Assessment of the Contribution of Groundwater Flow and Surface Flow from Bolmsö Island to Lake Bolmen, Sweden.

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Assessment of the Contribution of Groundwater Flow and Surface Flow from Bolmsö Island to Lake Bolmen, Sweden.

Uppskattning av grundvatten- och ytvattenflöde från Bolmsö till sjön Bolmen

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Lund, June 2020
Angelique UWERA

Abstract

The increase of brownification in surface waters has been a problem to rivers and lakes from northern hemisphere. The main factors of this water brownification are the increase of dissolved organic matter and iron in water bodies. This study aims to assess the contribution of groundwater flow and surface flow from Bolmsö Island to the water balance of Lake Bolmen, Sweden. This assessment helps to estimate the interaction between the groundwater and surface water at Bolmsö Island and make predictions about the groundwater and surface water flow influencing water browning inside Lake Bolmen.

MODFLOW within GMS 10.4 groundwater model was chosen. A steady-state condition was used during simulation and calibration of the model. To obtain a running model, different assumptions and simplifications were done.

The results of the simulation and the calibration show that the water balance between Bolmsö Island and Lake Bolmen includes a significant amount of groundwater almost 12970 m^3/d flowing from the island to the lake and a small amount of water approximately 30 m^3/d flowing from the lake to the island. The resulting amount of surface runoff was estimated to be 18100 m^3/d.

Water flowing from Bolmsö Island to Lake Bolmen is likely to contain an uncertain amount of red-brown colored soil particles from bogs and fens. Hence, there is a probability of brownification of water in the lake, however, to apply the results of this thesis, further investigation and simulations are required.

Keywords: Groundwater, Surface water, GMS-MODFLOW, Bolmsö Island, Lake Bolmen, Brownification.

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1 Introduction

1.1 General background

Water is very important for living organisms. Water appears chiefly as groundwater and surface water. Surface water consists of rivers, lakes, seawater, and other receiving waters that capture runoff water coming from precipitation and snowmelt. Groundwater consists of rainwater that has infiltrated the soil and stored in the saturated zone (Rajagopal et al., 2017). Groundwater is used for different purposes including irrigation, domestic needs, and livestock (Mathew & Krishnamurthy, 2014).

Heath (1983), defines groundwater as water located below the water table in the saturated zone, in the geological formations known as aquifers. It moves in two different ways; the vertical movement is driven by gravity, also known as percolation, in which surface water percolates the unsaturated zone and flows towards the groundwater table, this process can be also defined as groundwater recharge. The lateral movement in which groundwater flows from higher to lower groundwater levels referred as potentials or hydraulic heads (Elango, 2005). Water quality control is important in its use which is why due to the use of water, chemical, physical and biological standards must be complied with (Roy, 2019).Water pollution is a major problem for both human and aquatic organisms. Discharge of pollutants into water bodies is the major origin of the pollution of water (Koshal, 1976).

A special form of pollution is when the presence of a coloring agent in the water transforms its original color, often into brown(Inamori & Fujimoto, n.d.). There are also other possible changes in color, not to be mentioned here. Surface water runoff has also a great influence on the quality of water in reservoirs such as lakes, rivers, ponds, and other receiving water bodies. Materials such as sediments collected during the pass-through of water can be transported into the water bodies and affect their water quality as well as their color. Streams play an important role in the way that they carry sediments from upstream to downstream(Chapman et al., 2014).

1.2 Problem description

In recent years, brownification of surface water has become a problem in many lakes particularly located in the northern hemisphere. According to SLU (2003), it originates mainly from nearby humus-rich soils which are close to a water body leaching humic substances into the nearby water body. When dissolved organic matters that are in the water body, absorb short-wavelength visible solar radiation, the color of water becomes brown. Aquatic macrophytes and terrestrial or wetland origin are main sources of dissolved organic matter (Graneli, 2012).

The movement of groundwater can transport organic materials, which may dissolve and affect the color of surface waters (Ekström, 2013). Type of the soil, topography of the terrain as well as the climatic conditions, are key factors to determine the discharge rate into the surface water bodies. Depending on elevation of the groundwater table, the direction of water flow between groundwater and surface water can vary.

The movement of surface water towards groundwater can transport small particles and other dissolved substances. Some of these particles can be captured on the way while others will be transported away with groundwater flow (Winter et al., 1999).

Lake Bolmen is one of the two major sources of drinking water for southernmost Sweden and it is accessed through the Bolmen tunnel. This lake is getting gradually browner due to an increase of dissolved organic matters and the presence of iron ions. Ekström (2013) pointed out that the concentration of iron has increased significantly in Lake Bolmen. The contamination of groundwater can be connected to the quality of surface water and vice versa. The transported pollutants during the water flow to the recipients, play an important role in the quality of water (Winter et al., 1999). To assess the interactions between groundwater flow, surface water flow, and Lake Bolmen; it is necessary and required to know how each of them contributes to the brownification of the lake.

1.3 Objectives of the study

The main objective of this project is to investigate the impact of groundwater and surface water flow originating from Bolmsö Island to the water balance of Lake Bolmen. Through this main objective, it could be possible to estimate the interaction between the groundwater and surface water at Bolmsö Island and make predictions about the groundwater flow and surface water flow influencing water browning inside Lake Bolmen.

1.3.1 Specific objectives

In order to achieve the aim and objectives the following specific objectives will be determined

- Estimation of groundwater recharge and groundwater outflow of Bolmsö Island
- Estimation of the amount of surface water that discharges into Lake Bolmen from Bolmsö Island.
- Adapt a groundwater model in GMS MODFLOW of Bolmsö Island to simulate the present groundwater situation

1.4 Structure of the report

This thesis report consists of five chapters. The introduction as the first chapter describes the general background, the description of the problem in the study area and the objectives of the study. The second chapter is the literature review which highlights previous findings related to this study. The third chapter describes the material and methodological approach used for this study. The approaches of the used model MODFLOW within GMS 10.4 are extensively described. The results obtained from the model simulation are presented in the fourth chapter. The fifth chapter comprises the discussion of the results and the sixth chapter is made of the conclusion and the recommendation.

2 Literature review

2.1 Water quality

The quality of water generally refers to water which is safe from pollutions at acceptable standards. It depends on different factors such as climate, season of the year, the soil type and vegetation, human activities, and the flow conditions (Chaudhry & Malik, 2017). A change in water color is a one of the signs indicating that water does not have its chemical or physical quality (Jachimowski, 2017). That change in color often originates from the presence of dissolved organic carbon (DOC) and iron concentration in water bodies.

So far, it has been shown that DOC is the main cause of change of water color in water body, which increases highly when both DOC and iron are present in water body (Weyhenmeyer et al., 2016). Seasonal changes were found to be a possible driver of increasing of DOC in water, as it enhances the terrestrial productivity and transport of dissolved organic matter (Kritzberg et al., 2020). The increasing of DOC in water bodies has negative impacts on aquatic organisms which can result in reduction of food for aquatic animals (Feuchtmayr et al., 2019) . Precipitation, soil moisture, temperature and land use are the main elements that controls the formation of DOC (Tumdedo, 2010). Many presented theories about origin and driver of brownification show correlations, but they do still need more thorough verifications to be seen as proven.

2.2 Groundwater

Groundwater is a vital source of water for different purposes of usage (Yihdego & Khalil, 2017). It appears beneath the surface, in the pores of the soils and other geological formations. At some depth below the soil surface, those pores are fully saturated with water, on the top of the zone of saturation there is a water table (Jones et al., 2017). Depending on the climate, groundwater generates water for most of the surface-waters (Freeze & Cherry, 1979). Under the soil surface, there exist two different zones: the zone that is immediately below the surface and which is in contact with the air is the unsaturated zone; whereas the zone which is not in contact with air is the saturated zone.

The big amount of water that can be extracted is found in the saturated zone whereas a small amount of water is situated in the unsaturated zone, this water cannot be easily extracted. The flow of water occurs as a vertical movement through the unsaturated zone when precipitation infiltrates into the soil and moves downward by gravity. A lateral movement occurs mainly when groundwater moves from high hydraulic head to low hydraulic head (Winter et al., 1999). The recharge of groundwater originates chiefly from infiltration and percolation of precipitation in a humid climate like the one around Lake Bolmen. When water leaves the groundwater, the term is referred to as discharge; it occurs when groundwater flows towards surface water bodies, it can also be discharged by well extraction. Some amount of groundwater located near the ground surface can be discharged by evapotranspiration (Todd & Mays, 2005).

The groundwater flow is dependent on the soil type and its conductivity properties. It is relatively high in sandy and gravelly soils whereas in clayey soils, the flow is low (Harter, 2003).

2.3 Groundwater recharge

Precipitation is the main source of groundwater recharge. The recharge depends on the intensity and the duration of precipitation, the soil type which is characterized by the infiltration capacity, and the slope of the terrain. The groundwater can also be recharged by surface waters such as rivers, lakes etc. which are situated above the groundwater table. Water from rivers and canals above the groundwater table may infiltrate depending on the permeability of the geological layers between the surface water and the groundwater (Winter et al., 1999). Figure 2-1 shows the groundwater recharge of unconfined aquifer.

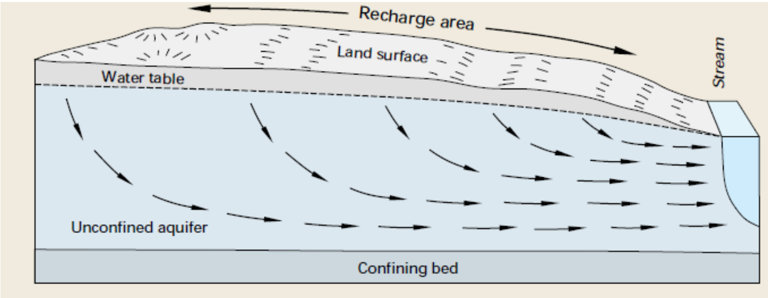


Figure 2-1. The recharge of groundwater of an unconfined aquifer by the precipitation water that infiltrates the soil. The arrows represent the flow of groundwater towards the nearby water body. (Winter et al., 1999).

Groundwater can also be recharged artificially in an area with little precipitation, where the infiltration rate is too small or has been reduced due to man-made activities. Artificial recharge is done by injecting water to the aquifer through shafts or percolation by gravity from open infiltration ponds (UNESCO, 1980). Figure 2-2 shows an example of how groundwater is artificially recharged.

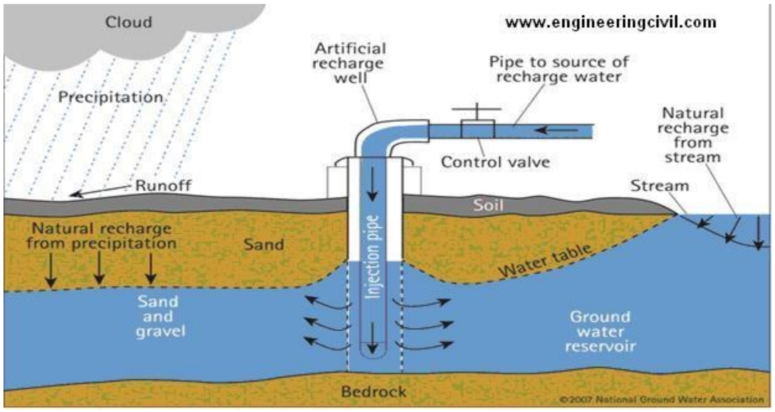


Figure 2- 2. The groundwater recharge by the artificial method (Shaikh et al., n.d.).

The surface water and the groundwater are interconnected. This can be proven by the pollution of groundwater that may be caused by the seepage of contaminants from the surface water to the subsurface water (Baalousha, 2012). Figure 2-3 shows how surface water interacts with the groundwater. Water may be discharged from the groundwater to the river if the water table level is higher than the level of neighboring surface water. If the soil that is above the water table is impermeable, the rainwater runs towards the rivers and lakes or other adjacent water bodies.

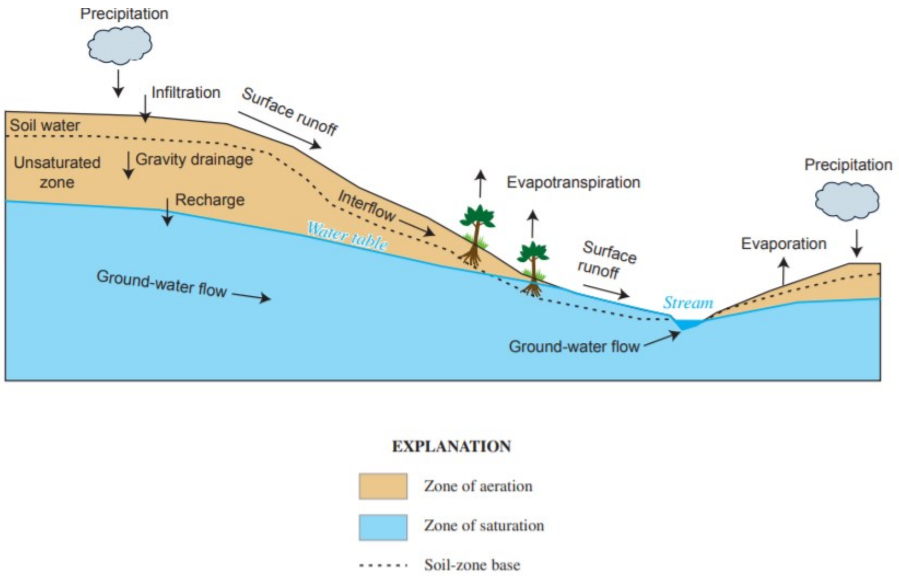


Figure 2- 3. Interaction between groundwater and surface water (Markstrom et al., 2008).

2.4 Surface runoff

Surface water occurs mainly as lakes and rivers, and in the surface depressions in which rainwater is detained. Surface water can be removed either by the evapotranspiration or the infiltration into the soil. Surface runoff occurs when the intensity of precipitation goes beyond the infiltration capacity of the soil and there is an inclination of the ground surface. It may also occur when the groundwater table reaches the surface. The factors that affect the rates of the surface runoff generally include the slope of the ground, the moisture content of the soil, and the intensity and duration of rainfall (Berris, 1995).

In figure 2-4, the precipitation may occur as rainfall or snowfall. Part of the precipitation can be intercepted by the vegetation and evaporated right away from the surface or from the vegetation. The other part of precipitation can infiltrate the soil or penetrate the vegetation referred as through fall. The remaining water may be retained by depression storage or run towards the streams known as overland flow.

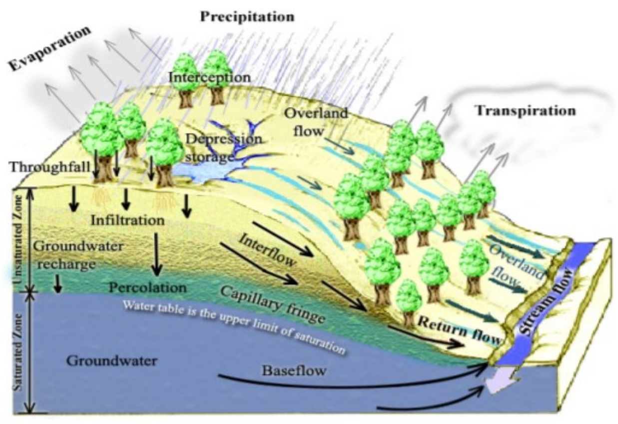


Figure 2-4. The mechanism of surface runoff generation (Tarboton, 2003).

