ASSESSMENT OF GROUNDWATER FLOW TO LAKE BOLMEN

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Lund University, Faculty of Engineering
Division of Engineering Geology

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Beräkning av inflöde av grundvatten till sjön Bolmen

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Abstract

This work reports the research and findings concerning the processes of groundwater flow and distribution to lake Bolmen in the Småland region, Sweden. The watershed of Bolmen is of high interest since it provides water for drinking and energy purposes, representing a resource of notable importance for the society of southern Sweden.

Among the main objectives there is the estimation of the water balance in a sub-area of the main Bolmen's catchment, the estimation of plausible values of hydrological parameters as for instance hydraulic conductivity and recharge rate characterizing the area and the development of a three-dimensional model simulating the real hydrological processes taking place in the area.

A hydrogeological conceptual model has been built to reproduce the actual hydrological dynamics existing in the study area of Bolmen's sub-catchment. The water budget of the lake is particularly in focus and the influence of the top unconfined aquifer composed mainly by Quaternary deposit. The information used to build up the conceptual model has been downloaded from the database of the Swedish Geological Survey. The conceptual model includes a description of the spatially heterogeneous elevation of the ground surface as well as of the gneiss bedrock, assumed as impermeable. Along with the dynamics of groundwater flow governed by the Darcy's law, also the effect of surface waters with tributaries and outflowing rivers or channels has been considered.

A finite difference grid has been created in the software MODFLOW to solve the groundwater flow equation. Before running the numerical model, the information of the conceptual model has been imported into the grid by means of GMS, a software providing a user interface to the solver.

Steady state simulations have been run with different plausible values of hydrological parameters as the recharge rate of the unconfined aquifer or the hydraulic conductivity to compute a value of groundwater level for every cell of the grid. The results of each simulation have been compared to observed in-situ data in order to adjust the parameters driving the flow dynamics and to obtain a model well representing the actual conditions.

The resulting model effectively reproduces the distribution of the groundwater table in certain portions of the study area, while it either overestimates or underestimates the hydraulic heads in the majority of the grid cells. This is due not only to a lack of data regarding the precise values of hydrological parameters characterizing the Quaternary deposits, but also to a lack of data with respect to the thickness of the deposits. A further reason is the non-homogeneous collection in time of the groundwater levels used for calibration. According to the computed water balance, the major flow direction is from the unconfined aquifer towards lake Bolmen.

Possible developments on this study include the use of other MODFLOW solvers, the reduction of data uncertainty through field tests at least collecting measurements of groundwater levels in water wells and the use of other modelling approaches as for instance finite element approximations to improve the quality of the results.

Popular science summary

Evaluation of fluxes of groundwater to lake Bolmen from its surrounding aquifer

The degree project is focused on an important water resource for southern Sweden, that is lake Bolmen. In particular, an evaluation of the amount of water being transferred from the aquifer in the lake's basin towards lake Bolmen is carried out with an appropriate software named MODFLOW. The latter is a software for numerical estimation of groundwater flow and it can work only after a simplification of the study area is introduced by dividing it in a grid made of squared cells with a defined dimension.

The work has been performed to reproduce the natural environment found in the area of the lake, to investigate its connection with other types of water occurrence, particularly rivers, channels and groundwater. Results of this research suggest that the path that water follows when it enters the area, for example in the form of rainfall, is mainly directed from the underground environments below the soil surface towards lake Bolmen. However, the path of water is not the only interesting information obtained with the project work, since also the amount of water moving is of great importance. From the calculations, it has been found that most likely tens, maybe hundreds of thousands cubic meters of groundwater are naturally transferred to lake Bolmen in a way that is not directly visible with human eyes.

Smart management of water resources is essential to maximize the benefits provided by their use, benefits that can include among others the production of electrical energy, the supply of drinking water and the maintenance of vital ecosystems. A considerable amount of study involves lake Bolmen, since it has been affected during the last decades by a problem that is also encountered in almost all Nordic regions, that is brownification. This means that the colour of the lake's water is turning browner and browner, causing issues related to the treatment of the water to make it potable, to the fishery and to the lake's aesthetic (it is indeed an attractive touristic area!). So, the study of the water movement is important to address the quantity of biological and chemical compounds that may affect brownification.

The model created inside the project work can be intended as a further tool to reach a sufficient understanding of the processes taking place in the area. A flaw of the model is that it tends to either overestimate or underestimate the observed values of groundwater levels in some parts of the Bolmen's basin. Usually, the goodness of a model is evaluated according to its capacity of reproducing real-life events or dynamics. This means that only when a satisfactory correspondence between what the model foresees and what actually happens is obtained, it will be possible to use it as technical support on the decisional phase. To achieve this, possible improvements include a data collection in the study area throughout field tests, among which there is the measure of the groundwater level in correspondence to drinking water wells, and the use of alternative software to build up the model.

