Groundwater flow modelling to address hydrogeological response of a contaminated site to remediation measures at Hjortsberga, southern Sweden

Adam Johansson

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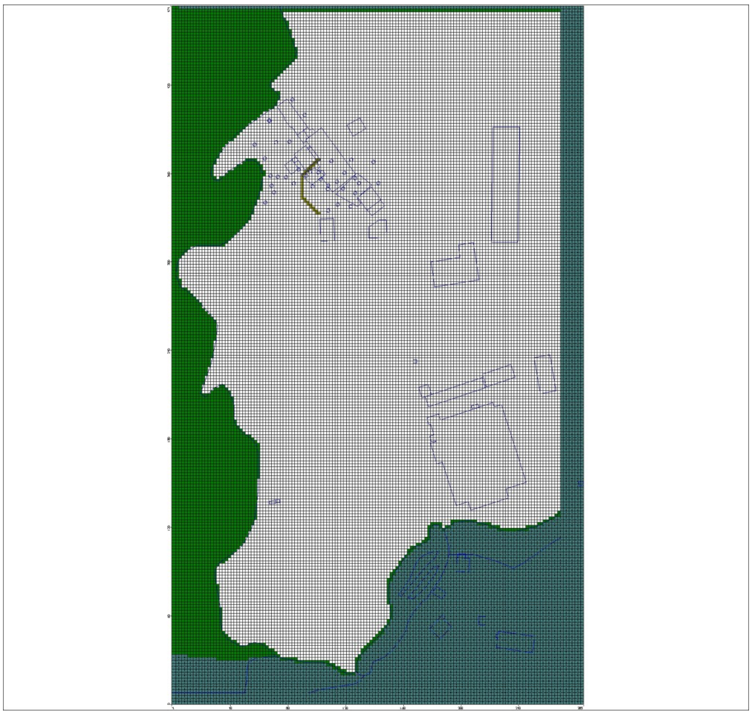

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Cover Picture: Output from the model, Modflow 2005, Input GHB screen view (Harbaugh 2017).

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Pentachlorophenol (PCP) is a chlorinated aromatic compound that was commonly used for treatment of wood against microbial degradation before it got banned in the 1970s. Due to its solubility in water, PCP is a common groundwater contaminant around old sawmills, for example near Hjortsberga in southern Sweden where this study was performed.. The contaminated groundwater is spreading and leaking into a nearby lake. It is of high importance to remediate the site. The area has been thoroughly investigated, and a few *in-situ* remediation methods have been attempted, but the problem is still not solved because of complex geology and severe contamination. Chemical and microbiological degradation of PCP is not fast enough. One way to slow down the groundwater flow and enhance the chemical oxidation could be to install a permeable reactive barrier. This can be done theoretically by the creation of a groundwater model. In this work a groundwater model was created with the code *MODFLOW 2005* developed by the United States Geological Survey. With the created model a "best placement" scenario was investigated. The results show that a barrier type called "funnel and gate barrier" most efficiently prolongs the groundwater path, extending the time it takes for groundwater to flow from the contaminated site to the lake.

Keywords: PCP, Groundwater modelling, Permeable reactive barrier, Hjortsberga sawmill

Supervisor(s): Mehran Naseri Rad (LTH) & Dan Hammarlund

Subject: Hydrogeology, Contaminated ground,

Adam Johansson Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: adam.johansson8835@gmail.com

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Pentaklorfenol (PCP) är en klorerad aromatisk förening som användes flitigt för att behandla trä mot mikrobiell nedbrytning innan den blev förbjuden på 70-talet. På grund av dess höga löslighet förekommer PCP som en grundvattenförorening kring äldre sågverk. Hjortsberga i södra Sverige är ett exempel på denna typ av förorening och är det område som undersöks i arbetet. Förorenat grundvatten sprids och förorenar bland annat en sjö som ligger alldeles i närheten. Det är av högsta vikt att sanera området. Det har genomförts en del undersökningar tidigare i området och flera in-situ saneringar har prövats. Problemet kvarstår dock på grund av områdets komplexa geologi och höga grad av förorening. Kemisk och mikrobiologisk nedbrytning av PCP sker alltför långsamt. Ett sätt att fördröja grundvattenflödet och därmed förstärka den kemiska oxidationen är att installera en permeabel reaktiv barriär. Detta kan göras teoretiskt med hjälp av en grundvattenmodell. I detta arbete har en grundvattenmodell skapats med hjälp av koden Modflow 2005 som har utarbetats av United States Geological Survey. Med grundvattenmodellen kan bästa möjliga placering av en sådan barriär simuleras. Resultatet visar att en barriär av typen "funnel and gate" mest effektivt kan fördröja grundvattnets flöde och öka tiden för förorenat grundvatten att flöda från den kontaminerade platsen till sjön.

Nyckelord: PCP, Grundvattenmodellering, PRB, Hjortsberga sågverk

Handledare: Mehran Naseri Rad (LTH), Dan Hammarlund

Ämnesinriktning: Hydrogeologi, Förorenad mark

Adam Johansson, Geologiska institutionen, Lunds universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: adam.johansson8835@gmail.com

1 Introduction

Industrial activities in late 20th century have led to spread of tremendous amounts of contaminants in soil, water, and air. In recent decades, such contamination has been proven to be a threat to the environment and human health in numerous places around the globe. At Hjortsberga, located in Alvesta Municipality, Kronoberg County, southern Sweden (Fig 1) groundwater contamination has been detected and investigated in recent years.

The contamination is caused by a former sawmill factory that operated from the early 1940's to the late 1970's (Elander and Eriksson, 2007). The main occurring contaminants are pentachlorophenol's (PCP) and dioxins, both exhibiting concentrations exceeding the maximum permissible levels (Johansson, 2006).PCP is a highly soluble chemical that easily spreads with groundwater flow. The contaminants are found in the local Quaternary deposits, groundwater and bark deposits produced by the factory.

The contamination is mainly threatening the nearby Lake Sjötorpasjön. There are many different potential methods for remediation of groundwater contaminants. In this study the permeable reactive barrier method is investigated. If a groundwater model for the area is created, flow patterns and dynamics of the groundwater system may be visualized. This enables testing different scenarios for potential remediation measures. Therefore, making a groundwater flow model for the main contaminated area and surroundings is practiced here and different potential scenarios of implementing a remediation method is tested based on the model. *Permeable Reactive Barrier*s (PRBs) technology is the remediation technique investigated in this study. This remediation method was chosen because of its relevance in relation to the hydrogeologic conditions at the site and its proven efficiency in treating a very wide spectrum of contaminants, including PCP. PRBs technology is a well stablished methodology in many countries and is preferred for this study due to its unique merits that the site managers at the Geological Survey of Sweden (SGU) consider as promising for the site.

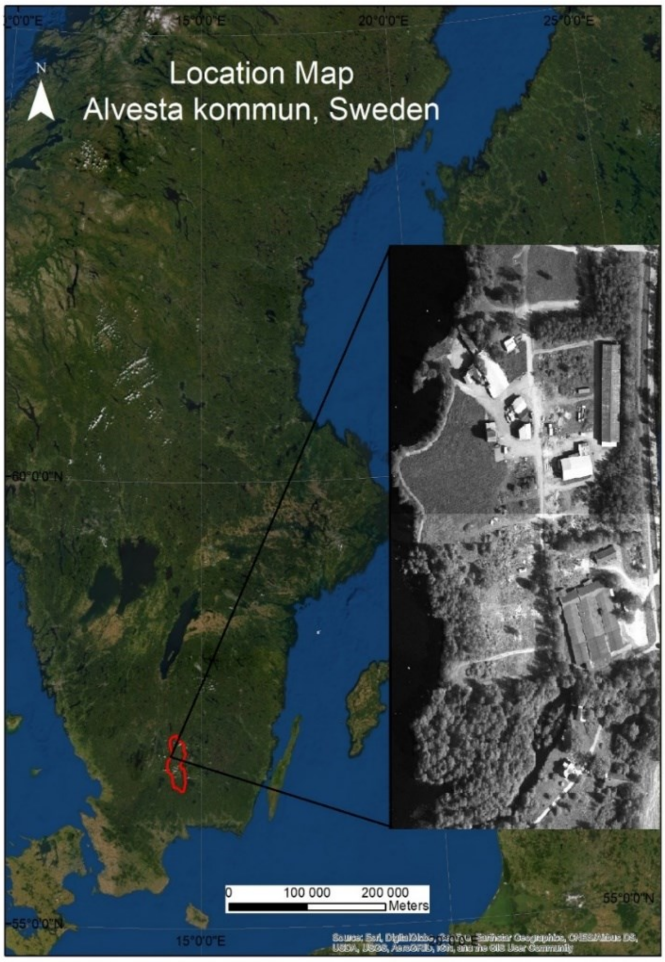
Abbreviations
PCP - Pentachlorophenol
PRB - Permeable reactive barrier
FGB - Funnel and gate barrier

Research Questions
- What is the most efficient location of a permeable reactive barrier based on flow patterns and velocities?