2.5 Transport of pollutants

The contamination of receiving water bodies originates mainly from pollutants transported during the surface runoff. Those pollutants can be dissolved in water or remain suspended in water. During the storm time, the soil materials can be washed away and transported to the water recipients (He et al., 2014). In both surface water and groundwater, the contaminants appear in particulate or in dissolved form. The solid pollutants are mainly the soil particles that are transported away and introduced to surface waters. Their transportation depends on the size, shape and density of the grains, and the flow velocity (Durães et al., 2018).

The contaminants in groundwater may occur as a non-aqueous liquid or in dissolved state if it is dissolvable in water. The latter are transported by three different processes which are: diffusion, dispersion and advection. Diffusion is the movement of soluble contaminants from high to low concentration. Dispersion is the process of reduction in concentration due to the mixing of uncontaminated groundwater with a solute in flowing water. Advection is the mode of transport by which the contaminants move along with the groundwater movement (Fetter, 2014).

2.6 Groundwater modeling system and MODFLOW

In order to investigate and quantify the hydrogeological conditions, and the groundwater conditions, models that use mathematical equations are needed. Groundwater models use assumptions considering the properties of the geological boundary conditions, the geometry of an aquifer/aquitard, heterogeneity or anisotropy of sediments or bedrock, and their properties within the aquifer (Kumar, 2002). There exist various type of models which can be used to simulate the groundwater situation, including Groundwater Modeling System GMS which aims at simulating groundwater flow and transport and MODFLOW which is a three dimensional and a block-centered finite-difference model that can simulate the groundwater flow in a saturated and porous medium. A simulation within MODFLOW is completed by considering the recharge, the groundwater flow to wells, rivers, and to drains (Fetter, 2014). The governing equation in describing the groundwater flow with a constant density, non-equilibrium conditions in a heterogeneous and anisotropic medium are described in equation 3-4 (McDonald & Harbaugh, 1984).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \textit{(2-1)}$$

Where

K_{xx}, K_{yy}, and K_{zz}, are values of hydraulic conductivity in x, y and z directions (LT^{-1}), h is the potentiometric head (L), W is the flux per unit volume and represent volumetric flux of groundwater sources and/or sinks of water (T^{-1}), S_s is the specific storage of the porous material (L^{-1}); and t is time (T). The model used the finite difference approach to solve the groundwater flow equation.

2.7 Aquifer and aquitard

An aquifer is a geological formation that is capable to store and transmit water in significant amounts for water supply. An aquitard is a geological formation that can store water but only allows the flow of water at a small rate, usually not enough for water supply. Clayey sand and till are examples of sediments that can form an aquitard due to low hydraulic conductivity. When an aquifer is located near the ground surface without any impermeable layer on the top of it, it is called unconfined aquifer (Freeze & Cherry, 1979). One of the characteristics of an aquifer-aquitard is hydraulic conductivity. The hydraulic conductivity is dependent on the soil permeability, the density of the fluid, the viscosity of the fluid, and the degree of saturation (Diminescu et al., 2019) and is mathematically defined as shown in equation 2-2 (assuming saturated conditions)

$$K = k\frac{\rho g}{\mu} \qquad \textit{(2-2)}$$

Where K is the hydraulic conductivity (in cm/s or m/s), k is the intrinsic permeability (in Darcys), ρ is the density of the fluid, g is the acceleration due to the gravity, and μ is the dynamic viscosity of the fluid (Porges & Hammer, 2001). Fetter (2014) has reported the hydraulic conductivity of different geological materials as ranges of values presented in table 2-1.

*Table 2-1. Intrinsic permeabilty and hydraulic conductivity in cm/s of different soil*s *(Fetter, 2014).*

Material	Intrinsic Permeability(Darcys)	Hydraulic conductivity(m/d)
Clay	10^{-6}-10^{-3}	$8.6x10^{-7}$-$8.6x10^{-4}$
Silt, sandy silts, clayey sands, till	10^{-3}- 10^{-1}	$8.6x10^{-4}$-$8.6x10^{-2}$
Silty sands, fine sands	10^{-2}-1	$8.6x10^{-3}$-0.864
Glacial outwash	1-100	0.864-86.4
Well-sorted gravel	10 - 10^{3}	8.64-864

3 Material and methods

3.1 Description of Study Area

This study was carried out in Bolmsö Island, the biggest island of the Lake Bolmen located in the south of Sweden as shown in figure 3-1. The island extends from the middle towards the north of the lake. The island is 18 km long and has a width of between 3 km and 4 km. The Bolmsö Island covers an area of 42 km^2 calculated in GIS software, and its land is mostly made up of forests.

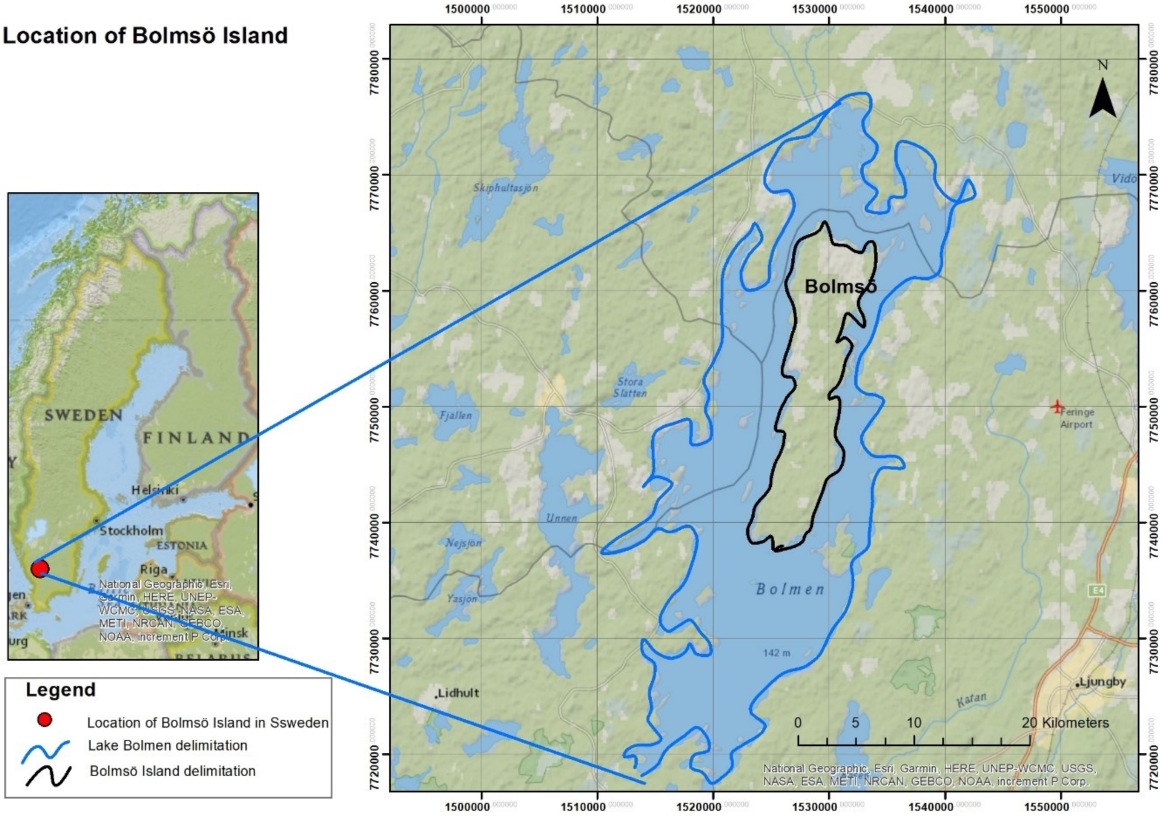


Figure 3- 1. The location of the Lake Bolmen and Bolmsö Island.

3.1.1 Hydrology

The hydrology of Bolmsö Island mainly consists of Lake Bolmen surrounding the island, groundwater and a few small streams on the island. Surface water of the island is discharged into Lake Bolmen, twelfth of the largest lakes in Sweden with an area of 184 km^2 and with 30 km and 10 km of length and width respectively. The lake serves as drinking water source for the western region of Scania. The island and the lake are parts of the Bolmen basin that covers an area of 1640 km^2 and is the largest sub-basin of the River Lagan watershed, which has a total area of 6454 km^2 (Persson, 2011).

3.1.2 Geology and Hydrogeology

The geology of Bolmsö Island consists of a basement of Precambrian crystalline bedrock, which is the oldest geological formation in the area, more than 1,700 million years old. On top of the bedrock different Quaternary formations are found, less than 100,000 years old. Some of them are not resistant against erosion and may partly have been "wiped" away over time. For the case of Bolmsö Island, there is nothing on top of the old Precambrian bedrock in a few places (outcrops of rock), however in most areas the rock is covered by glacial till directly on top of the bedrock. There are also glaciofluvial deposits in some areas, usually as a third layer, situated on top of the till. In other zones there exist bogs and fens situated in depressions in the till layer.

From the figure A presented in Appendix 1, the geological formations that are situated on top of the Precambrian rocks in the Bolmsö Island can be seen. As shown in the figure, almost 68% of the island consists of sandy-till. The glaciofluvial deposits are located in the northern and eastern parts of the island, and small zones with sand are located in the northern and southern parts and bogs and fens are scattered all over the island.

3.1.3 Hydrogeological cross sections

Hydrogeological cross sections are one of the ways to graphically represent the hydrogeological situation (Struckmeier & Margat, 1995). The locations and the thickness of soils and other geological formations are shown in the cross sections. The following figure 3-2 represents the cross sections of the terrain made in the southern, middle and northern part of Bolmsö Island. All three cross sections represent the variation of the soil elevation with respect to the distance. The small circles from the cross sections represent glaciofluvial deposits, small triangles represent till. The till soils are dominant in all sections and have big thickness. In cross section 1 as well as in section 2 and 3, the precambrian rock (bed rock) lies in the bottom, the till soil comes on top of the bedrock apart from in section 3 where glaciofluvial deposits are situated directly on top of the bedrock in the north-eastern zone of Bolmsö Island. The layers of sand, fens and bogs have a very small thickness and lie on top of the till soil in the sections 1 and 2, and on top of glaciofluvial deposit in the section 3. The sharp peaks located in cross section 3 are due to the small scale used on the distance.

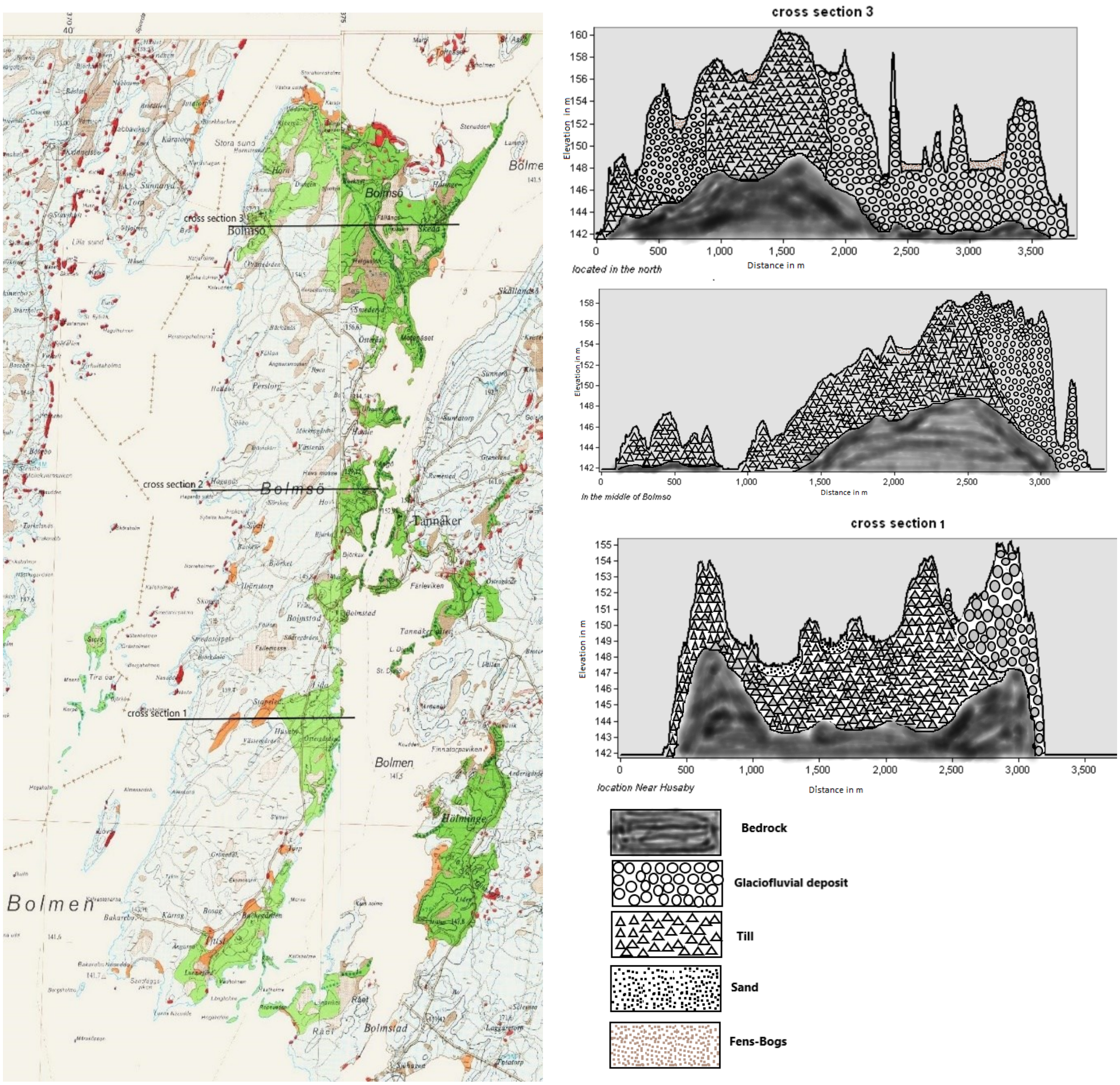


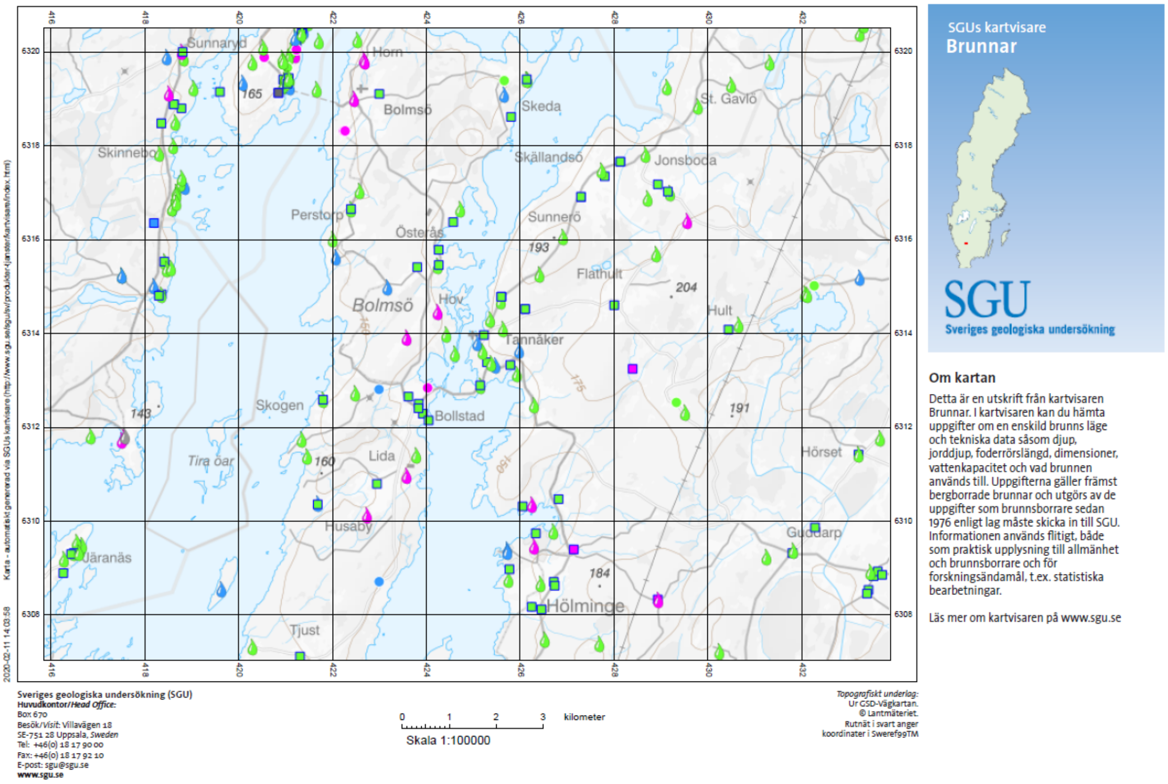
Figure 3- 2. Schematic representation of three cross sections: cross section 1, 2 and 3 were taken in the southern, middle and northern parts of Bolmsö Island respectively.

