demand it in the near future for new mining permits. The tools developed in this project are undergoing further commercialization by private enterprises and water balance modelling services will soon be available.

Successful water balance modelling requires the knowledge and methodologies of several partners. Surface water and groundwater models can be coupled through algorithms or by using a dynamic modelling platform. Coupling these with process control and initializing early warning systems gives the operators the tools to control the water balance in real time.

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Appendix

Table 1. Results of the slug tests in sediment observation wells at Luikonlahti.

Obs. Well	K (m/sec)			Average K	GWL	Well bottom	Saturated zone thickness	Screen depth
	Test 1	Test 2	Test 3	(m/sec)	m bgs	m bgs	m	m bgs
HP0	$2,5 \times 10^{-5}$	$1,9 \times 10^{-5}$		$2,2 \times 10^{-5}$	3,67	10,96	7,29	8,2-10,2
PP4	$3,5 \times 10^{-5}$	$3,8 \times 10^{-5}$	$5,1 \times 10^{-5}$	$4,1 \times 10^{-5}$	1,04	3,32	2,28	1,45-3,45
PP8	$3,0 \times 10^{-5}$	$2,6 \times 10^{-5}$	$2,6 \times 10^{-5}$	$2,7 \times 10^{-5}$	1,16	4,74	3,58	2,8-4,8
PP102	$5,0 \times 10^{-5}$	$2,6 \times 10^{-5}$	$3,2 \times 10^{-5}$	$3,6 \times 10^{-5}$	1,27	4,61	3,34	2,8-4,8
PV03	$1,4 \times 10^{-4}$	$1,5 \times 10^{-4}$	$1,4 \times 10^{-4}$	$1,5 \times 10^{-4}$	2	8,94	6,94	2,0-9,0
PV04	$1,1 \times 10^{-5}$			$1,1 \times 10^{-5}$	3,1	5,95	2,85	3,0-6,0
PV05	$3,0 \times 10^{-6}$	$3,0 \times 10^{-6}$	$2,9 \times 10^{-6}$	$2,9 \times 10^{-6}$	1,56	5,5	3,94	1,55-5,55
PV07-1	$4,0 \times 10^{-5}$	$4,5 \times 10^{-5}$	$4,3 \times 10^{-5}$	$4,2 \times 10^{-5}$	3,51	6,85	3,34	3,0-7,0
PV07-2	$5,2 \times 10^{-5}$	$5,0 \times 10^{-5}$		$5,1 \times 10^{-5}$	3,51	6,85	3,34	3,0-7,0
PV09	$3,6 \times 10^{-6}$	$2,9 \times 10^{-6}$	$2,8 \times 10^{-6}$	$3,1 \times 10^{-6}$	3,32	8,44	5,12	4,5-8,4
PV12	$9,0 \times 10^{-5}$	$1,2 \times 10^{-4}$	$1,5 \times 10^{-4}$	$1,2 \times 10^{-4}$	2,52	4,24	1,72	2,3-4,3
PV16	$3,1 \times 10^{-4}$	$2,9 \times 10^{-4}$	$1,5 \times 10^{-4}$	$2,5 \times 10^{-4}$	3,24	6,68	3,44	na
PV17	$1,8 \times 10^{-6}$	$1,6 \times 10^{-6}$		$1,7 \times 10^{-6}$	1,44	3,2	1,76	2,0-4,0
PV21	$4,7 \times 10^{-6}$	$5,9 \times 10^{-6}$	$5,7 \times 10^{-6}$	$5,4 \times 10^{-6}$	2,24	7,68	5,44	4,0-8,0
PV22	$1,5 \times 10^{-5}$	$1,1 \times 10^{-5}$	$1,3 \times 10^{-5}$	$1,3 \times 10^{-5}$	2,32	5,95	3,63	3,0-6,0
PV23	$2,4 \times 10^{-6}$	$2,2 \times 10^{-6}$	$2,4 \times 10^{-6}$	$2,3 \times 10^{-6}$	2,17	8,14	5,97	3,0-6,0

Table 2. Results of the slug tests and single well pumping tests in bedrock wells at the Luikonlahti site. In KPV1 only pumping tests are performed, in KPV2 only slug tests are performed.