- How do different physical parameters of the barrier affect the groundwater flow pattern over time?

How do variations in hydraulic conductivity of the geologic media affect the flow velocity and residence time of groundwater?

The aim of the thesis is firstly to make a groundwater flow model to help understand the hydrogeology of the site and secondly to suggest an optimal location of a permeable reactive barrier to be placed across groundwater flow direction to slow down the flow rate or to treat the contamination. The thesis could possibly explore a future remediation method. This work could also serve as a basis for future investigations at the site which is being performed continuously.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1 Location of former sawmill at Hjortsberga, Alvesta Muncipality. Background satellite picture: Esri, DigitalGlobe, Earthstar Geographics, CNESAirbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

2 Background and site description

2.1 Earlier investigations

Many investigations have taken place at the site so far. SGU and local authorities have been hiring several different consultant companies to examine the Hjortsberga Sawmill site during the last 20 years. Most of the investigations have been compiled in a report by RGS Nordic (Nord 2018). In Table 1 the investigations are briefly reviewed in chronological order.

2.2 Geological setting

The regional bedrock geology at the site is described as a peneplain. Typical for peneplains are landscapes with low relief (Daniel 1989). There is no local bedrock description for the site but a more general one for the Växjö region where Hjortsberga is located is available. The crystalline bedrock is part of the Protogine Zone, with gneisses dominating in the west and granites in the east (Daniel 1989). The Protogine Zone is characterized by crush zones developed during heavy movements of the bedrock (NE 2020). The directions of the crush zones are from north to south (Daniel 1989). At the site, there seems to exist water-bearing fractures in the bedrock. It is assumed that the fractures have a north-northwest to south-southeast and south-southwest to north-northeast direction (Johansson 2006).

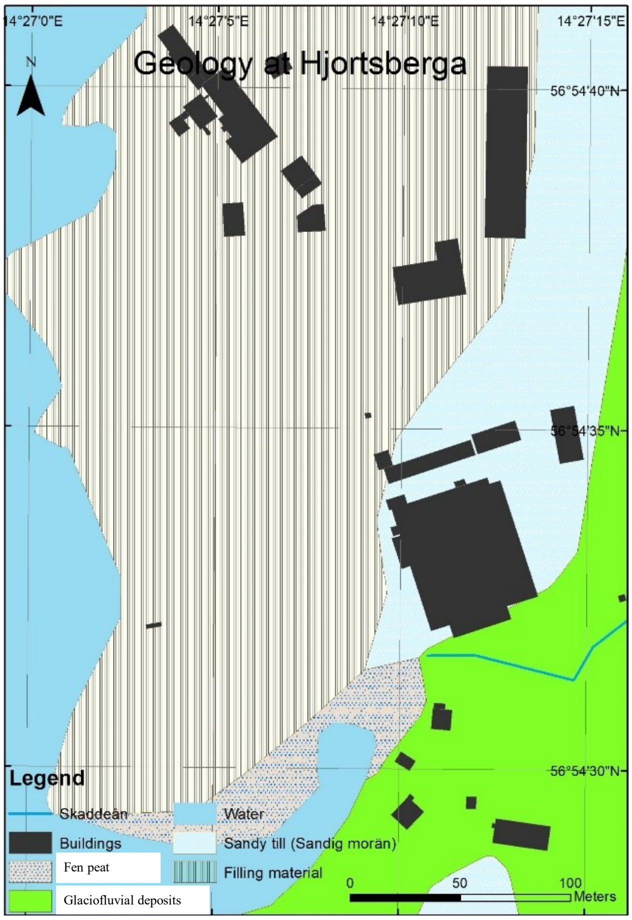


Figure 2 Map of Quaternary deposits in the study area. Data from the Geological Survey of Sweden.

The Quaternary deposits at Hjortsberga are described as "complex" and "heterogeneous" (Nord 2018). According to SGU, the surface deposits at the site mainly consist of filling material (Fig. 2). Other deposits existing around the site are coarse-grained glaciofluvial sediments, tills with different grain sizes, and peat (Fig. 2). The model area, which is confined by the extent of Fig. 2, is limited by Lake Sjöatorpasjön to the west and a small river to the south called Skaddeån. Careful attention is paid to the filling material layer because of the proven existence of in-

Table 1 Compilation of earlier investigations performed at Hjortsberga

Company	Brief description
SWECO VIAK (2006)	Soil and groundwater investigation. Archived by taking samples for lab analysis and installation of boreholes with groundwater pipes. Surface water samples and permeability measures was also performed.
ENVIPRO (2007)	Borehole drilling and installation of wells. Groundwater sampling and sediment sampling from Sjöatorpasjön. A Geophysical investigation was also performed to measure the depth to bedrock surface.
VECTURA (2012)	The company investigated for preparation of taking action. They drilled boreholes and installed wells. They also measured hydraulic conductivity by taking slug tests
Elander miljöteknik (2018)	The company assisted in performing one of the in-situ remediation methods. Calculated and estimated PCP transport.
TYRÉNS (2018)	Geophysical investigation (resistivity measurements)
RGS Nordic (2015-2020)	Performed installations of wells and sampled groundwater. They made multiple in-situ remediation methods followed by taking samples for laboratory analysis to evaluate the results of the remediation. They also measured the content of natural microorganisms relevant for degradation of contaminants.

tense contamination in this layer. Vertically, the model is divided into two layers, Quaternary deposits and bedrock.

The unconsolidated deposits are Quaternary sediments from the last deglaciation. The filling material is most probably from modern times. Till dominates in the area but glaciofluvial sand, clay, and different types of peat also occur at the surface. When till is the topmost deposit, the unconsolidated layer is often thin. Commonly the depth to bedrock is less than 5 m in the area (Daniel 1989). Therefore, the surface topography primarily reflects minor irregularities of the bedrock surface. The composition of the till in the region is mostly sandy-silty with a normal to low content of boulders (Daniel 1989). The till has been described in a similar fashion in the consultancy reports (Johansson 2006).

The composition of the filling material is mostly sand and gravel but asphalt also occurs in some places (Tyréns 2018). Organic material in the form of bark and sawdust also occurs. The filling material reaches a maximum thickness of 1-2 m (Johansson 2006). Normally the filling material is underlain by till, but it can also rest on bedrock (Tyréns 2018). The typical natural stratigraphy in the area is bedrock covered by till.

2.3 Earlier investigations

PCP has been a common treatment chemical in the sawmill industry for many decades. It has been used vastly for its capacity in protecting wood from blue stain (SGF – åtgärdsportalen 2018). Environmental concerns on production, storage, and consumption of PCP led the environmental policy makers in different countries to ban the chemical in the 1970s. The sawmill industry at Hjortsberga ceased to operate in 1981 (SGF – åtgärdsportalen) (Elander and Eriksson, 2007).

There are two areas at the former sawmill which are highly contaminated (Fig. 3). These are referred to as source regions A and B and may be recognized as contamination plumes in the area. Using these two specific areas for chemical treatment of wood and storage of the treated products have resulted in intense contamination locally (Tyréns 2018). The wood has been treated in different ways, of which one of the most hazardous for the local environment is curtain spraying. While this was practiced at Hjortsberga, there was no ground surface protection to prevent direct infiltration of the hazardous chemical (Nord 2018). Remediation methods have been applied and tested at the site by the company RGS Nordic. In 2013 a shaft remediation was performed, which removes contaminated soil with an excavator. This was to remove dioxin from contaminated soil (Nord 2018).

Between 2014 and 2017 multiple attempts were made to reduce PCP in-situ by oxidation and soil washing. However, the PCP concentrations are still too high today (Holmström 2020).