3.2 Materials

3.2.1 Wells

Well information was accessed through open source SGU (n.d.a). In the island there is a variety of wells installed for various usages. Most of the wells are still active and are mainly used as energy source and for household purposes. Maximum possible water extraction from active wells is 36000 l/h whereas the minimum is 50 l/h. The depth, soil depth, casing, dimensions, water capacity and the tested exploration rate of each individual well is given in the open database of SGU.

The data mainly consist of wells drilled into the bedrock from 1976 to 2018 without hydraulic contact with layers of soil/unconsolidated sediments (well cemented casing tubing from ground surface downwards into the fresh bedrock). Figure 3-3 shows the existing wells in Bolmsö Island.



Om kartan

Detta är en utskrift från kartvisaren Brunnar. I kartvisaren kan du hämta uppgifter om en enskild brunns läge och tekniska data såsom djup, jorddjup, foderrörslängd, dimensioner, vattenkapacitet och vad brunnen används till. Uppgifterna gäller främst bergborrade brunnar och utgörs av de uppgifter som brunnsborrare sedan 1976 enligt lag måste skicka in till SGU. Informationen används flitigt, både som praktisk upplysning till allmänhet och brunnsborrare och för forskningsändamål, t.ex. statistiska bearbetningar.

Läs mer om kartvisaren på www.sgu.se

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www.sgu.se

Topografiskt underlag:
Ur GSD-Vägkartan.
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Rutnät i svart anger
koordinater i Sweref99TM

Figure 3-3. Some of the existing wells located in Bolmsö Island (SGU, n.d. a). The green squares indicate the wells used as energy source. The blue and green droplets represent the wells used for household purposes with the uncertainty of the position of 250 m and 100 m respectively. The purple droplets are wells used for household purpose without precise location. The blue and purple dots are wells with unknown use.

3.2.2 Recharge

Aquifer recharge in Bolmsö Island occurs by infiltration of rainwater through soil, or leakage of water from Lake Bolmen. Freeze & Cherry (1979), present a classical simplified way of estimating the groundwater recharge by only taking into consideration the precipitation, the surface runoff and the evapotranspiration. From equation 3-1 which represents the water budget, equation 3-2 is extracted for the computation of recharge

$$P = Q_s + R + E_r \qquad (3\text{-}1)$$

$$R = P - (Q_s + E_r) \qquad (3\text{-}2)$$

Where:

P=precipitation, Q_s = surface runoff, R= recharge, and E_r= evapotranspiration

3.2.3 Meteorological data

Meteorological data were obtained from Swedish Meteorological and Hydrological Institute (SMHI). The data include precipitation in terms of rainfall and snowfall, evapotranspiration, and runoff for different parts of Sweden. In Bolmsö Island there are three stations of precipitations measurement. Two of them are located in the Northern part of the island and one in the Southern. Monthly precipitation from the north was measured from 1921 to 1970 and from 1971 to 1993 at Dungen station and Bolmsö station respectively. Bakarebo station situated in the south measures precipitation from 1994 until now. The average yearly precipitation of all three stations was arithmetically estimated to be 780.3 mm. A map showing the location of the three stations is presented in figure B available in appendix 2.

An annual average evaporation for a period that ranges between 1961 and 1990 in the study area was assumed to be 500 mm/year (SMHI, 2017). Figures 3-4, 3-5, and 3-6 show the amount of precipitation in mm that was measured in Bolmsö Island.

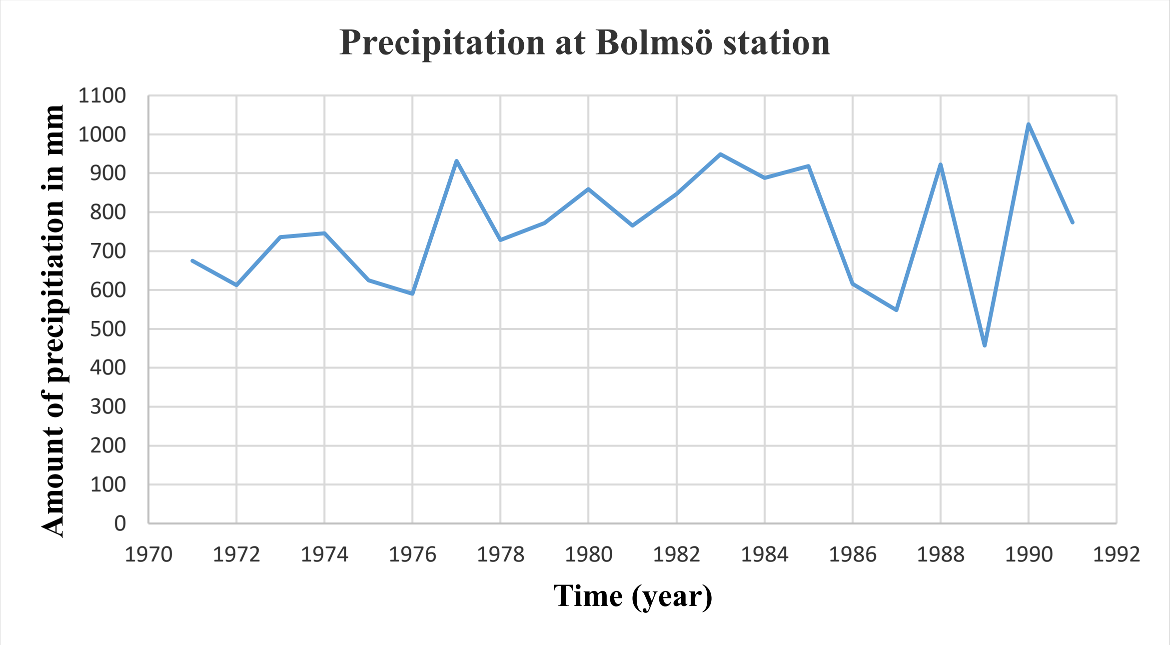


Figure 3-4. A schematic representation of the annual precipitation at Bolmsö station measured from 1970 to 1991. The blue trace corresponds to the amount of precipitation measured in each year. 1021 mm was the highest amount of rainfall which took place in 1990. The lowest amount of precipitation is 457 mm that took place in 1989. The average precipitation between 1970 and 1991 is 760 mm.

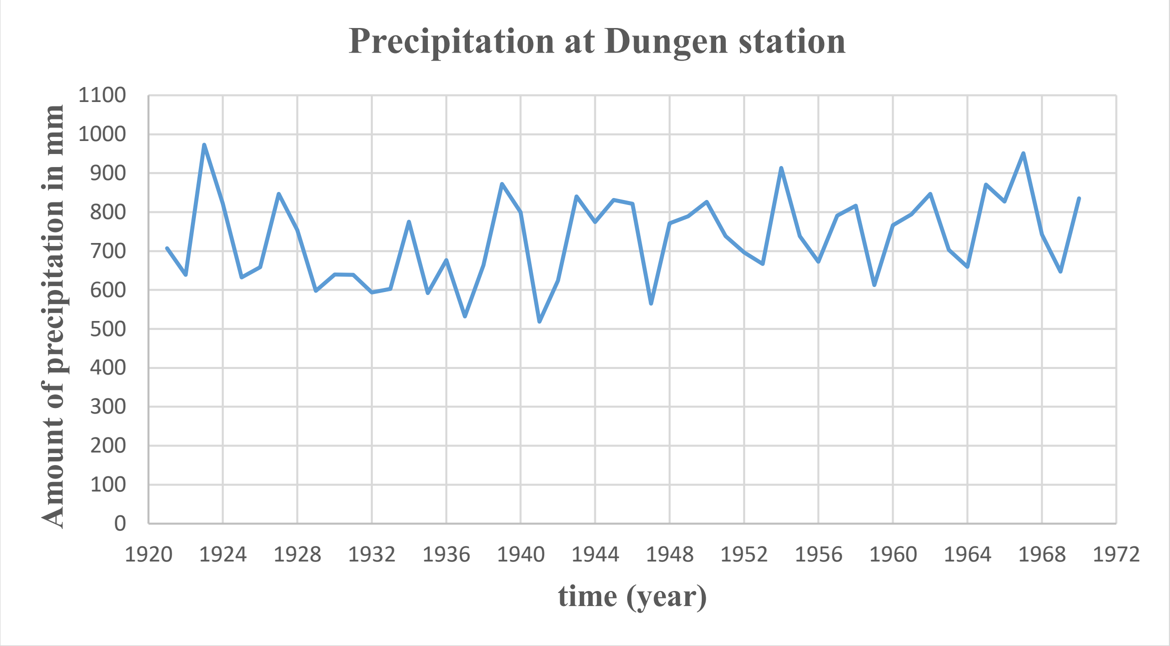


Figure 3-5. Graphical representation of the precipitation at Dungen station measured from 1920 to 1970. The blue represents the amount of precipitation measured in each year. 973 mm and 518 mm are the maximum and minimum amount of precipitation that took place in 1923 and 1941 respectively. The average precipitation between 1920 and 1970 is 733 mm.

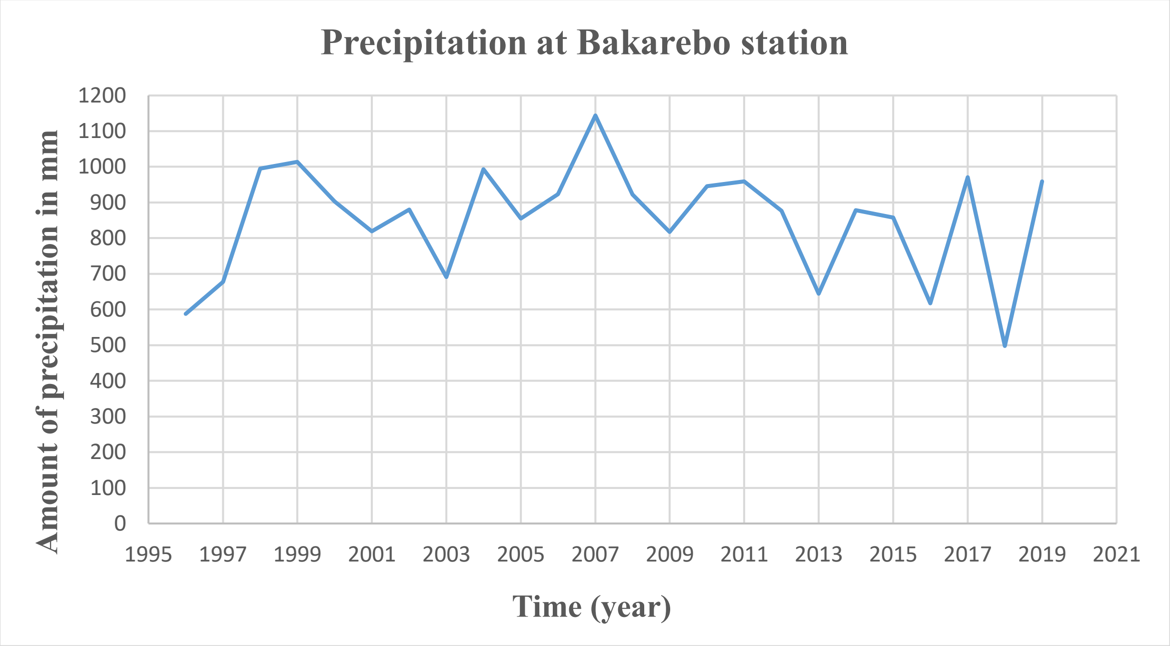


Figure 3-6. Graphical representation of the precipitation at Bakarebo station measured from 1995 to 2019. The blue trace corresponds to the amount of precipitation measured in each year. 1144 mm is the highest amount of rainfall which took place in 2007.The lowest amount of precipitation is 497 mm that took place in 2018. The average precipitation between 1995 and 2019 is 846 mm.

3.2.4 Runoff data

Annual runoff data for Bolmsö Island have been available since 1981 from the Swedish Meteorological and Hydrological Institute, as presented in figure 3-7. The yearly average runoff was estimated to be 436 mm/year, the maximum runoff is 610 mm/year occurred in 2007 and the minimum runoff is 253 mm/year occurred in 1996. According to SMHI (2016), the runoff data were assumed to be a difference between the precipitation and evapotranspiration for the areas within and around Lake Bolmen. Therefore, the data are not a very precise estimation of runoff at the Bolmsö Island. Further considerations were made to estimate the runoff based on the available data of precipitation and the average evapotranspiration in Bolmsö Island. The annual average value of general runoff was obtained by computing the difference between the average precipitation and the average evapotranspiration. It turned out to be 280 mm/y and it includes both the overland flow, that is surface runoff, and infiltration, which should be considered as groundwater recharge.