Obs. Well	K (m/sec)		Average K	T (m²/sec)		Average T	GWL	Well bottom	Saturated zone thickness
	Test 1	Test 2	(m/sec)	Test 1	Test 2	(m²/sec)	m bgs	m bgs	m
KPV1	$1,5 \times 10^{-5}$	$2,2 \times 10^{-5}$	$1,85 \times 10^{-5}$	$6,04 \times 10^{-4}$	$9,2 \times 10^{-4}$	$7,62 \times 10^{-4}$	1,26	42	40,74
KPV2	$2,3 \times 10^{-7}$	$3,2 \times 10^{-7}$	$2,75 \times 10^{-7}$	$2,1 \times 10^{-5}$		$2,1 \times 10^{-5}$	6,94	84	77,06
KPV3	$5,4 \times 10^{-7}$	$2,1 \times 10^{-6}$	$1,32 \times 10^{-7}$	$6,3 \times 10^{-5}$		$6,3 \times 10^{-5}$	1,92	126	124,08
KPV4	$1,4 \times 10^{-7}$	$3,7 \times 10^{-6}$	$2,55 \times 10^{-7}$				2,94	96	93,06

Table 3. Results of the slug tests at Siilinjärvi study site.

Obs, Well	K (m/sec)			Average K	GWL	Well bottom	Saturated zone thickness	Screen depth
	Test 1	Test 2	Test 3	(m/sec)	m bgs	m bgs	m	m bgs
KA1	2,1 x 10-7			2,1 x 10-7	0,52	5,04	4,52	
KA2	1,5 x 10-4	1,1 x 10-4		1,3 x 10-4	0,05	17,33	17,28	
KA3	1,3 x 10-6	1,3 x 10-6		1,3 x 10-6	-0,54	6,66	7,2	
KA6	4,1 x 10-5	5,0 x 10-5		4,5 x 10-5	-0,37	8,69	9,06	
KA10	3,9 x 10-6	4,5 x 10-6	4,3 x 10-6	4,2 x 10-6	1,3	5,37	4,07	
KA12	2,8 x 10-5	2,1 x 10-5	2,3 x 10-5	2,4 x 10-5	0,26	16,34	16,08	
KA18	5,2 x 10-6	5,6 x 10-6	5,5 x 10-6	5,4 x 10-6	0,58	3,77	3,19	
KA20	2,2 x 10-6	4,8 x 10-6	5,4 x 10-6	4,1 x 10-6	0,56	8,43	7,87	
KA26	1,9 x 10-7			1,9 x 10-7	3,26	10,54	7,28	
KA27	4,1 x 10-8			4,1 x 10-8	2,56	8	5,44	
KA28	1,8 x 10-5	8,7 x 10-6	8,3 x 10-6	1,1 x 10-5	6,05	13,4	7,35	
KA29	2,2 x 10-5	2,3 x 10-5	1,9 x 10-5	2,1 x 10-5	1,78	4,7	2,92	
VPP1	1,3 x 10-5	6,9 x 10-6	1,0 x 10-5	1,0 x 10-5	0,85	7,6	6,75	
VPP2	5,7 x 10-6	3,8 x 10-6		4,75 x 10-6	0,7	2,3	1,6	
VPP3	3,1 x 10-6	2,3 x 10-6	2,8 x 10-6	2,7 x 10-6	-0,02	6,36	6,38	
VPP4	7,8 x 10-7	8,4 x 10-7		8,1 x 10-7	1,03	6,93	5,9	
Fk4	1,7 x 10-7			1,7 x 10-7	0,78	11,26	10,48	
Fk41	1,3 x 10-7	1,8 x 10-7		1,6 x 10-7	1,32	6,88	5,56	
Fk42	3,4 x 10-6	2,2 x 10-6		2,8 x 10-6	1,03	7,05	6,02	
Fk44	9,1 x 10-6	9,6 x 10-6	9,1 x 10-6	9,3 x 10-6	0,7	9,02	8,32	
Fk45	1,1 x 10-5	1,0 x 10-5	6,8 x 10-6	9,3 x 10-6	1,76	6,5	4,74	
M3	1,5 x 10-6	1,5 x 10-6		1,5 x 10-6	0,78	5,46	4,68	
M4	9,2x 10-6	9,4 x 10-6		9,3 x 10-6	8,34	10,36	2,02	
M5	3,7 x 10-8			3,7 x 10-8	6,84	9,5	2,66	
M6	1,7 x 10-6	5,7 x 10-7	1,0 x 10-6	1,1 x 10-6	2,96	9,88	6,92	
M7	3,8 x 10-6	3,7 x 10-6	3,9 x 10-6	3,8 x 10-6	5,3	10,62	5,32	
KC-1	8,8 x 10-6	8,5 x 10-6		8,7 x 10-6	2,76	7,33	4,57	
KC-3	3,3 x 10-6	3,2 x 10-6	3,2 x 10-6	3,2 x 10-6	2,8	8,16	5,36	
PA17	1,6 x 10-5	1,4 x 10-5	1,4 x 10-5	1,4 x 10-5	8,11	12,68	4,57	
PA27	1,2 x 10-5	1,2 x 10-5	1,2 x 10-5	1,2 x 10-5	2,45	15,56	13,11	
PA28	5,7 x 10-6	5,2 x 10-6		5,5 x 10-6	4,8	27,3	22,5	
PA61	7,9 x 10-6	8,1 x 10-6		8 x 10-6	3,4	11,94	8,54	
PA62	4,4 x10-6	4,4 x 10-6	4,5 x 10-6	4,4 x 10-6	5,17	14,37	9,2	
PA63	1,1 x 10-5	1,0 x 10-5	1,0 x 10-5	1,0 x 10-5	3,08	22,4	19,32	
PA64	1,8 x 10-5	1,8 x 10-5	1,8 x 10-5	1,8 x10-5	0,16	8,12	7,96	