The PCP contamination at Hjortsberga could be a real threat to human health and the local environment. The lake is used for recreational purposes and especially swimming. Farming activities are also practiced by residents who reside close to the lake (Elander & Eriksson 2007).

The final aim of the whole investigation at Hjortsberga is to treat the area from all contamination which threaten the environment and public health. However, this report will only focus on PCP. This is because of its different chemical behaviour as compared to dioxin. The solubility of PCP is 14 mg/l while dioxin (2,3,7,8-Tetrachlorodibenzo-P-dioxin) is insoluble in water (NCBI 2020 A-B). Also, most of the hazardous dioxin in the soil has already been excavated and removed. Evidently, dioxin is not a major threat at the site anymore (SGU 2017) and groundwater concerns are much more serious for the site managers.

Figur 3 Ortophoto covering the sawmill area with contamination source areas indicated. Extracted from ©Lantmäteriet.

3 Methods

Groundwater modelling was the main tool used in this work to simplify the complex hydrogeological system in order for different remediation scenarios to be tested before the real implementation. However, PRBs were chosen to focus on in this work to narrow down the aims and functions of the model to a reliable level for testing placement scenarios for this technology. By groundwater modelling the flow patterns are visualized and a possible groundwater contamination spreading can be explored. The Modelling process will be described in this part of the report. Used programs/ codes are listed below (Table 2).

Table 2 List of softwares/ codes/programs

Programs/Codes	Description
MODFLOW 2005 USGS (United states geological survey)	A groundwater simulation code
MODPATH	Particle tracking engine
ArcMap 10.5.1 ESRI	GIS software

The code "MODFLOW 2005" for simulating groundwater flow created by the United States Geological Survey was used to create the groundwater model (USGS 2019). To manage the hydrogeological data from the site, ESRI ArcMap and ArcCatalog were used. With ArcMap different types of shapefiles were created based on available data taken from SGU. A Shapefile stores geographic features and their shapes, locations and other attributes given to them. The file is stored in vector format with one feature class (e.g point, line, or polygon) (ESRI 2020). Several maps, and figures were also created by ArcMap.

In the following sections the steps I took to create the groundwater flow model are presented.

3.1 Settings for the model

In the first step, the type of model was defined and what size the model was going to have. The settings for the model are listed in Table 3. To define a coordinate system for the model a shapefile was imported with a projected coordinate system. When importing the shapefile, the assigned coordinate system transfers into the model in Modflow. SWEREF 99 TM was the chosen coordinate system for this model as all the data with coordinates had SWEREF coordinates. This is also the reason why it was necessary to import a coordinate system into the model. Most of the input data, e.g wells, geographical objects and elevations had coordinates.

3.2 Importing elevation data into the model

The bedrock surface elevation was one of the imported elevations. This approach differs from the surface layer, mainly because bedrock surface data do not have the same availability as surface elevation. Basically, there are limited measurements. I was provided

Table 3 List of a numerous important settings for the created model and short explanations.

Flow type	Saturated (constant density)	It is necessary to choose a flow type. To be able to simulate a groundwater flow, the flow type must have a compatible flow numeric engine. Saturated flow is compatible with MODFLOW 2005 (see below).
Numeric engine	USGS MODFLOW 2005	This is one of the modular three-dimensional finite groundwater flow models. It was created in 2005. See (USGS 2019)
Run Type	Steady-state Flow	Steady state flow means that the model will prepare a simulation for the first stress period. This means that there is a start time and a stop time.
Grid Size	X: 284 m Y: 476 m	This is the size of the model. The y- axis (north direction) and the x-axis (eastern direction).
Cell Size	2X2m Columns: 142 Rows: 238	The model is designed as a grid. The "boxes" in the grid are often referred to as cells. The resolution of the model is set by defining cell size. Smaller cells equal more cells.
Number of layers	2	It can be of use to divide the vertical direction of a model into different layers. This is because the vertical direction can have varying physical parameters.

with measurements taken from consultant reports. The available measurements covered only a small part of the model area. Bedrock surface elevation measurements from wells seemed not to have been measured systematically and were performed at different times and by different companies. Also, measurements were only available around the sawmill, which was insufficient for the larger model area. Because of the data insufficiency the bedrock surface had to be interpolated. This interpolation was already made by RGS Nordic (Nord 2019a). Since my model area was larger than the interpolation, the interpolation was extrapolated to the corners of the model area using ArcMap. The interpolation method chosen for this work was the *Inverse Distance Weighting* (IDW) interpolation method (App. 2). The interpolation in ArcMap is not transferable to Modflow. To import the interpolation of the bedrock surface I did a similar conversion as the one with the elevation (see below).

The ground surface elevation was imported by retrieving elevation data from Geodatabase of the Swedish University of Agricultural Sciences (SLU), originally produced as raster data by the Swedish National Land Survey. As the raster files were incompatible for importing into Modflow they were handled in ArcMap. The raster files were cut to fit the exact model area and converted to a point (feature) shape file (App. 3).

3.3 Flow properties and boundary conditions

A very important property of any water-bearing geological material is the hydraulic conductivity (K), which is a measure of how well water can flow through a material, the unit is m/s. In my model, I assumed that there are two separate layers which are homogeneous in terms of K in all directions. The top layer represents the filling material and the underlaying till. The top layer was set to a K value of $3*10^{-5}$ m/s (Lagergren 2019). The bottom layer represents the bedrock with a set K value of $1*10^{-9}$ m/s. This means that flow can occur in both layers. At the site the Quaternary top layer can be seen as an aquifer where most of the groundwater flows, while the underlying bedrock can be seen as an aquitard with a slower flow or no flow.

Recharge is a feature to add in Modflow, representing precipitation that infiltrates and creates groundwater. The value was set to 265 mm/year based on data from the Swedish Meteorological and Hydrological Institute (SMHI) as reported by Elander & Eriksson (2007). The next feature to add was hydraulic head observations. To add these observations, I created a shapefile containing point features from boreholes with groundwater surface data (obtained from piezometers). This was done in ArcMap with the use of an Excel spreadsheet containing head values and coordinates. Then I imported the shapefile into Modflow for exact locations of head observations. The coordinates of boreholes with measured head values were found in the consultancy reports and provided in an Excel file.

To run a model successfully, it is of paramount importance to initially define proper boundaries for the model. Otherwise, no matter how much input data is provided, the model cannot simulate groundwater flow properly and the results would be irrelevant or even misleading. Below I describe how and why model boundaries are defined in this study. The western border, defined as the shoreline of Lake Sjötorpasjön, was treated with a head package called *general head boundary.* This means that the selected cells were assigned identical head values along the entire western border. The head value for the lake was set to 157.7 meters above sea level. Conductance is a parameter that is either calculated or set as a value, representing the resistance of water flow within an individual cell. To simulate a lake the conductance had to be an insignificance factor since there is no resistance of flow in a body of water. To simulate no resistance flow, the value for the input of conductance was set to a high value compared to the rather low values for hydraulic conductivity. At the eastern border, cells were defined as a no-flow boundary because of the existence of a water divide in this direction, close to the former sawmill (SMHI 2020). These inactive areas are visualized with a darker green colour (Fig 4).

The southern border was defined as River Skaddeån, which is the outlet from Lake Sjöatorpasjön. The cells along the river were assigned with general head values to 157.7 and 157.5 meters above sea level (m a.s.l.). The river cells are divided into two segments. The segment closest to the lake have the value of 157.7 masl which are the same value as for the lake. At the segment there seems to be a slower flow environment with some kind of fen. The other segment have visible outflow marks in the elevation indicating a high flow environment. Because of this, the value for the cells were set to 157.5 masl which is slightly lower than the lake (App. 3). The northern border lacked available groundwater data. I decided to estimate a value based on elevation and distance to the lake. At the corner where the western and northern boundaries meet (lake and land), I decided that the head value would be slightly higher on the land area. The elevation generally increases to the east. Therefore, the head value increases correspondingly. I decided to reduce the hydraulic head gradient further away from the lake, meaning that the saturated zone surface and the elevation surface diverge away from each other in an easterly direction. All the input data for creating the model head contour lines were now in place, after which the model could be run. The start time was set to 0 days and the stop time to 1460 days (4 years).