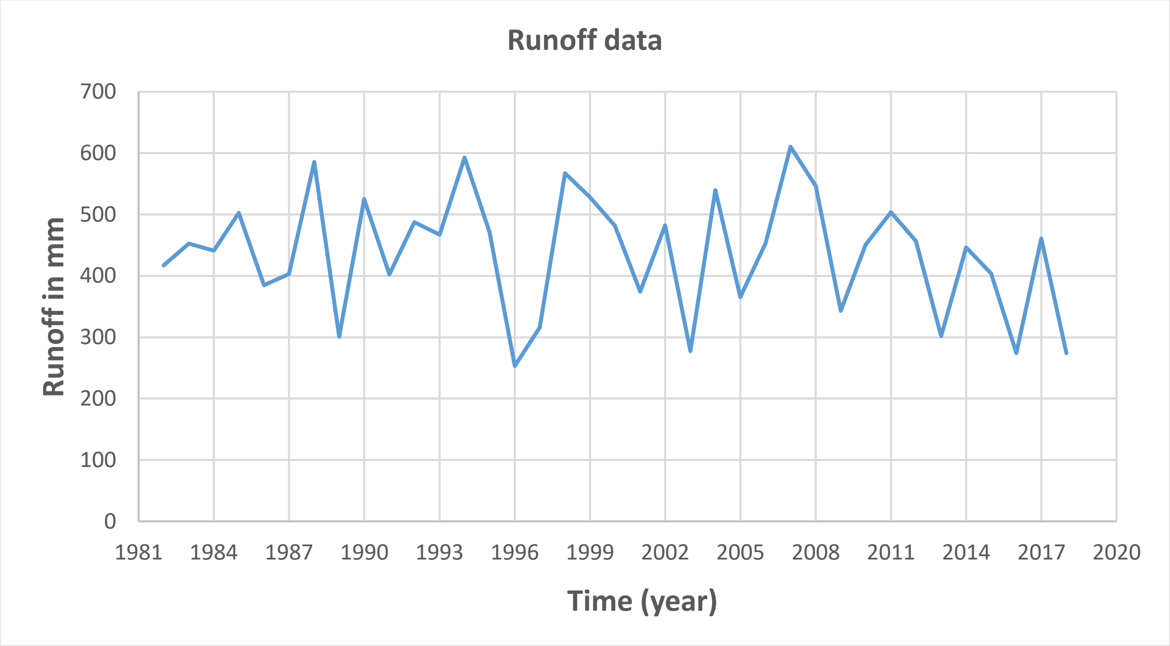


Figure 3-7. Graphical representation of runoff data taken as the difference between the precipitation and the evapotranspiration inside and around Lake Bolmen (SMHI, 2016). The data are calculated from 1981 until 2019 with the maximum of 610 mm and minimum of 253 mm occurred in 2007 and 1996 respectively. The blue line represents the amount of runoff available in each year from 1981 to 2019.

The infiltration rate varies in function of the soil type. The clayey soil generally has a low infiltration rate, on the contrary the sandy and gravel soil has a high infiltration rate. The area of each soil type located in Bolmsö Island was computed and assigned to its corresponding infiltration rate (Freeze & Cherry, 1979).

3.3 Methods

3.3.1 Conceptual model

A conceptual model was created to illustrate a representation of the hydrogeological units and the flow system of groundwater within the aquifer Figures 3-8, 3-9, and 3-10 indicate the concept on which the hydrogeological model was built. They represent a cross-section W-E, a profile N-S along the island, and a planar geological surface map respectively. On all the figures the boundary conditions and the geological units are marked. The contacts with the Precambrian bedrock, assumed to be an aquiclude or confining layer, are marked as a no-flow boundary (N.F.B). The observed sharp peaks are due to the scale used

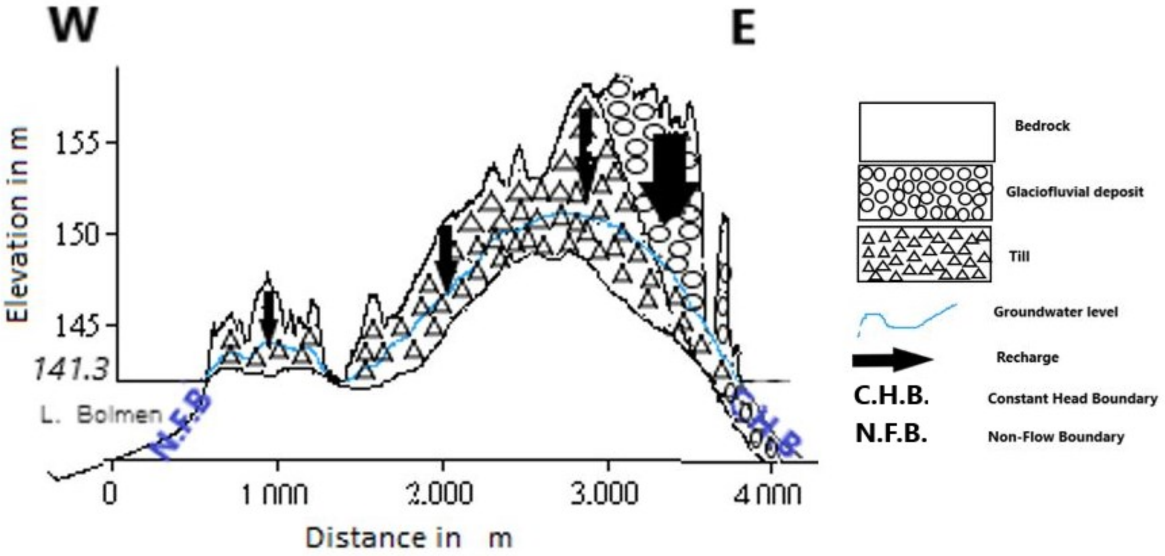


Figure 3-8. The cross-section W-E used to build a conceptual model (the position is marked in Figure 3-10). On top of the bedrock, assumed to be impermeable, you find a big aquitard consisting of till and a small unconfined aquifer made of glaciofluvial deposits.

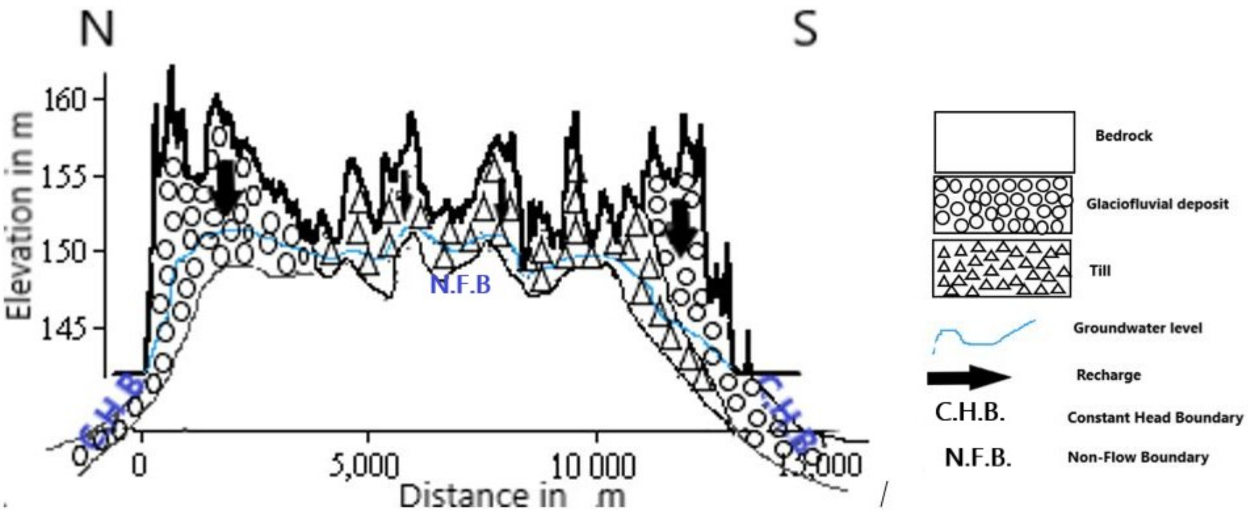


Figure 3-9. The profile N-S along Bolmsö Island used to build a conceptual model (the position is marked in Figure 3-10).

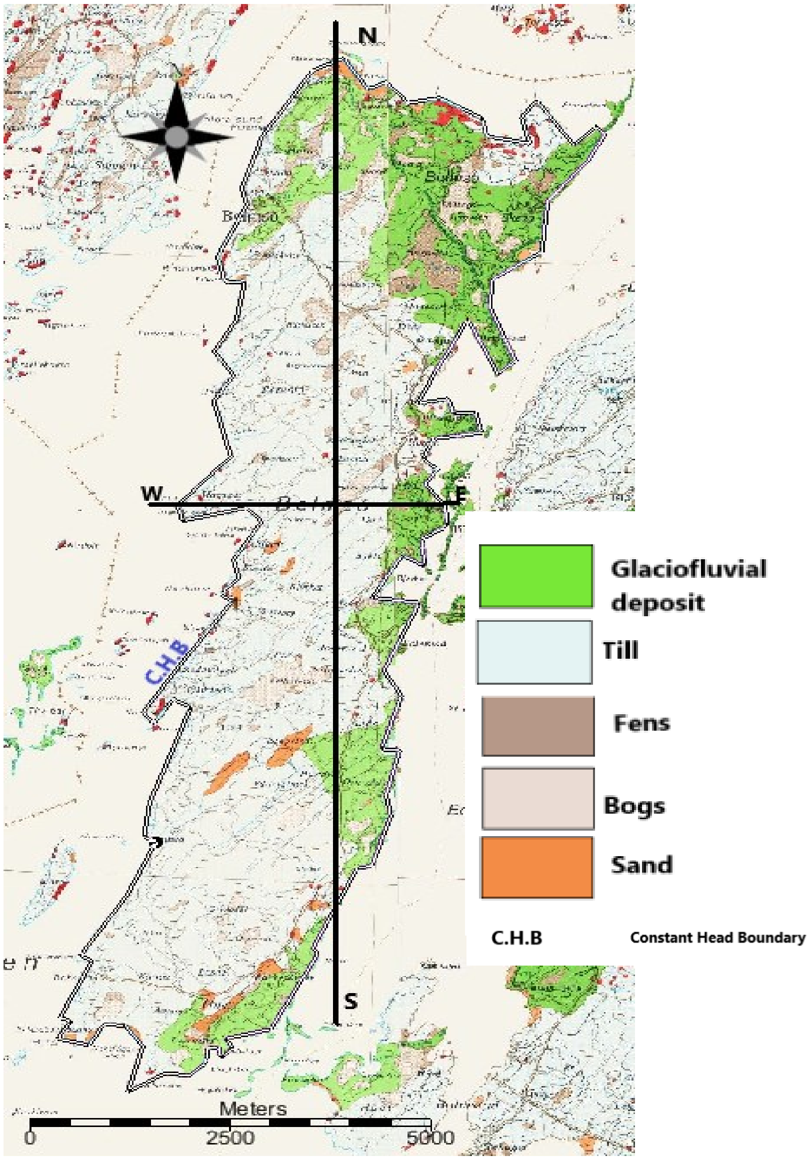


Figure 3-10. The planar map of the study area. The lines W-E and N-S represent the cross-section and the profile in figures 3-8 and 3-9 respectively. The contour line represents the constant head boundary conditions of the model.

3.3.2 Model setup and development

The simulation of a three-dimensional steady groundwater flow was completed by utilizing the most reliable available information about the groundwater system within the study area. Digital elevation model (DEM), shapefile of creeks located in Bolmsö Island modelled as drain and the aquifer/aquitard thickness were used to create and develop a simulation model based on the conceptual model. The boundary conditions defined by the boundary head were assumed to be 141.3 m which is the average water surface elevation of Lake Bolmen. The hydraulic properties of the aquifer/aquitard were assumed based on the values presented in table 2-1. The ArcGIS software was used to create shapefiles and to define the cross-sections across the Bolmsö Island that were used to describe the conceptual model (see sections 3.1.2-3 and also 3.3.1). The layers from ArcGIS were then imported into GMS 10.4 software to develop the model that was adapted to a MODFLOW model in a 3D grid and the simulations were run.

3.3.3 Initial conditions

The model was chosen to reflect a long-term average groundwater flow situation and thus to be in steady state, where the magnitude and the direction of the flow are constant with time (Freeze & Cherry, 1979). Some initial conditions were defined when creating MODFLOW simulations and running the model. The most important are the starting heads and they were set to be at the elevation of the ground surface.

3.3.4 Boundary conditions

Boundary conditions were defined while building the MODFLOW model and mainly following the description within the conceptual model. As the island is surrounded by Lake Bolmen, the boundaries were delineated following the contour of Bolmsö Island. The specified hydraulic heads were used to define the constant head of the layer boundary and were assigned to the value of 141.3 m that corresponds to the elevation of the lake.

3.3.5 Aquifer, aquitard and recharge zones

The bottom elevation of the main model layer (making up the simulated aquifer and aquitard) was considered to be the top elevation of the bedrock and it was obtained by subtracting the soil thickness from the ground surface elevation. The aquifer and the aquitard of the study area were subdivided into nine zones as shown in figure 3-11, based on the assessment of hydraulic conductivity of the soil that can be found in Bolmsö Island. The table 3-1 shows the hydraulic conductivity intervals of each zone. Zones 1, 2, 3, 4, and 6 have the same soil type which is glaciofluvial deposit while zones 5, 7, 8, and 9 are made of till soil type.

Table 3-1. Hydraulic conductivity of soil layers at Bolmsö Island

Zone ID	1,2, 3, 4, 6	5, 7, 8, 9
Predominant geological unit on top of the bedrock	Glaciofluvial deposits	Till
Hydraulic conductivity (m/d)	15-40	0.1-1

In zones 1, 2, 3, 4 and 6, the glaciofluvial deposits mainly consist of coarse-grained material that are predominant thus the soil was assumed to have the same hydraulic conductivity as sand. While in zones 5, 7, 8 and 9 the predominant soil is the sandy- till, the assigned hydraulic conductivity was assumed to be between fine sands and till. Till soil was subdivided into different zones because the used values are different. All values assigned to the hydraulic conductivity falls within the allowable interval from the table 2-1. The groundwater recharge occurs when surface water infiltrates into the soil and increases the level of the groundwater table (Islam et al., 2016). The net precipitation was considered to be the main source of recharge. The values of the recharge of different zones were estimated based on the infiltration capacity of soil types. Savva & Frenken, (2002) provided the values of typical infiltration rate which range between 0.0008 m/d-0.001m/d for sandy soil and less than 0.0002 m/d for clayey soil. In this study, six zones of recharge were created and the corresponding recharge rates in meter per day were assigned to each zone see figure 3-11 The zones 1, 2, 3, 4 and 6 are predominantly made of the glaciofluvial deposits, hence during the calibration, the recharge rate was set to 0.0008 m/d. The zone 5 is made of the till, the recharge rate was assumed to be 0.00009 m/d. Table 3-2 shows the recharge rate and the area assigned to each zone. The total area of the island is 42 km^2.