Table 4. Available water level and discharge data on the area.

Water level observations (by YARA)	
Observation point	**Observation period**
Jaakonlampi	2012-2015
Kolmisoppi	2007-2014
Mustin allas	2012-2015
Raasio	2012-2015
Vesiallas	2012-2015
Discharge observations (by YARA and EHP-tekniikka)	
Observation point	**Observation period**
Jaakonlampi to Sikopuro	2012-2015
Jaakonlampi to reuse	2012-2015
Pumping into Mustiin	2012-2015
Vesiallas to Raasio	2012-2015
Louhosvesi Itäallas to Jaakonlampi	2012-2015
Intake from Sulkavanjärvi	2012-2015
EHP Itäallas to Jaakonlampi	2014-2015
EHP Itäaltas to Sikopuro	2014-2015
EHP Raasio to Jaakonlampi	2014-2015
EHP suotovedet länsipadolta	2014-2015

Table 5. Siilinjärvi model flow rates in and out of the modelling domain from FeFlow modelling.

Area	In	Out
Model edges	2100 m³/d	7120 m³/d
Waterbodies	3660 m³/d	3190 m³/d
Drains	0 m³/d	4720 m³/d
Open pit	0 m³/d	1190 m³/d
Percolation (whole domain)	11070 m³/d	0 m³/d
Total	16730 m³/d	16220 m³/d

Table 6. Table_luikonlahti_flow_rates.xlsx. Luikonlahti model flow rates in and out of the modelling domain from FeFlow modelling.

Source/Sink	In	Out
Model edges	1360 m³/d	10360 m³/d
Waterbodies	10190 m³/d	320 m³/d
Drains	0 m³/d	2610 m³/d
Percolation	2120 m³/d	0 m³/d
Total	13670 m³/d	13290 m³/d

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