3.4 Modpath and barrier

One of the aims of this study was to assess how groundwater flows. This was simulated in the model by adding particles following the groundwater flow to the model and then run the model with an engine called Modpath. Between the start position and the stop location a line is drawn and called “*path line*”. The start position was chosen by me. The stop position of each individual particle is set were the cell along the flow direction have a greater sink of groundwater flow than addition of flow from adjacent cells. Since the direction of the flow is towards the west particles were placed along a line perpendicular to the flow (north to south) with an initial distance between the particles of 1.4 m and a total of 60 particles (App. 4).

Another aim was to explore the performance of a permeable barrier to extend the groundwater residence time. Barriers were built in Modflow with the input feature called “*Wall package*”. The barriers were also placed perpendicular to the flow in order to maximize their blocking effect. Another consideration when placing the barrier is the location of contamination source areas.

Two types of barriers were tested. The first one is called “*continuous*” barrier, which is a simple straight-line barrier. The other barrier is referred to as “*funnel and gate*” barrier and consists of a permeable straight line (gate) and two other straight, impermeable lines attached at the edges of the gate line (Fig 6). The purpose of this is to force the flow through the gate or a longer path around the barrier.

Further field monitoring, tests and geochemical numerical modelling are needed for calculating an optimum thickness of a PRB. However, barrier thickness was set to 1 m in this study as a very common thickness in recent projects with similar site characteristics (Thakur et al., 2020).

4 Results

One of the main questions to be addressed was the best location to place a barrier. The first aspect to look at was the groundwater surface. This gives a visualization of how the groundwater flows. A greater hydraulic gradient result in a greater flow. The heads are visualized in Fig. 5.

The groundwater flow is from east to west according to the model results (App. 4, 5 and 6). Since the bedrock has a low permeability the main groundwater flow occurs in the Quaternary deposits. The flow in the figures visualises flow in the top layer. An east to west flow direction dominates in the area where the sawmill is located. In this location the flow is slightly directed towards the surface in the direction of the bay right west of the mill. Flow also occurs to the river in the southern part of the model.

Figure 4 shows a condensed map of the Modpath run. The coloured path lines in the map are chosen because they intersect with the contamination sources. The path lines have an individual colour together with individual boreholes. Boreholes that occurs along the individual path lines are set with the same colour as the path line. According to the flow model these path lines most likely represent the direction of groundwater flow across the contaminated site. Uncontaminated groundwater from the east enters the source areas

Table 4 Path line results

	Averge travel time (day)	Average travel distance (m)	Average velocity (m/day)
No barrier	316	88	0.2796
Continous	451	100	0.2217
Funnel and gate barrier	507	105	0.2071

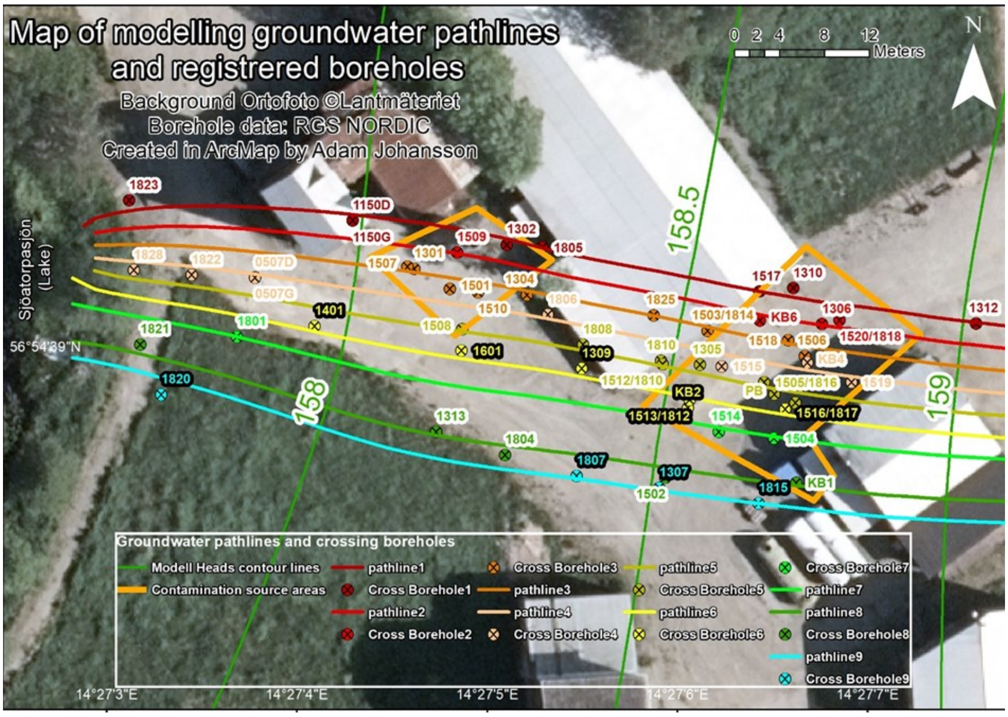


Figure 4 Map of boreholes and path lines marked in different colours representing paths intersecting boreholes. Boreholes are set with the same colour as the intersecting path line.

and might dissolve and carry the contamination to the west, where the lake is located.

The spread of the contamination "plume" could be mapped by sampling the boreholes. The expected spread would be along the path lines. The most suitable place for constructing a barrier based on the modelled flow would be somewhere between the bay area of the lake and the western source area (source area A in Fig 3).

The second question was how different physical parameters of the barrier affect the flow pattern and the groundwater residence time. The barrier scenarios (Figs 6 and 7, Table 4) were compared with a non-barrier scenario flow model (Fig 4, App 4). The funnel and gate barrier gave the longest average groundwater travel distance and residence time (Table 4).

Rotation of the barrier was also one of the physical parameters that was tested. Rotating the FGB gave no significant increase in residual time. However, for the continuous barrier it was beneficial to rotate the barrier slightly with the top end to the east and the bottom to the west, as it enabled to extend it more to the north without intersecting with buildings.

The third question to be answered was how different values of hydraulic conductivity of the assumed homogenous bedrock affect the flow. This was tested with the funnel and gate barrier. The results showed that a barrier with a lower hydraulic conductivity than the bedrock resulted in a very long residence time for flow and a substantial

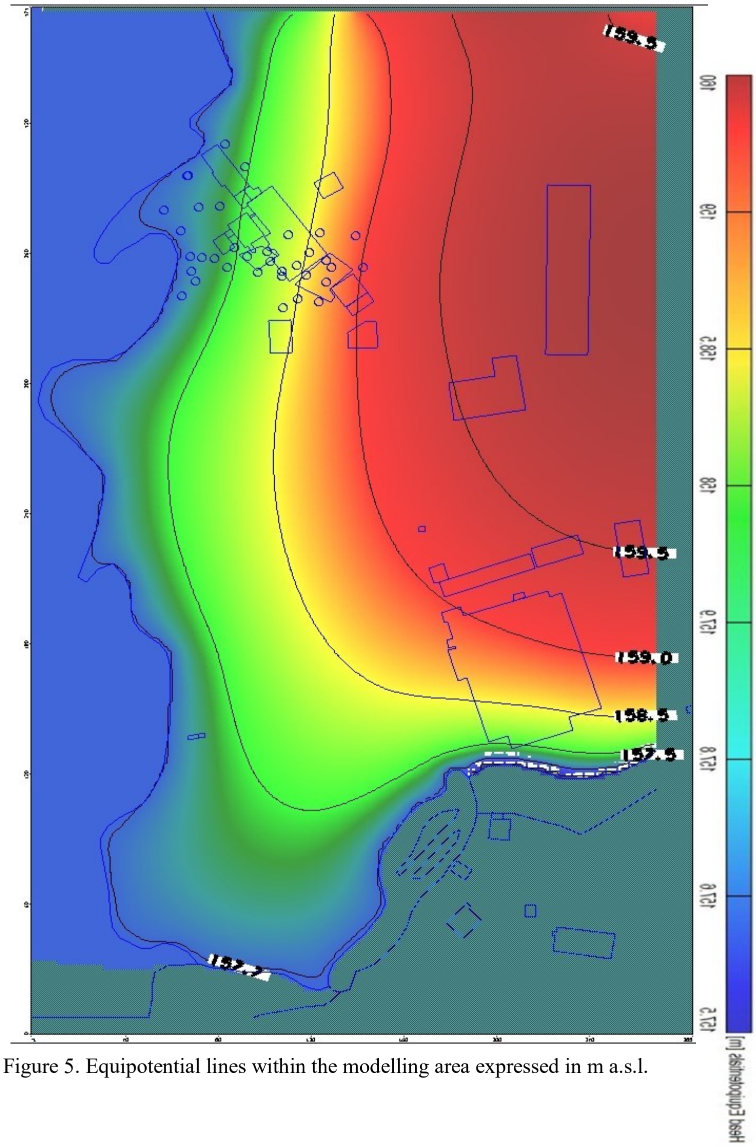


Figure 5. Equipotential lines within the modelling area expressed in m a.s.l.