Table 3-2. The recharge rates in m/d assigned to the recharge zone and the corresponding recharge area in m^2.

zone ID	Area in m^2	Recharge rate in m/d
1	827829	0.0008
2	523638	0.0008
3	1947596	0.0008
4	9634364	0.0008
5	26543348	0.00009
6	2263970	0.0008

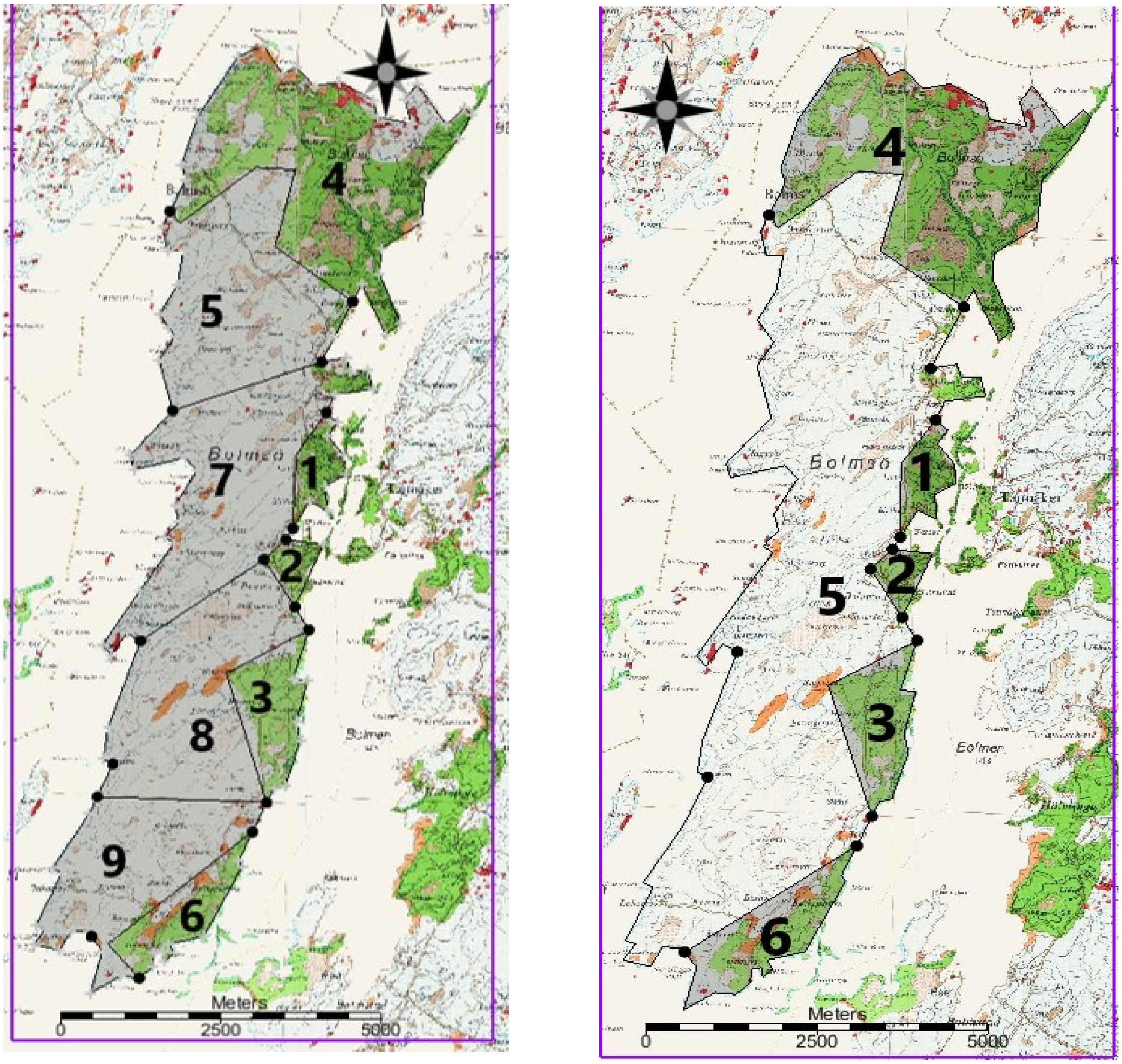


Figure 3-11. The zones representing the hydraulic conductivity on the left of the picture and the recharge rate on the right of the picture. The hydraulic conductivity and the recharge rate were assigned to each zone based on the predominant soil type available.

3.3.6 Drain

There exist several creeks in Bolmsö Island and most of them are too small to be considered available at open source of Lantmäteriet, a Swedish authority of surveying and cartography. Figure D presented in appendix 4 shows all creeks available in the island and creeks considered as substantial are modelled as drains and are marked in green. Fifteen of the drains, approximately 15% of all drains, were used in the model. From GIS, drain dimensions were extracted, they are in average nearly 0.7 m wide and the thickness of their bottom sediments (drain beds) are estimated to be 1 m. The hydraulic conductivity of the drain bed was taken to be the same as the hydraulic conductivity of the corresponding geological units, located in the same area. The drain is characterized by its conductance, which is the ratio between the hydraulic conductivity of the bed materials multiplied by the cross-sectional area (seen from above), and divided by the vertical thickness of the drain bed (McDonald & Harbaugh, 1984). It is simply expressed in equation 3-3

$$C = \frac{K * A}{L} \tag{3-3}$$

Where

C is the conductance in (m2/d)/m, K is the hydraulic conductivity in m/d, A is the gross cross-sectional area in m^2, and L is the flow length (=thickness of the drain bed) in m. Table 3-3 shows the conductance values used during the simulations.

Table 3-3. Conductance values in (m2/d)/(m) assigned to different drains. The Drain ID:s are marked in figure D available in Appendix 4.

Drain ID	Conductance (m^2/d)/(m)
2	0.35
4	0.35
5	0.35
6	0.35
7	0.35
9	0.28
11	0.35
13	0.35
15	0.35
16	0.35
17	0.35
19	0.35
20	14
21	0.35
22	0.35

3.3.7 Model grid setup

MODFLOW requires subdividing the groundwater flow region into cells, when working with finite difference calculations and simulations. Each cell is assumed to be homogeneous and therefore average values of groundwater variables are applied to the block. Each cell of the grid model of Bolmsö Island consists of 30 m x 30 m.

3.3.8 Calibration of the groundwater flow model

Using information from the Swedish Geological Survey (SGU, n.d.a), thirteen observation points were created in the model. Based on the available data regarding groundwater levels when the boreholes were created, thirteen observation points were used for model calibration as shown in figure 3-13.The used observed groundwater levels for the calibration are valid for the fractured bedrock (assumed to be impermeable in the current simulation model), however, it may happen that the fractured bedrock in reality is in hydraulic contact with the unconsolidated sediments that are on the top of it and that the fractures of the bedrock make up a fractured aquifer. The calibration was carried out by changing certain parameters mainly the hydraulic conductivity of the soil and the recharge rate, using a trial and error method until a satisfactory small difference between the calculated and measured heads was reached. Figure 3-12 represents the calibration target. The top of the target corresponds to the observed value plus an interval and the bottom corresponds to the observed value minus the interval. The interval was set to 1.5 m and it serves as a calibration target for the observed wells in the model.

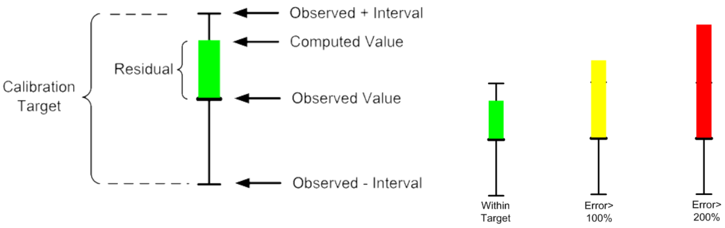


Figure 3-12. The calibration target of the model. The colored bar represents the error. If the calibration target is met, the color bar is green. If the bar is outside the target, but the error is less than 200% of the interval, the bar is drawn in yellow. If the error is greater than 200%, the bar is drawn in red.

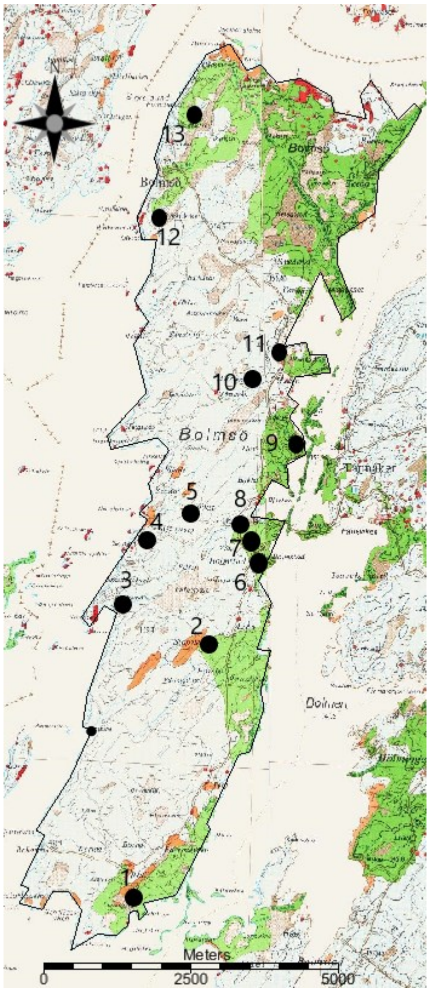


Figure 3-12. Observation points located in Bolmsö Island

4 Results

This chapter contains the simulation and calibration results. In subchapter 4.1, the results from a preliminary attempt are presented, some of them are presented in Appendix 3. The calibration and worst case scenario results are presented in subchapter 4.2 and 4.3 respectively. Subchapters 4.4 and 4.5 compare computed against observed groundwater levels and residual against observed values respectively. Total groundwater recharge and surface runoff are estimated in subchapter 4.6.

4.1 Preliminary attempt

Initially, the starting heads or initial groundwater levels of each cell were assumed to be equal to the ground surface elevation. In this preliminary attempt the bottom elevations of the simulated layer of aquifers and aquitards were set equal to the top elevations of the bedrock, assumed to be an impermeable no-flow boundary. The obtained results show that most of the cells are dry. It is observed that more than 80% of the grid cells are dry as indicated by the red cells in figure C.1 presented in appendix 3. Similarly, the hydraulic gradient is small, most likely at least partly due to the used relatively big values of hydraulic conductivity, particularly for the layer of till. As presented in table 4-1, the resulting flow budget becomes small with the total daily outflow of 7,266 m^3/d from Bolmsö Island to Lake Bolmen, the detailed flow budget is presented in figure C. 2 available in Appendix 3.

Table 4-1. The resulting inflow and outflow from the preliminary attempt of a simulation.

Type of soil	Hydraulic conductivity m/d	Recharge rate m/d	Total inflow m^3 /d	Total outflow m^3 /d
Till	0.5	0.00009	7,266	7,266
Glaciofluvial deposits	35- 40	0.0008		

Hydraulic conductivity, recharge and bottom elevations were changed to avoid drying of the cells. The hydraulic conductivity of the soil was lowered depending on the soil type properties presented in table 2-1, and the recharge rate was increased. The bottom elevations of the aquifer and the aquitard were lowered by between 1 and 4 m depending on locations where the cells were dry. The results show an increased hydraulic gradient of the head and an increased volume of groundwater flowing out from the island.

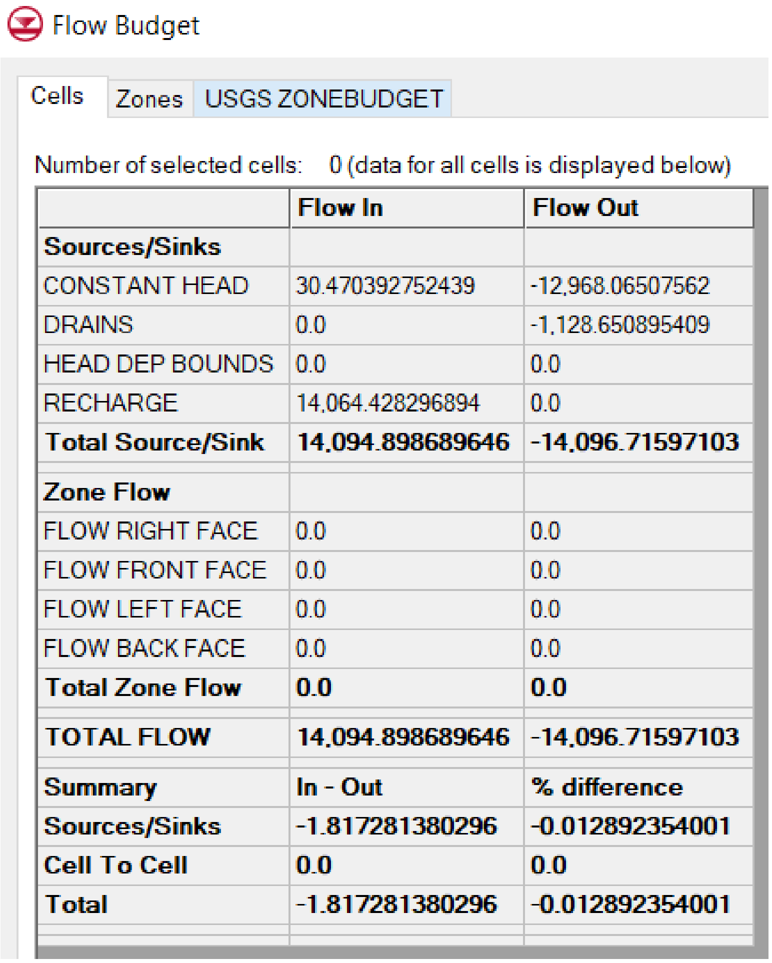
The resulting total recharge available was estimated to be about 14064 m^3/d. The total volume of water leaving Lake Bolmen to Bolmsö Island through the boundaries was 30 m^3/d and it makes the total flow to 14094 m^3/d. The quantity of groundwater leaving Bolmsö Island to the Lake Bolmen is 12970 m^3/d.

4.2 Calibration results

Groundwater levels were simulated and calibrated in the model, even though some observation points are uncertain. During the calibration, the recharge rate was kept the same as that obtained after the preliminary attempt, the hydraulic conductivity of the soil was lowered as presented in table 4-2. Among thirteen observation points that were calibrated, the calibration target was met for seven. Five and one of the observation points occurred with the error greater than 100% and 200% respectively. The calibration results of all observation points are indicated with green, yellow, and red colors as shown in figure 4-2. Due to the reduction of hydraulic conductivity, the hydraulic gradient of the head has increased and resulted in more flooded cells. The zones are referred to the figure 3-11.

Table 4-2. Used hydraulic conductivity and recharge rate, and the resulting inflow and outflow from the calibration.

Zone ID	Type of soil	Hydraulic conductivity m/d	Recharge rate m	Total inflow m^3/d	Total outflow m^3/d
1	Glaciofluvial deposits	25	0.0008	14,094	14,097
2, 3	Glaciofluvial deposits	15	0.0008		
4	Glaciofluvial deposits	20	0.0008		
5,8,9	Till	0.5	0.00009		
6	Glaciofluvial deposits	18	0.0008		
7	Till	0.4	0.00009		



Flow Budget

Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	**Flow Out**
Sources/Sinks		
CONSTANT HEAD	30.470392752439	-12,968.06507562
DRAINS	0.0	-1,128.650895409
HEAD DEP BOUNDS	0.0	0.0
RECHARGE	14,064.428296894	0.0
Total Source/Sink	**14,094.898689646**	**-14,096.71597103**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**14,094.898689646**	**-14,096.71597103**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-1.817281380296**	**-0.012892354001**
Cell To Cell	**0.0**	**0.0**
Total	**-1.817281380296**	**-0.012892354001**

Figure 4-1. The flow budget after the calibration. The units are in m^3/d.