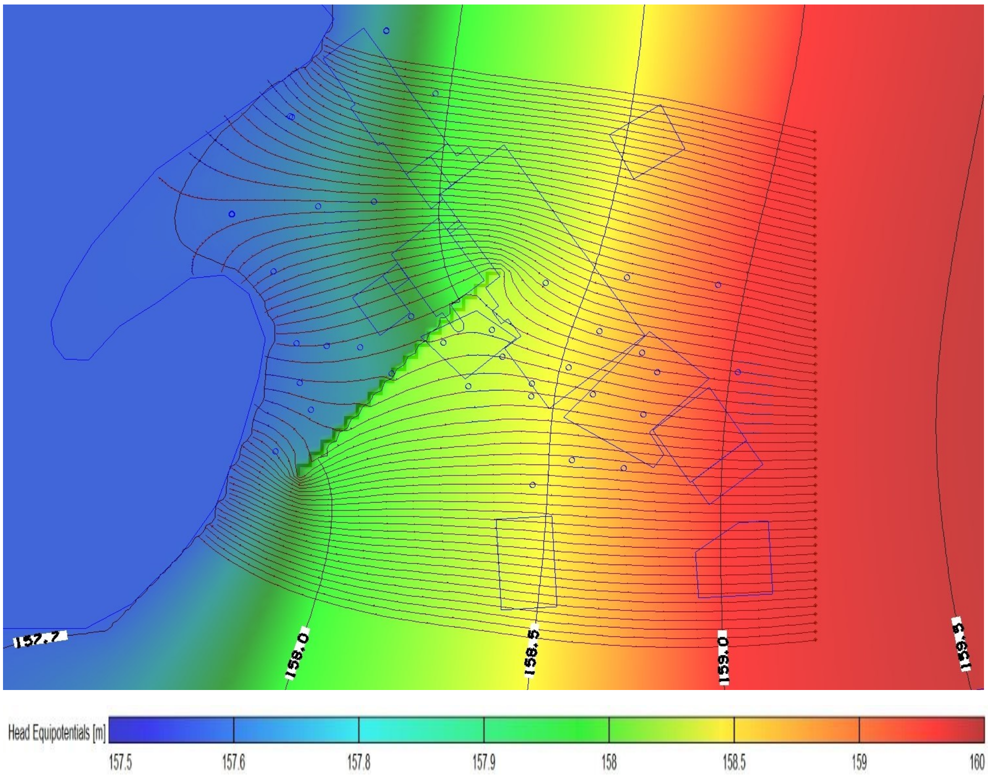


Figure 6 The location of the most suitable continuous barrier. The horizontal lines represent particle path lines. Equipotential lines are given in m a.s.l.

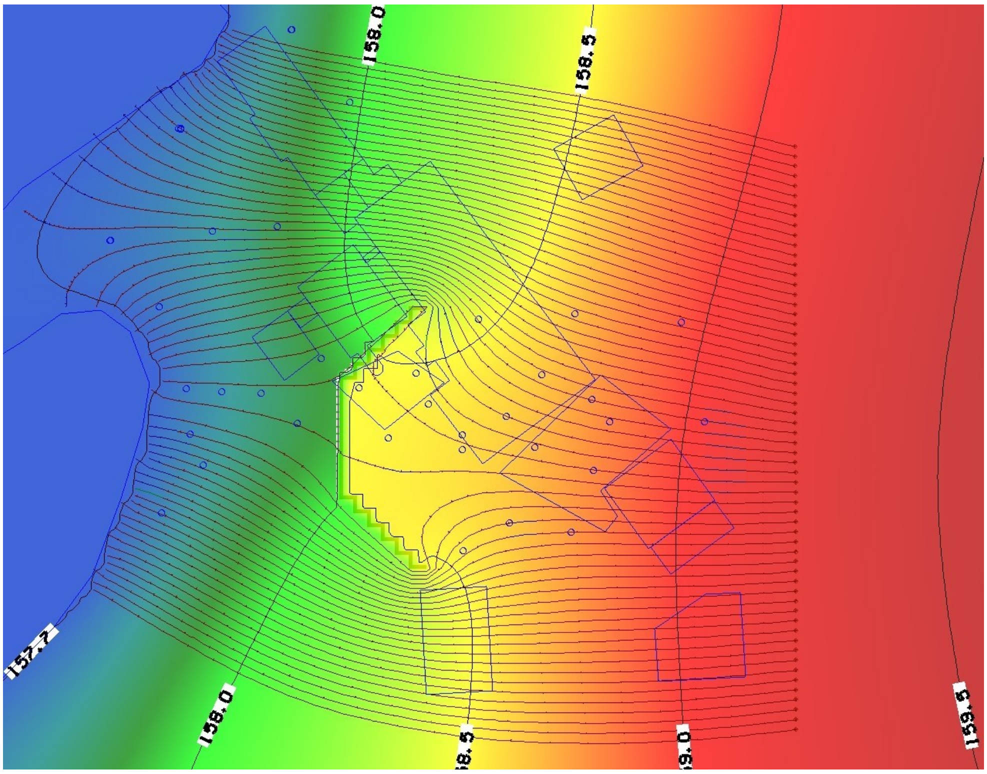


Figure 7 *The location of the most suitable funnel and gate barrier. The horizontal lines represent particle path lines.* Equipotential lines are given in m a.s.l.

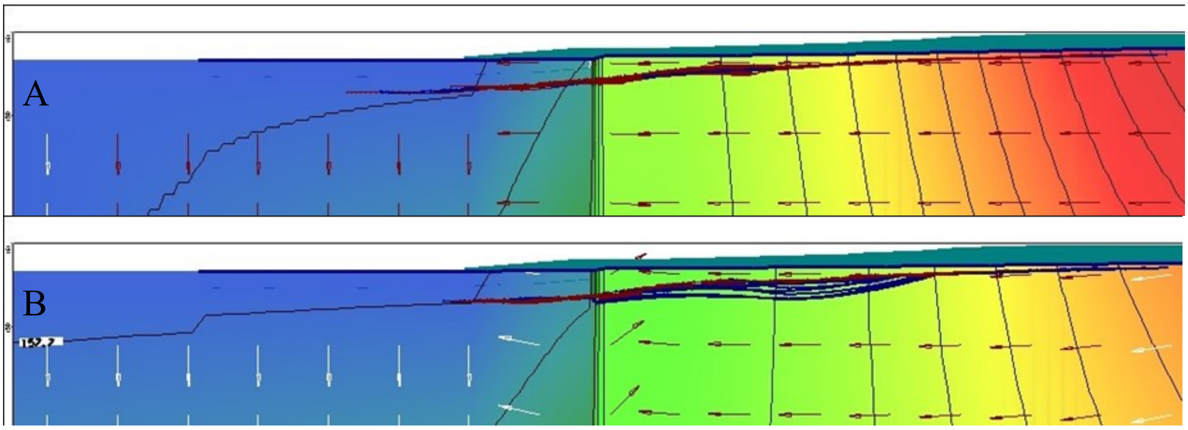


Figure 8 Modpath runs seen from vertical point of view. The blue colour to the left is the lake. The barrier is roughly located where green and blue colour meets. In A the hydraulic conductivity for bedrock is lower than for the barrier, resulting in a gathering of path lines at the top surface of the bedrock layer. In B the hydraulic conductivity for bedrock is higher than the barrier. It is visible that path lines go deeper into the bedrock layer in this scenrio.

amount of flow entering the bedrock. In the opposite situation where the barrier conductivity was higher than bedrock the residence time was shorter and most of the flow occurred in the quaternary top layer (Fig. 8).

5 Discussion

The groundwater head contour line results are the first results that need to be considered. Most of the sources of error relates to the input of model data.

The surface elevation was an example of complete data input. This data source contained a lot of data in a small scale, resulting in a precise data input for the model. However, the bedrock surface elevation is poorly constrained because of the extrapolation. Data were only provided for a small part of the study area (App. 2). The bedrock data are also taken from boreholes, which in themselves are sources of errors.