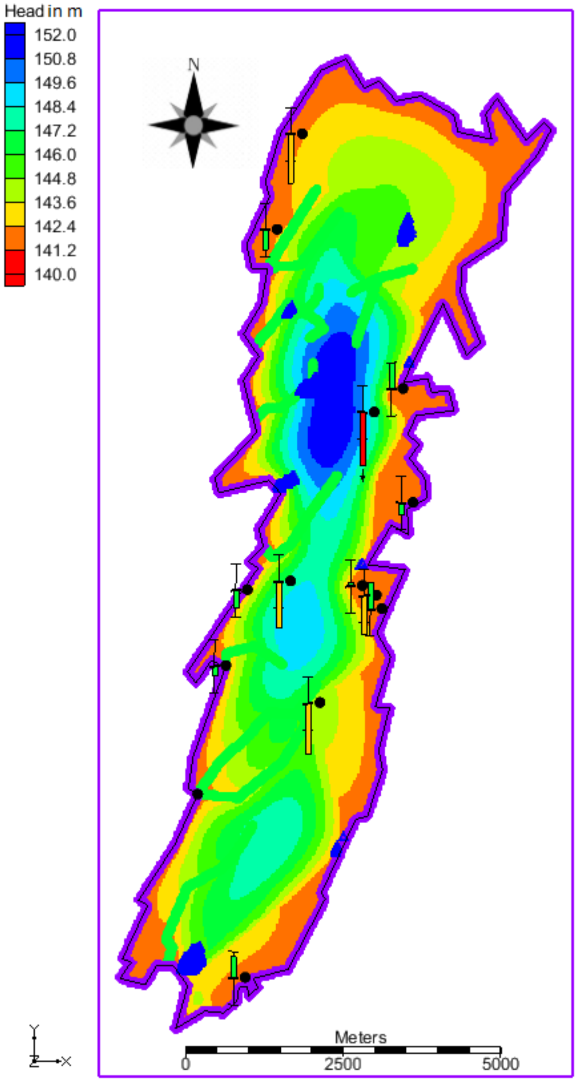


Figure 4-2. The calibration results of the model. The bars in green color indicate that the calibration target was met, whereas the bars in yellow represent where the calibration was outside the target with the error less than 100%. The bar drawn in red represents where the calibration lies outside the target with the error greater than 200%.

4.3 Hydraulic conductivity of till

The hydraulic conductivity of till soil was changed to 0.1 m/d in all till zones. The results show an increase in flooded cells and hydraulic gradient of the head. The blue color in figure 4-3 represents the hydraulic head where the cells are flooded.

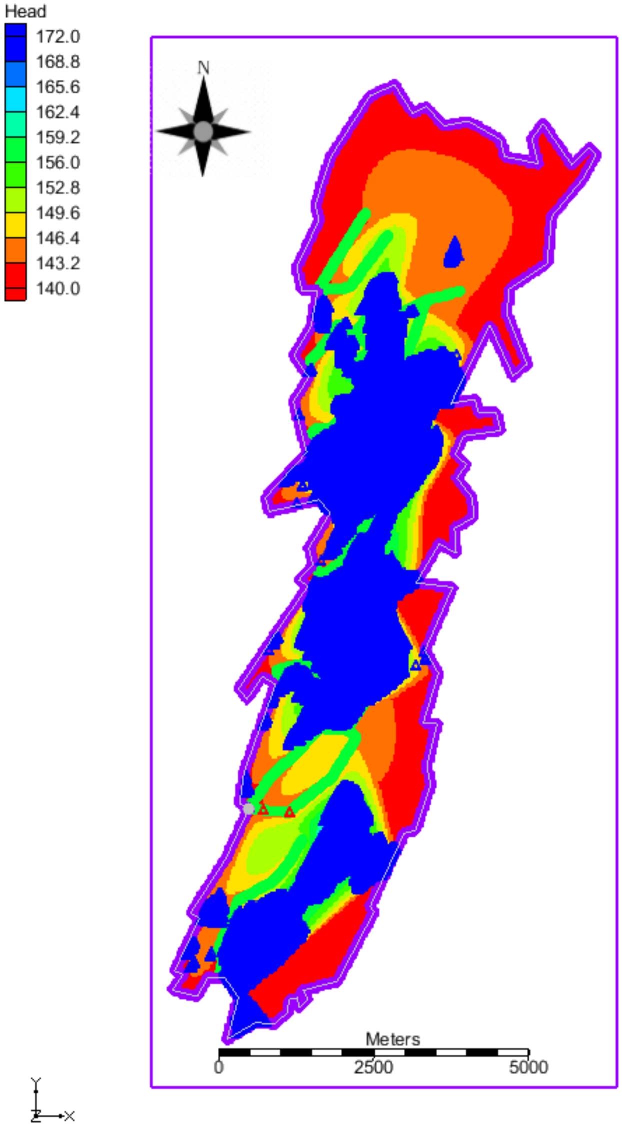


Figure 4-3. The increase of flooded cells due to the change of hydraulic conductivity of till soil.

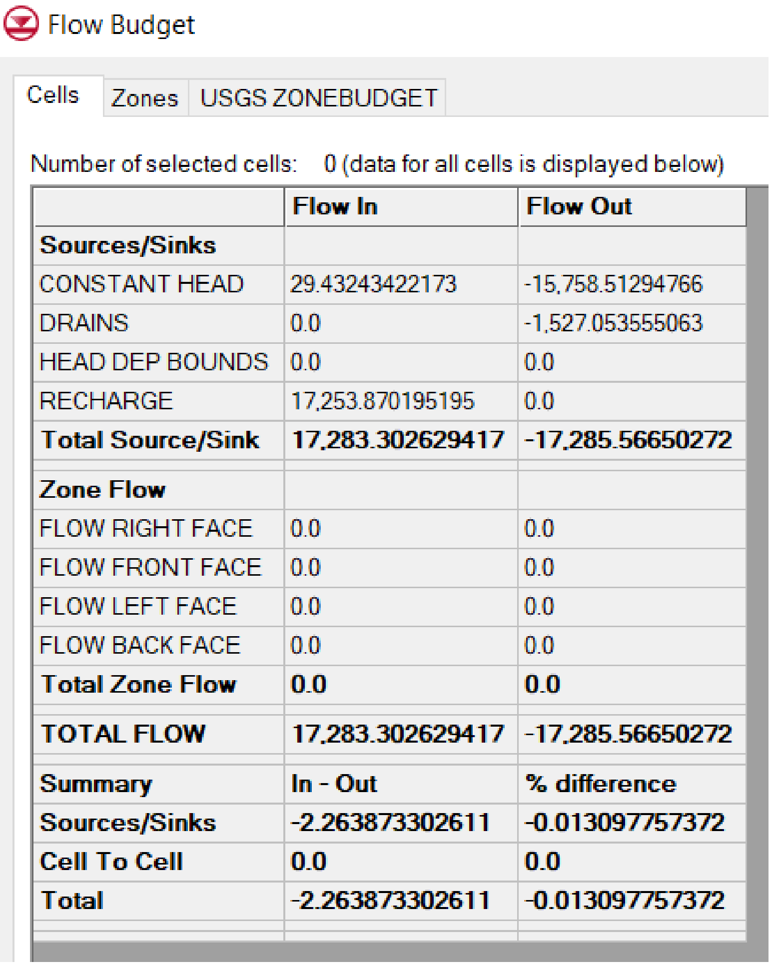
4.4 Worst case scenario- extreme recharge

During the worst case simulation, the model was run by using the maximum values of the input data such as the recharge rate in order to know its impact once the worst case happens.

The hydraulic conductivity of the soil was kept the same as in the calibration. The maximum recharge rate was used, resulting in an increase of the quantity of groundwater running from Bolmsö Island to Lake Bolmen. Figure 4-3 shows the flow budget obtained by maximizing the recharge.

Table 4-3. The resulting inflow and outflow obtained at a maximum recharge rate. The zones are referred to the figure 3-11.

Zone ID	Type of soil	Hydraulic conductivity in m/d	Recharge rate m/d	Total inflow m^3/d	Total outflow m^3/d
1	Glaciofluvial deposits	25	0.001	17,283	17,285
2, 3	Glaciofluvial deposits	15	0.001		
4	Glaciofluvial deposits	20	0.001		
5,8,9	Till	0.4	0.0001		
6	Glaciofluvial deposits	18	0.001		
7	Till	0.5	0.0001		



Number of selected cells: 0 (data for all cells is displayed below)

	Flow In	**Flow Out**
Sources/Sinks		
CONSTANT HEAD	29.43243422173	-15,758.51294766
DRAINS	0.0	-1,527.053555063
HEAD DEP BOUNDS	0.0	0.0
RECHARGE	17,253.870195195	0.0
Total Source/Sink	**17,283.302629417**	**-17,285.56650272**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**17,283.302629417**	**-17,285.56650272**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-2.263873302611**	**-0.013097757372**
Cell To Cell	**0.0**	**0.0**
Total	**-2.263873302611**	**-0.013097757372**

Figure 4-4. The flow budget after the increase of recharge rate maximum. The units are in m^3/d.

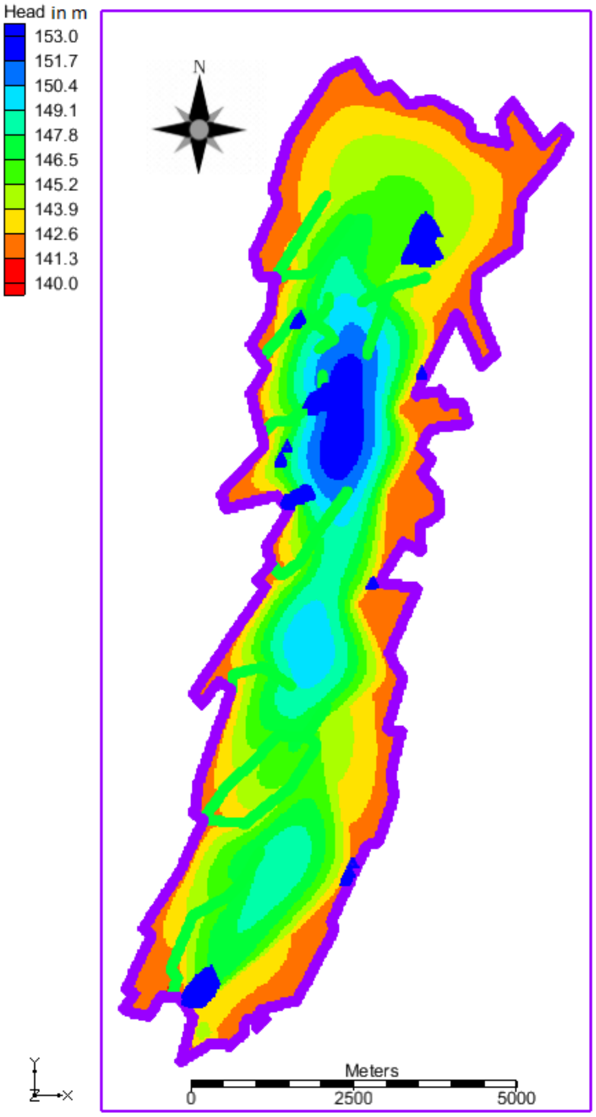


Figure 4-5. The results from the worst case scenario with maximum value of the recharge rate.

4.5 Computed and observed groundwater levels

Figure 4-5 compares the observed values with the corresponding calculated values from the simulation model. The straight line represents a perfect correspondence between the observed data and the computed values. A regression approach was performed in Microsoft Excel to determine the root mean square of the difference between observed and computed values. To have a good calibration or fit between computed and observed values, the R^2 value should be close to 0.9 or higher. For this study R^2 turned out to be 0.88. Table 4-4, shows the observed values, computed values, residuals, and regression statistics.

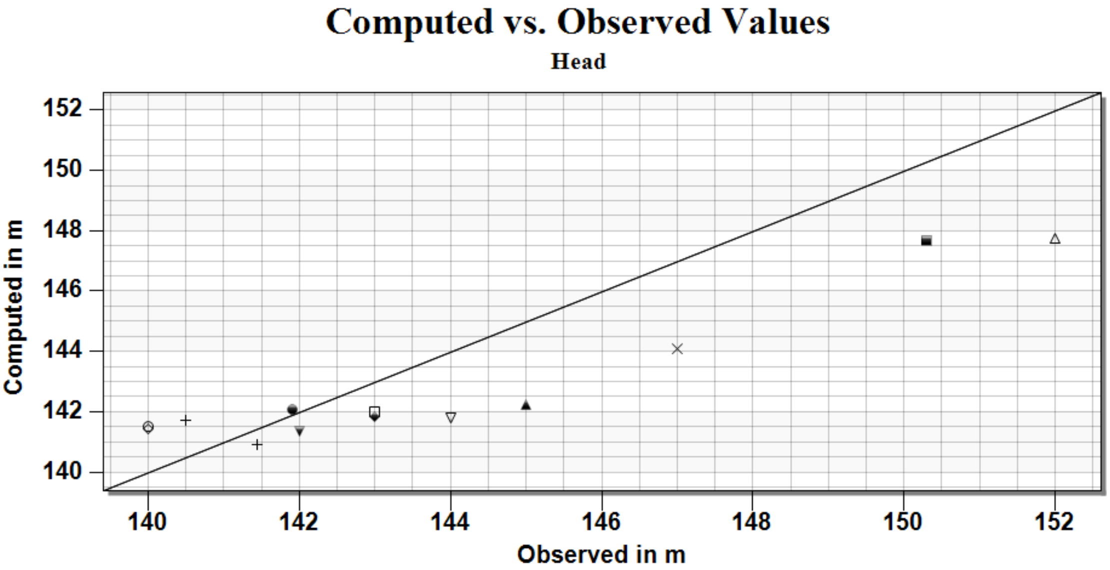


Figure 4-6. Graphical representation of observed and computed values of groundwater levels

Table 4-4. Regression statistics for between computed and observed values. The ID numbers are the same as the number of observation points presented in figure 3-13.

Id	Observed in m	Computed in m	Residual in m	Regression	Statistics
1	140.5	141.72	1.22		
2	147	144.105	-2.895	R Square	0.8819456
3	141.45	140.904	-0.546		
4	143	142.009	-0.991	Standard Error	0.8256913
5	150.3	147.686	-2.614		
6	140	141.494	1.494	Observations	13
7	144	141.792	-2.208		
8	141.9	142.096	0.196		
9	142	141.362	-0.638		
10	152	147.739	-4.261		
11	140	141.441	1.441		
12	143	141.849	-1.151		
13	145	142.238	-2.762		

4.6 Residual and observed values

The graph in figure 4-6 shows how the residual between computed and observed values vary with the observed values. The horizontal line shows a perfect correspondence between the observed data and the solution values. The symbols on the graph represent each observed value at the intersect and residual (computed-observed) values for the points.

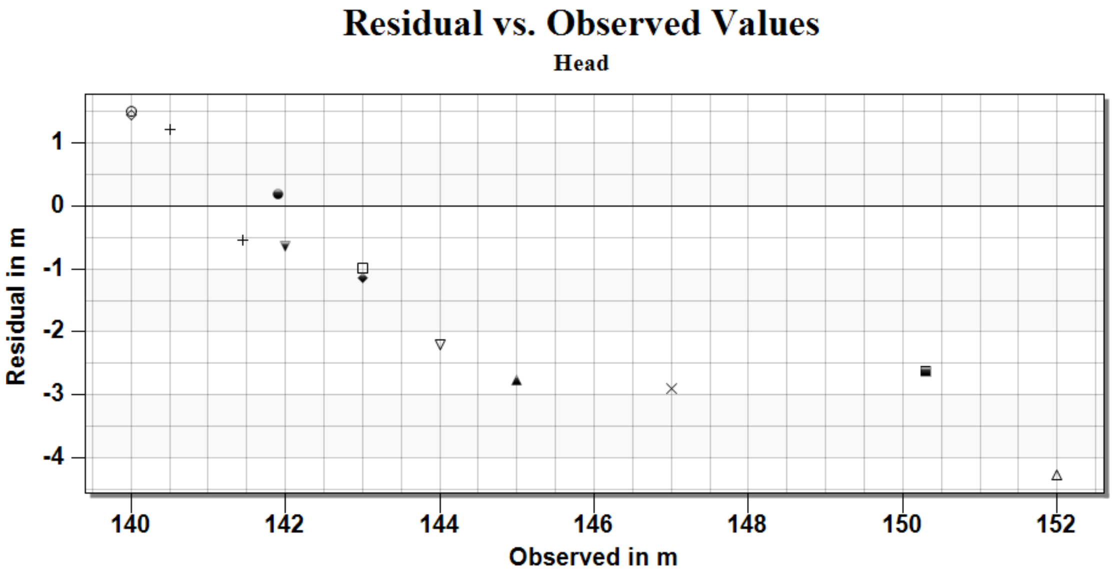


Figure 4-7. Graphical representation between residual and observed values.