Another important type of model input that most likely contains large source errors is the hydraulic conductivity. First, the model is segmented into two layers. One for the unconsolidated Quaternary top layer and one for the crystalline bedrock below. The unconsolidated layer was in the model assigned a constant value of $3*10^{-5}$ m/s. This value is a geometric mean value based on the slug tests (Lagergren 2019), which represents the entirety of the layer. The layer contains two different units, the filling material, and the till. In the model there was no separation of the two. Based on assumed grains sizes it is apparent that the filling material has a higher K than the till. The K-value test was only performed inside the former sawmill area while the model covers a larger area. The till is also known to be heterogenous with substantial variability within the study area (Nord 2018). Making the model more realistic by dividing the unconsolidated layer into filling material and till with different K-values is a suggestion for additional investigations of the site.

The hydraulic conductivity of the bedrock, which is based on general averages in the absence of local data, is also a major source of error. The value $1*10^{-9}$ m/s was used. Crystalline bedrock usually has a very low hydraulic conductivity, but it depends to a large extent on the amount of fractures. Air magnetic photos can discover water bearing fractures (Johansson 2006). According to the Geological Survey of Sweden the hydraulic conductivity is often in the range of $1*10^{-10.8}$ – $1*10^{-7}$ for crystalline bedrock in most parts of Sweden (Wahlgren 2015). Another source of error is the recharge, which is difficult to estimate accurately. The value used in the model was taken from a consultancy report (Axelsson & Håkansson 2012).

The “best location” of a permeable barrier was motivated by the Modpath run. It could be seen that the flow had a western direction with a slight bend towards north. This seems logical since the bay area is the point where the lake is closest to the site. This is based on that groundwater flows towards the lake, although lake water may also infiltrate to the land area. Placing the barrier as close as possible to the contamination source is of importance. A few runs indicated that placing the barrier more to the west yielded a longer transport time for water. However, the main purpose of the barrier is to prolong the residence time of contaminated water, not just groundwater in general. The barrier needs to be installed in front of the groundwater path from where the flow intersects with the contamination sources. It is also negative in a constructional point of view; the barrier should not be installed too close to the lake. In the model the barrier was installed with a depth to the bedrock surface, forcing groundwater to flow either through or around the barrier.

It should be noted how the FGB affects the groundwater level. The model runs for four years, which raises the question of whether the area around the barrier will be saturated because of a raising groundwater level caused by the excessive blocking of the flow. On the other hand, the continuous barrier does not block groundwater flow as efficiently but allows groundwater flow to cross through the barrier, possibly making it better for chemical oxidation. This is because the barrier can be built with a oxidizing material and can then chemically oxidize the entering groundwater.

Because the hydraulic conductivity of the bedrock is unknown it was important to test different K values for the bedrock. In Fig. 8B the flow in this figure yielded a very long travel time, which is preferable. But as seen in the figure, the path lines (blue) are travelling further down in the bedrock. This is not beneficial because spreading of contaminants to the bedrock should be avoided. Remediation of bedrock is usually very complicated and costly. Decreasing the hydraulic conductivity (K) of the bedrock compared with a barrier with a constant K which is lower than the unconsolidated layer only works to a certain point. At this point the system reaches an equilibrium where the system reflects the flow through and around the barrier. This is because the K value of bedrock has decreased to the point where the bedrock layer acts as if it were impermeable. In this scenario the flow is mostly located in the top layer with the Quaternary deposit (Fig. 8A).

Lastly, there is an inherent uncertainty in any modelling exercise that limits its functions and our expectations from it. Still, we consider models as useful as they enable understanding of complex situations, which facilitates communication with different stakeholders.

6 Conclusions

* The best location for placing a barrier is between the bay area of the lake and the western contamination source, preferably closer to the contamination source.

* The FGB is evidently more efficient than the continuous for slowing down groundwater flow, resulting in a longer residence time.

* The continuous barrier benefitted from being rotated with the top end towards east and the bottom end to the west. This is because the rotation creates space which makes it possible to extend the construction of the barrier.

* The long-term use of FGB is uncertain. The continuous barrier might be better for adding an oxidation medium because the barrier does not block flow as efficiently which allows more flow to go through the barrier rather than around the barrier.

* A barrier permeability lower than the bedrock is obviously not preferable because it can cause contamination spreading to the bedrock

* The input data in the model can cause big sources of error. It is recommended to gather more data for building a more reliable model depending on availability of resources and time. K-values for geological units are of most importance in this view as they are playing the main role in the modelling practice. Having more reliable K-values reduces the uncertainty of the model and the consecutive results.

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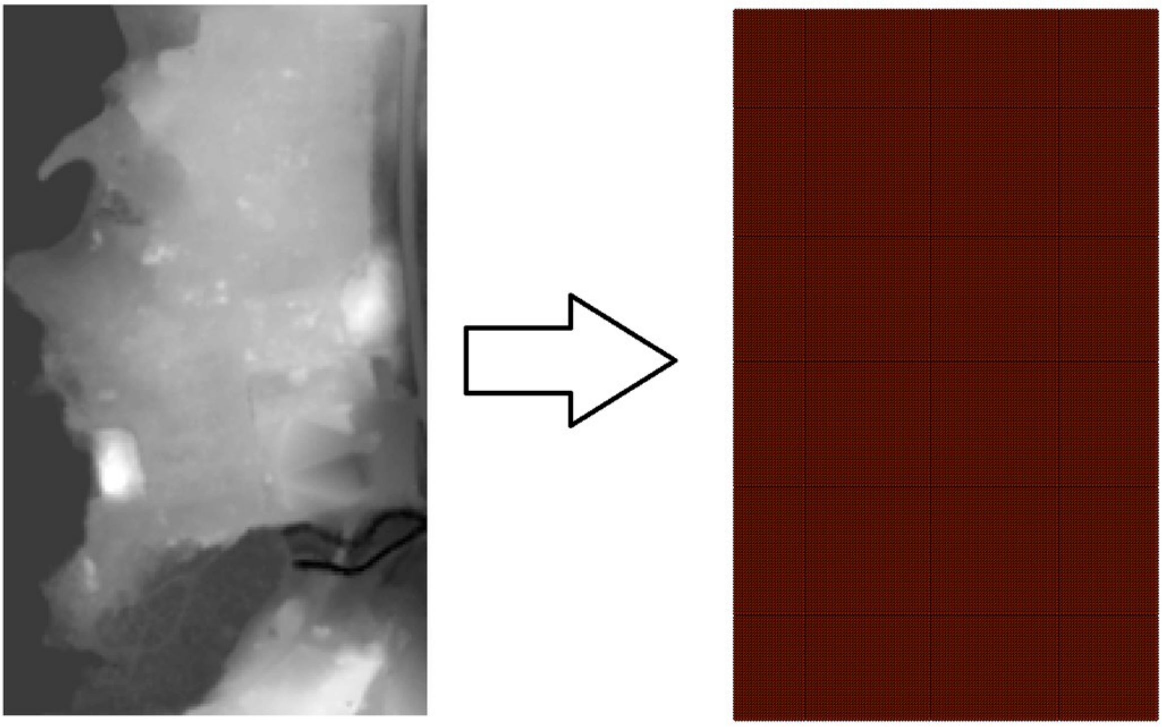
9. Appendices