4.7 Groundwater recharge and surface runoff

Using the equation 3-1 the surface runoff was estimated. The table 4-5 summarizes the estimated results of surface runoff for the given amounts of net precipitation and groundwater recharge after the calibration (upper line) and the worst case scenario (lower line).

Table 4-5. Estimated groundwater recharge and surface runoff at Bolmsö Island.

Recharge m^3/d	Recharge mm/y	Net precipitation mm/y	Surface runoff mm/y
14,064	122	280	158
17,253	150	280	130

5 Discussion

A groundwater model is prepared for a better understanding of the hydrogeological situation such as the flow system behavior within an aquifer (Fetter, 2014) and hence all model parameters and boundary conditions must be defined clearly. Initial estimates are undertaken using measurements that relate directly to the quantities being represented by parameters. When measurements in observation wells of groundwater levels are available, an opportunity arises for this data to be utilized to verify and improve the estimates of model parameters. This process, known as calibration, should test various sets of model parameters to find the set that best fits the observed groundwater levels (Barnett et al., 2012). The model parameters used in this study, do most likely not correlate enough with the reality because the model was not fully calibrated due to the uncertainty of available groundwater levels and lack of detailed information regarding the hydrogeological properties.

5.1 Model Simplification

Dry cells may be due to low recharge rate, high hydraulic conductivity or bottom elevations that are above the water table. The aquifer and aquitard thickness are only known at a limited number of points within the study area. Based on these data, an initial estimate of the thickness was extrapolated. In some areas the estimated thickness became very thin, and as a consequence it was difficult to converge for the MODFLOW model. Some approximations were performed by lowering the estimated top of the bedrock and thereby get thicker aquifer and aquitard layers, in order to converge for the model and reduce the number of dry cells observed after the preliminary attempt of the model. There was no data of the bedrock regarding the cracks and fractures. Therefore, the model was simplified by assuming that the bedrock has no cracks and fractures and forms an impermeable bottom of the aquifer and aquitard layer.

5.2 Model performance and calibration target

When calibrating the model by altering the parameters such as hydraulic conductivity and the recharge rate, the model performance was estimated. By using relatively low and realistic values of the hydraulic conductivity of till soil, the simulation model resulted in many flooded cells leading to a substantial surface runoff via drains and overland flow. During calibration the hydraulic conductivity of till was increased to an absolute maximum, even a bit above a plausible realistic value and the results of such values are presented in chapter 4.2. If lower and more realistic values of the till had been used, the calculated groundwater levels would have been higher in large parts of the study area and there would have been a bit less of groundwater discharge to Lake Bolmen and a little bit more of surface runoff.

For the present model, the calibration resulted in a R^2 of the difference between computed and observed groundwater levels of 0.88 which gives a general indication of the reliability of the model. However, the levels of groundwater that were taken as observed values were measured on different dates and in a different aquifer than the simulated one. The observed groundwater levels used for the calibration are valid for the bedrock, and it is likely that there are fractures in the bedrock which constitutes a fractured aquifer and that this aquifer is in hydraulic contact with the unconsolidated sediments that are on the top of it.

This discussion could be elaborated a little bit more as the observed groundwater levels used for the calibration are valid for the fractured bedrock and not for the aquifer layers included in our conceptual model, which probably is too simplified. These findings indicate a strong need for more data and an improvement of both the conceptual and the simulation model.

5.3 Recharge and surface runoff

Recharge is an important parameter to describe aquifer and aquitard conditions. The calibration resulted in a total recharge rate of 14064 m^3/d for Bolmsö Island and this gives an average annual recharge depth of 122 mm/y, less than the average surface runoff which is 158 mm/y when the average net precipitation is 280 mm/y.

5.4 Well extraction

According to SGU (n.d.a), 52 wells out of 54 available in Bolmsö Island are drilled into the bedrock and cased off from the layers of unconsolidated sediments. That means that more than 96% of the drilled wells only could extract water from bedrock fractures. However, there are no data to know whether the water in the bedrock fractures is recharged by the shallow aquifer at Bolmsö Island or by water from Lake Bolmen. In addition, the total amount of water extracted from wells at the island is in average less than 100 m^3/d and this is relatively small compared to the total flow budget of 14097 m^3/d. Another factor to consider is that almost all wells are cased off, indicating that there is no direct contact between the wells and the unconsolidated deposits, and there is no influence of the wells on the water in the shallow aquifer and aquitard units. There could be a hydraulic contact between fractures in the bedrock and downward movement of groundwater through the unconsolidated sediments.

5.5 Flow budget

From the calibrated model, the flow budget represented by the total flow in and out indicates that there is a substantial exchange of water between Bolmsö Island and Lake Bolmen. A big amount of groundwater that is recharged by precipitation on the island flows out to Lake Bolmen. For this study, it is possible to approximate the influence of Bolmsö Island on the Lake Bolmen and vice versa based on the obtained flow budget.

5.6 Effect of surface runoff on brownification

Water from the net precipitation is composed of two parts, one that infiltrates into the soil and recharges the groundwater, and the remaining part runs over the soil surface towards the Lake Bolmen.

Among the top layer of the soils, there exist bogs and fens located in the northern part of Bolmsö Island. Peatlands mainly composed of bogs and fens that are rich in iron and organic content

(Freppaz & Williams, 2015). In the northern part of Bolmsö Island, there is a lot of glaciofluvial deposits which have high hydraulic conductivity and high infiltration capacity that allows a major part of the net precipitation to recharge the groundwater. However, there is still a volume of water that flows over the ground surface and runs towards Lake Bolmen that could contribute to its brownification due to the content of organic content from numerous bogs and fens in the area.

A few bogs and fens are found in the middle and in the southern part of Bolmsö Island situated on top of the till, which has low permeability (Kessler, 2012). In this area, the big amount of the net precipitation occurs as surface runoff that also could contribute to the brownification of water in the Lake Bolmen due to the presence of bogs and fens.

5.7 Effect of groundwater on brownification

Fens are defined as wetlands, the water available in fens originates from inflow of groundwater, from the surroundings. There is an exchange, which means that chemical constituents of fens can exist in adjacent groundwater in a dissolved state or suspended (Winter et al., 1999). During groundwater flow, dissolved organic matter from bogs and fens are transported away (Kellner, 2002). In the north-eastern part of Bolmsö Island there exists fen soils which indicate that there exists a certain amount of organic content in the groundwater in that part of the island.

Due to the brown color of the fens and bogs also referred as brown mosses (Vitt, 2008), there is a possibility that groundwater flowing out from Bolmsö Island in the Lake Bolmen is brown and hence contributes to the brownification of the lake. In the worst-case scenario, when the recharge rate is set to the maximum value, there is most likely also an increase of organic content in the groundwater adjacent to the fen and bog soils due an increase in the flow. Thus, it is probable that there will be an increase of the brown water in the Lake Bolmen resulting from a high value of groundwater recharge and discharge of Bolmsö Island.

5.8 Limitations

This study was carried out without conducting any field visit of the study area and without the collection of missing data due to the transport restrictions related to the COVID-19 pandemic. GMS-MODFLOW was used accordingly depending on the available data, although the aim of the study was reached, there were some unavoidable limitations. Firstly, the available data used in the research presented here are limited. Secondly, the study did not examine in detail the conditions of groundwater level due to the limited number and uncertainty of observation points. Lastly but not least, the results of this study may not be completely reliable because the bedrock was assumed to be without fractures which is not the case in reality.

6 Conclusion and Recommendation

6.1 Conclusion

In this project, the groundwater system in Bolmsö Island was studied. GMS MODFLOW was used to study the interaction between Bolmsö Island and the Lake Bolmen to investigate the impact of groundwater and surface water flow originating from the island to the water balance of the lake. The obtained results are reliable when it comes to indicate the water flow between Bolmsö Island and Lake Bolmen.

The main aims of the project have been accomplished even if there are some uncertainties of the data used in this study. The amount of groundwater recharge and surface runoff have been estimated. The average volume of groundwater and surface water flowing from Bolmsö Island to the Lake Bolmen are estimated to be 12970 m^3/d and 18100 m^3/d respectively. Part of groundwater recharge which discharges to the island as surface runoff has been estimated to be 1130 m^3/d The estimated amount of water that flows from the lake to the island is 30 m^3/d, it is a small value and can be ignored when it comes to compare water that discharges into the lake with water that leaves the lake. The obtained results indicate clearly that there is an interaction between Bolmsö Island and Lake Bolmen.

The purpose of this investigation, was also to identify the role played by Bolmsö Island to the browning of water in Lake Bolmen. Water flowing from the island to the lake passes an uncertain amount of bogs and fens that are red-brown colored soils. Organic matter from the latter may be transported with the groundwater and, it is assumed that the discharging groundwater contributes to the water browning of Lake Bolmen. In the northern part of the Bolmsö Island, the quantity of bogs and fens is significant and may influence the brownification of Lake Bolmen.

6.2 Recommendations

The model results could become more accurate by conducting further studies considering field observations related to the bedrock fractures to know whether the water in fractures is coming from groundwater or the Lake Bolmen and install an appropriate number of observation well with frequent recording. The site verification of bedrock elevations is also required as the existing data could not give reliable results. In addition, simultaneous measurements of groundwater levels and measurements or assessments of hydraulic condictivities need to be conducted in the Bolmso Island.A study of pollutant concentrations and transport of groundwater and surface water from Bolmsö Island to the Lake Bolmen must be conducted to know the extent at which the pollutants affect the brownification of water in the lake.

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Appendix 1: Geological formations

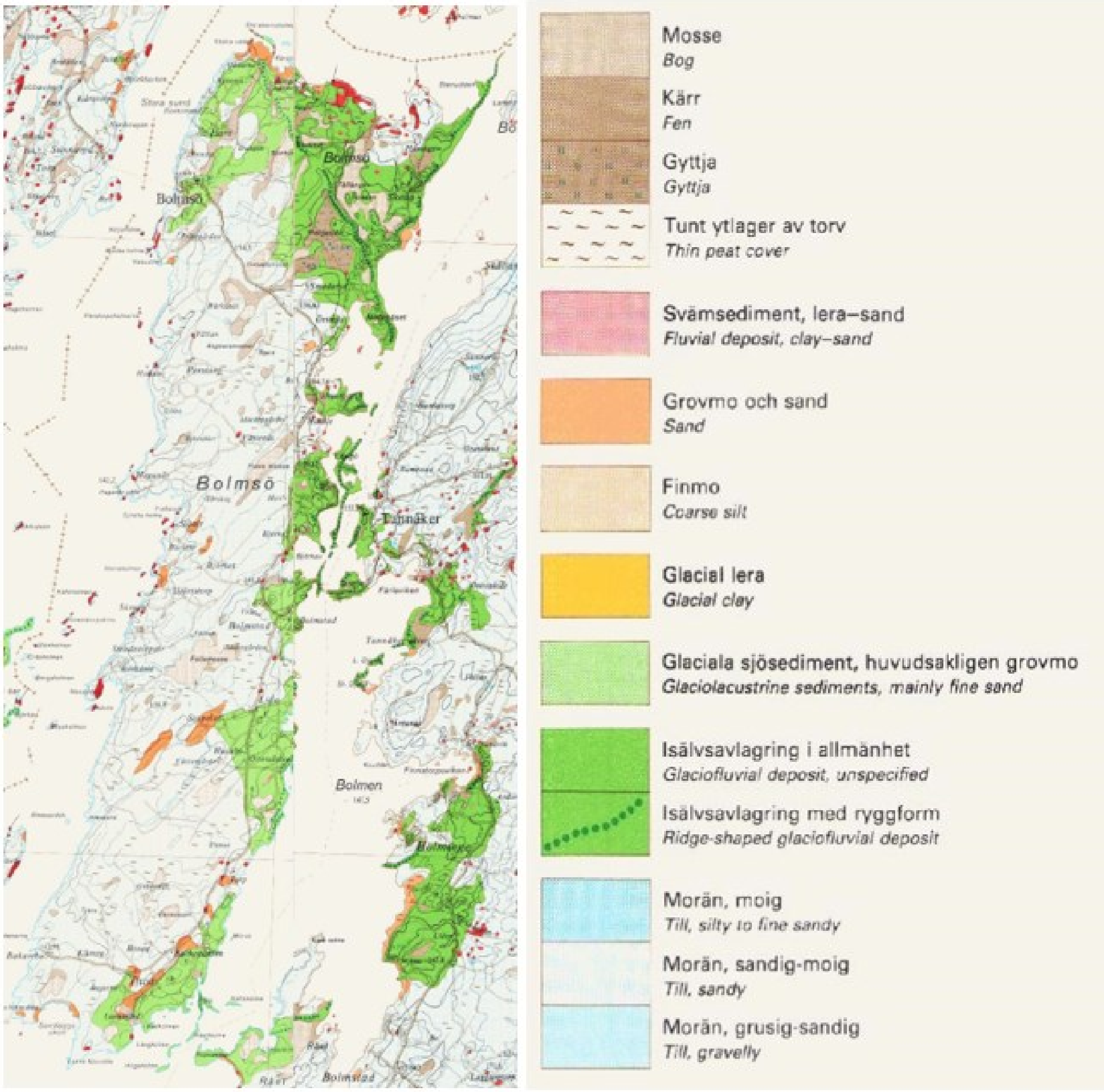


Figure A. Geological formation of the study area (SGU, n.d.b).The transparent blue color represents the till soil which is the most abundant soil. The green color shows glaciofluvial deposit which is the dominant soil in the northern part of Bolmsö Island whereas the yellow and brown color represent sand and fens-bogs soils respectively.

Appendix 2: Precipitation measurement stations

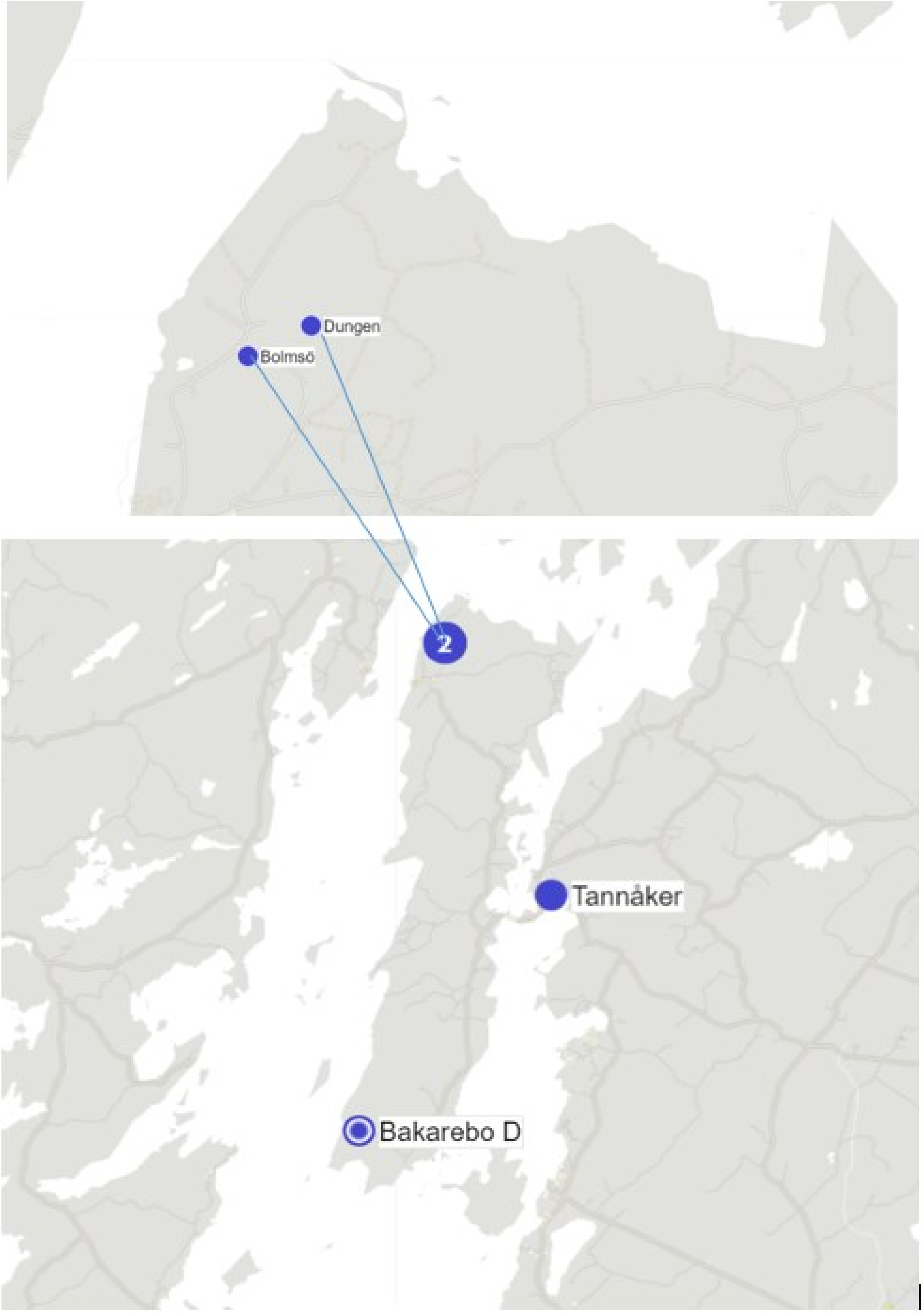


Figure B. The location of three stations of precipitation measurement Bakarebo, Dungen and Bolmsö

Appendix 3: Preliminary attempt results

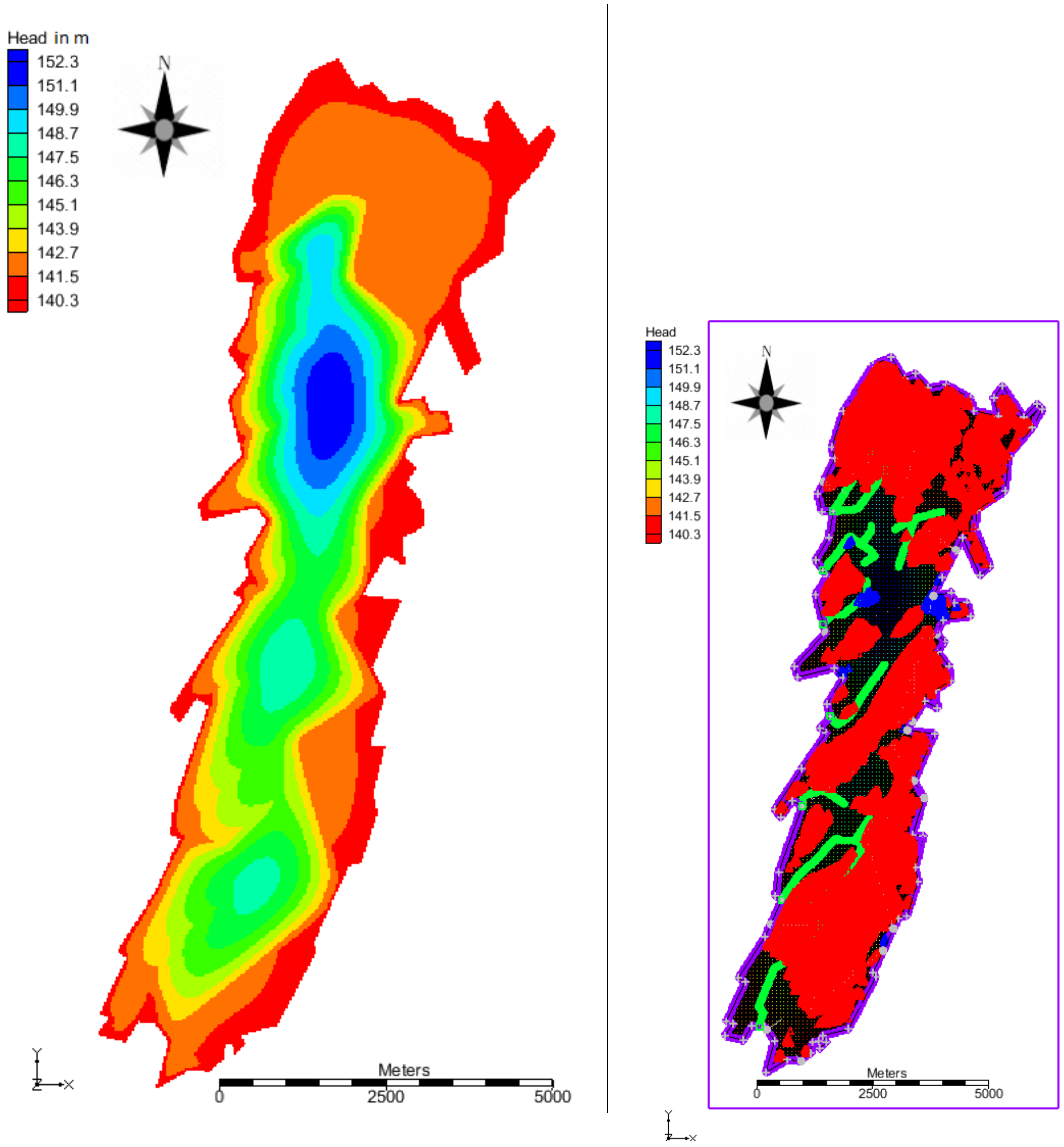
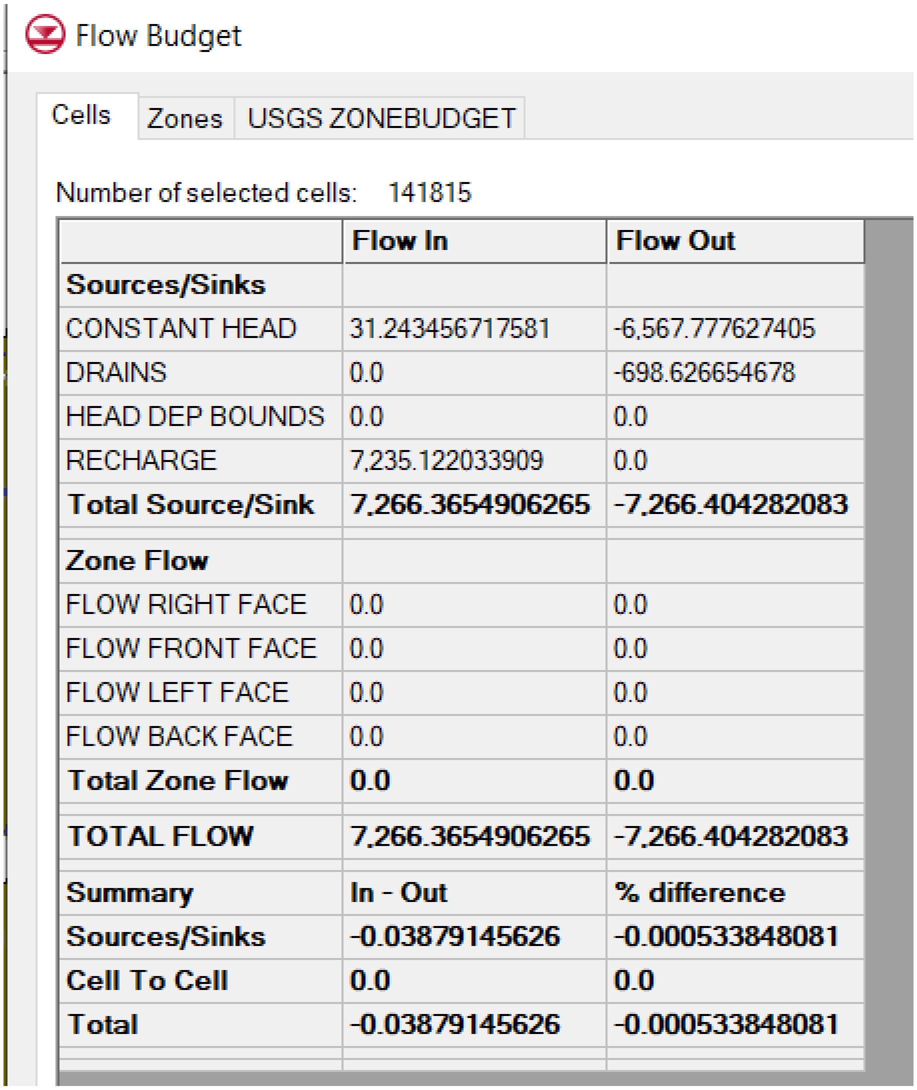


Figure C.1. The results showing the amount of dry cells (cells in red color in the figure on the right side) during the preliminary attempt. The figure on the left side indicates the variation of the head. The purple line along the coast of the island is indicating the constant head boundary.



Number of selected cells: 141815

	Flow In	**Flow Out**
Sources/Sinks		
CONSTANT HEAD	31.243456717581	-6,567.777627405
DRAINS	0.0	-698.626654678
HEAD DEP BOUNDS	0.0	0.0
RECHARGE	7,235.122033909	0.0
Total Source/Sink	**7,266.3654906265**	**-7,266.404282083**
Zone Flow		
FLOW RIGHT FACE	0.0	0.0
FLOW FRONT FACE	0.0	0.0
FLOW LEFT FACE	0.0	0.0
FLOW BACK FACE	0.0	0.0
Total Zone Flow	**0.0**	**0.0**
TOTAL FLOW	**7,266.3654906265**	**-7,266.404282083**
Summary	**In - Out**	**% difference**
Sources/Sinks	**-0.03879145626**	**-0.000533848081**
Cell To Cell	**0.0**	**0.0**
Total	**-0.03879145626**	**-0.000533848081**

Figure C.2. The results showing the flow budget during preliminary attempt, when a big number of the cells (in figure c.1) are dry.

Appendix 4: Drain

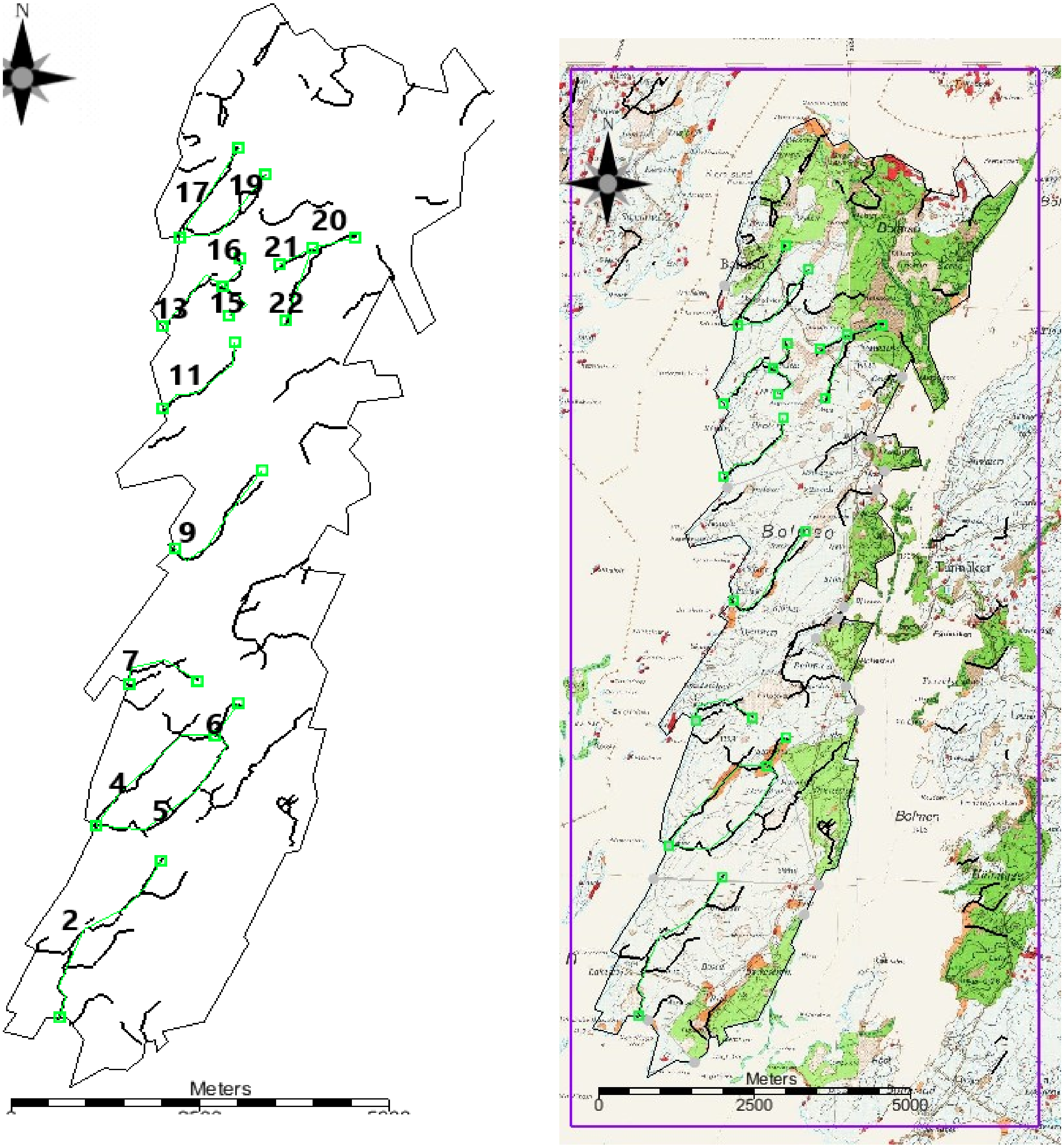


Figure D. The number of considered drain during the simulations highlighted in green and their locations.