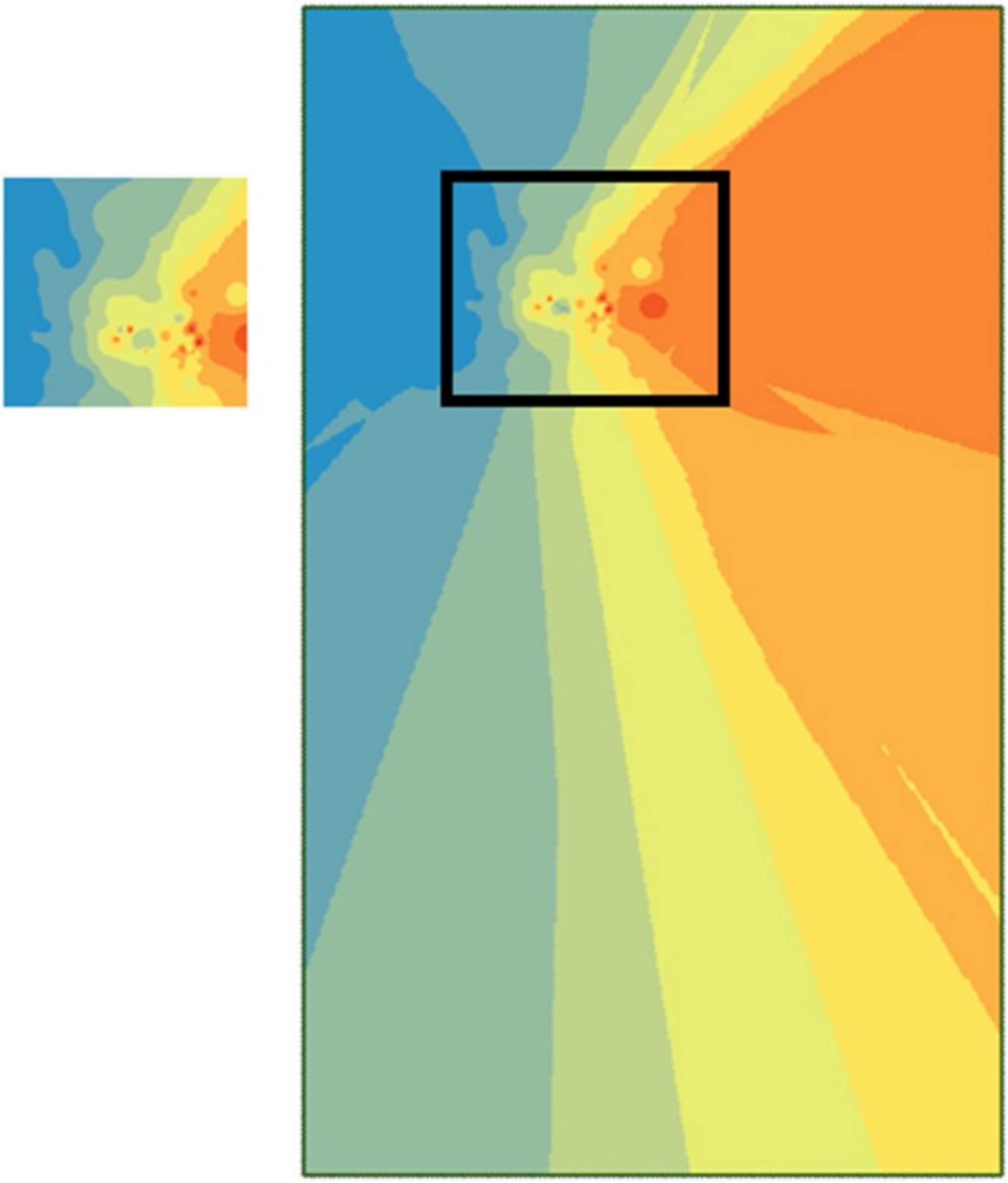
Appendix 1

Conversion from elevation data to shapefile point elevation. The red picture to the right is illustrating a shapefile with dense elevation data points. Created in ArcMap and edited in Paint.
© Microsoft Corporation 2019. Elevation data ©Lantmäteriet..



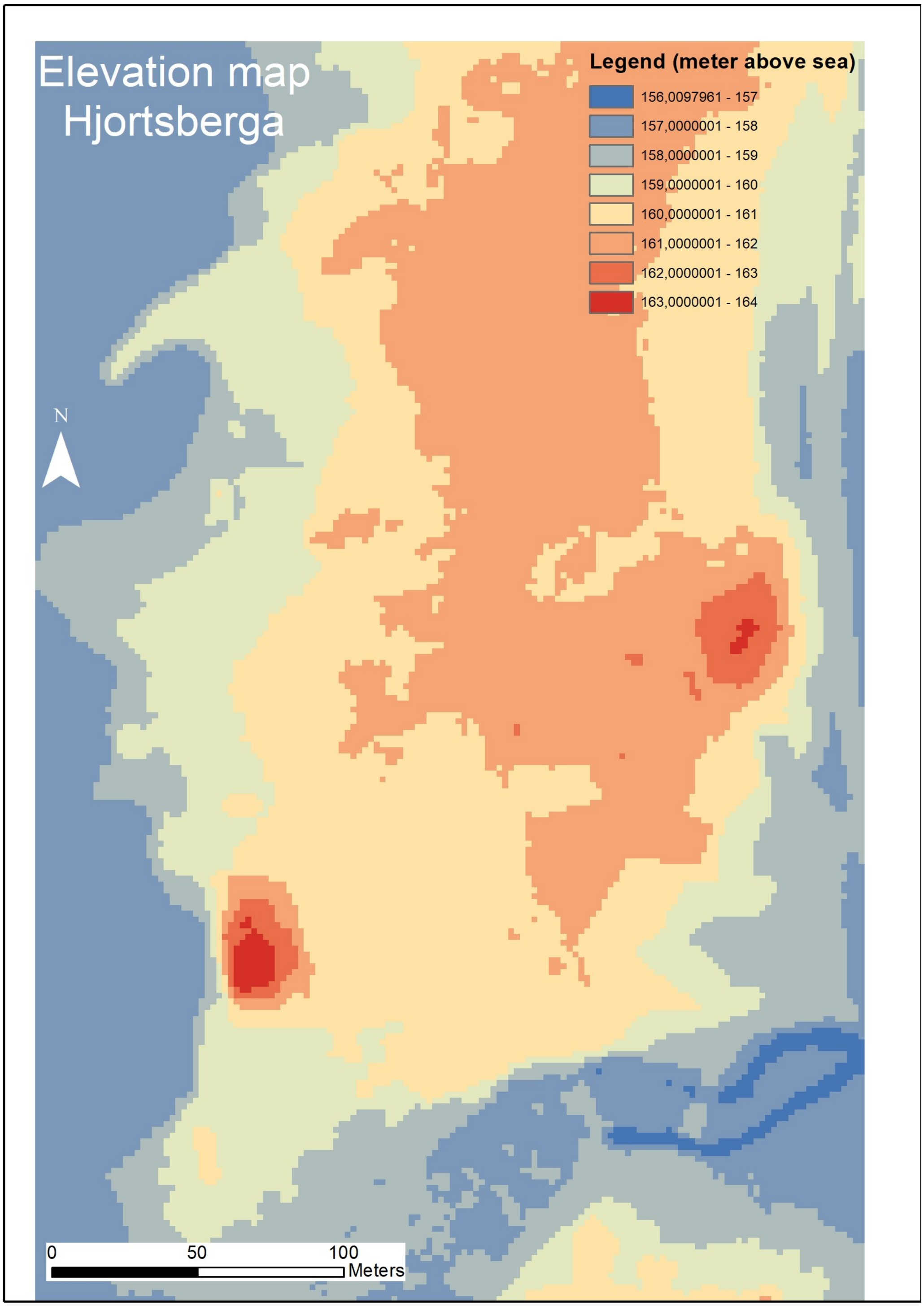
Appendix 2

Bedrock interpolation elevation. Created in ArcMap and edited in Paint.
© Microsoft Corporation 2019. Borehole Elevation data RGS NORDIC (Nord 2017).



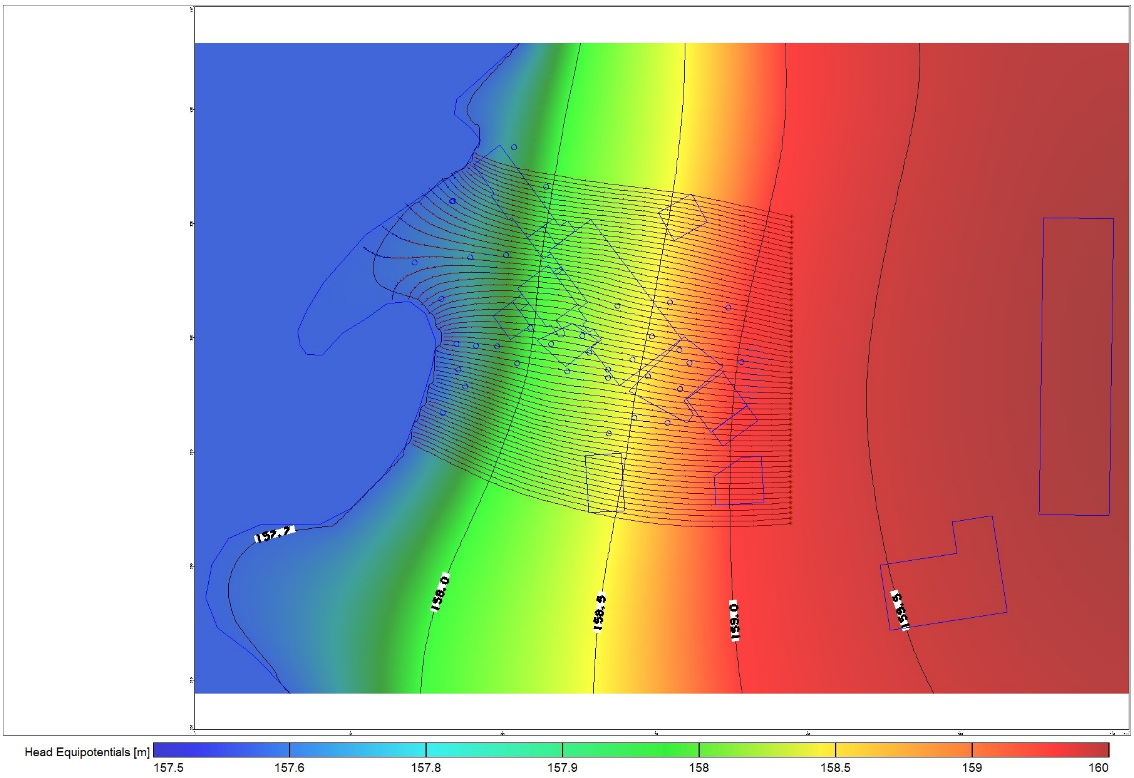
Appendix 3

Surface elevation map. Created in ArcMap. Elevation data ©Lantmäteriet..



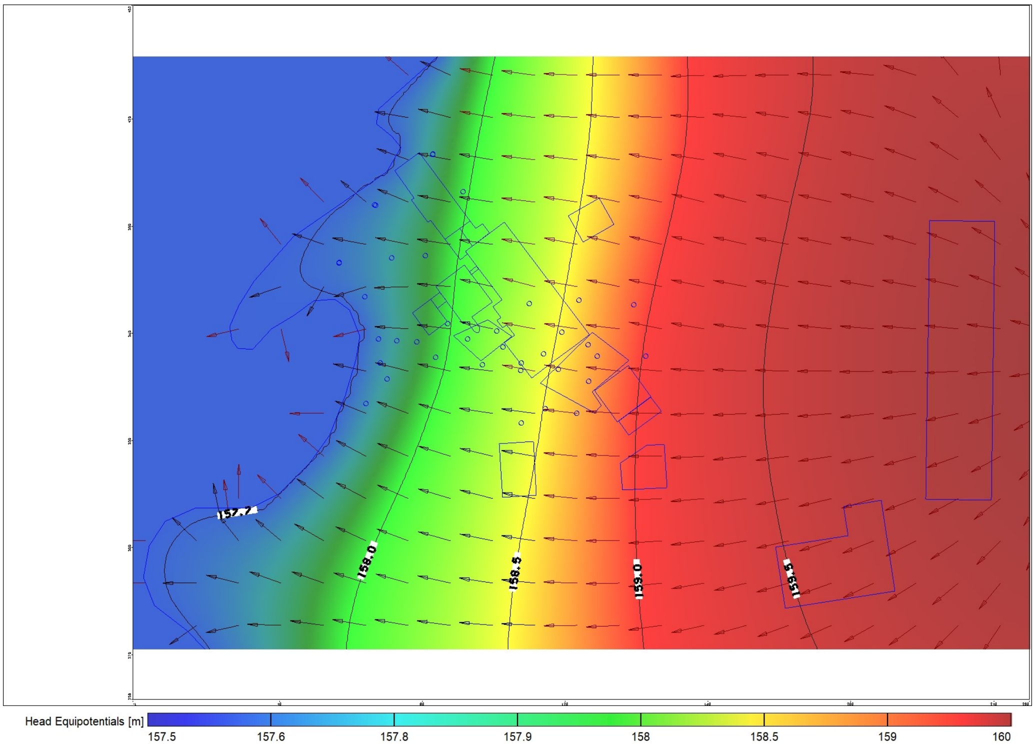
Appendix 4

Modpath run without any barrier. The starting positing (to the right of the pathlines) is where particles are set (Harbaugh 2017).



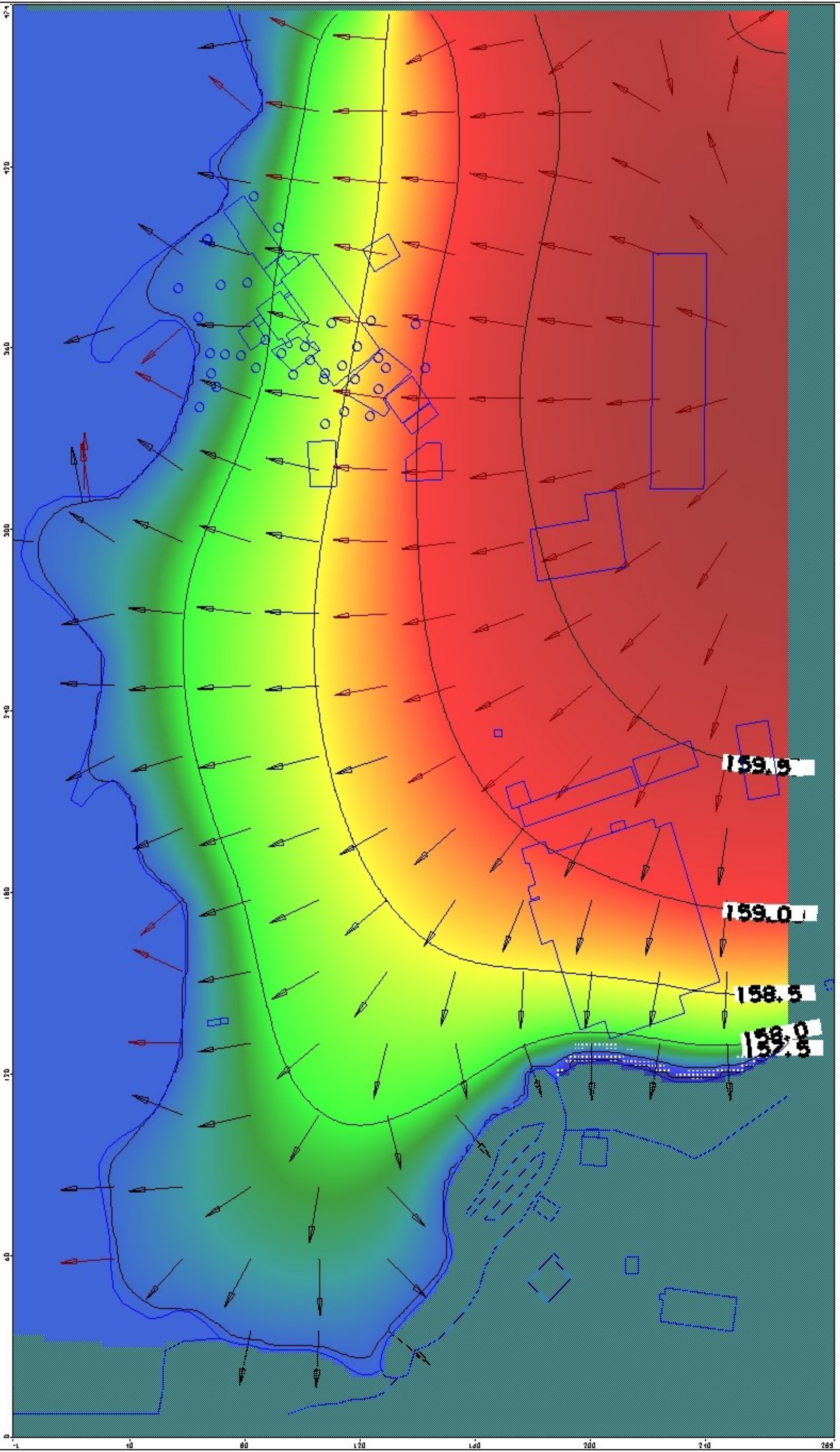
Appendix 5

Flow velocity direction at the sawmill site (Harbaugh 2017).



Appendix 6

Flow velociy direction for the whole model area (Harbaugh 2017).



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