Acknowledgments

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Lund, June 2021

Massimiliano Favaro

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1.Introduction

Water is essential for life and all living organisms. It is known to be a universal solvent as it is able to dissolve more substances than any other known liquid. As a precious resource it has been used for all mankind time.

All water present at the Earth is in continuous circulation between the three possible phases found in nature: solid, liquid and gaseous. This is the hydrological cycle (Figure 1-1), driven by solar radiation, in which water experiences all possible forms. The hydrological cycle describes how water is being continuously recycled in the Earth system (Arkhangelski et al., 2016). Five steps are considered as fundamental: evapotranspiration, water vapour transport, condensation and precipitation, overland flow or percolation and channel runoff (Schroeder, 2004). When water evaporates either from a surface waterbody or from the bare soil, the vapour will rise up along the troposphere. The same happens when plants transpire and release water into the outer environment. The water vapour can condense in the atmosphere and accretion of rain drops can take place. Eventually they will reach a dimension that will let them precipitate in the form of rainfall or snow if temperature is low enough. The precipitation can then either reach an open water body or the soil surface, with possibility to infiltrate into the ground or to form surface runoff towards the closure section of a basin. After this the cycle can start again.

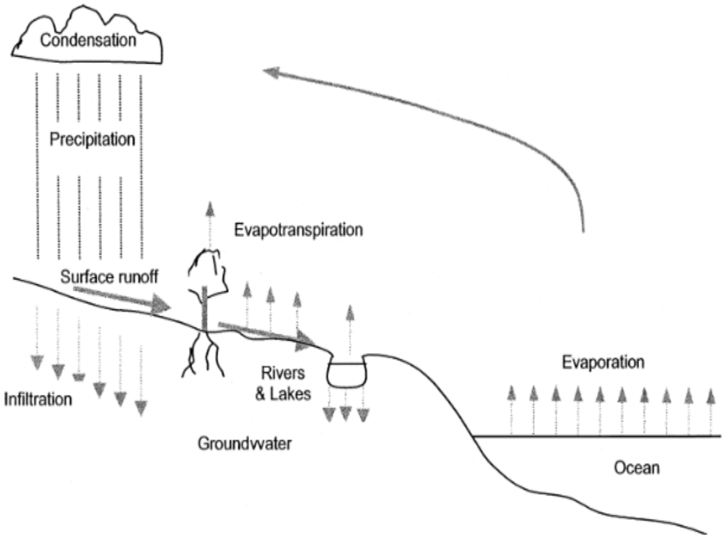

***Figure 1-1**: The hydrological cycle (Schroeder, 2014)*

Groundwater is a fundamental part of the hydrological cycle. It constitutes 1.69% of all water on Earth and 30% of all global freshwater. Freshwater available for human consumption or use is only a fraction between 0.3% and 0.5% of the total water of the planet (Khadri and Pande, 2016). Groundwater is defined as the water existing in subsurface pores and in underground karst channels and formations (Brands et al., 2016). It is found almost everywhere beneath the ground surface and plays a crucial role in the contribution of flow rate to lakes, creeks, rivers, springs and wetlands (Alley, 2009). Depending on the characteristics of the subsurface environment, the residence time on the subsurface since recharge for groundwater can vary broadly, but generally it ranges from some months for shallow layers to tens of thousands of years for deep rocky aquifers (Ge and Gorelick, 2015). Residence times and groundwater ages can be estimated through the use of several environmental tracers as for example carbon-14 and they can give hints on the possible chemical composition of the analysed water. The infiltration of rainfall is a source of recharge of groundwater through a downward vertical leaching to the water table, that could take a long time or short time mainly depending on the distance from the ground surface to the water table. Water then travels in subsurface environments with a specific flow rate: in a saturated porous media like an aquifer made of Quaternary deposits, flow rate (Q) is conceptualized as driven by the mean hydraulic conductivity (K) and the hydraulic gradient (i) multiplied by the cross-sectional area (A) according to the Darcy's law (Alley, 2009):

$$Q = -\mathrm{K}Ai \tag{1.1}$$

Instead for an unsaturated media the flow depends on the soil water content according to a non-linear relationship. No flow can be observed if the soil water content is too low, as water is too strongly attached to soil particles through molecular interactions: in this condition the water content is referred to as irreducible water saturation.

Due to a rapid economic development and growth of population particularly in some areas of the world, an increasing pressure on groundwater resources has been exerted by mankind. It is estimated that at least half of the world's population is currently living in urban areas and that at least half of the mega-cities (cities with more than 10 million inhabitants) are mainly dependent on groundwater as a water supply source (Khadri and Pande, 2016). This is why a great attention is being posed on groundwater study all over the world.

A groundwater model is any computational method approximating the real water system of the subsurface (Kumar, 2019). Models have proved to be important to address groundwater problems and to support the decision-making phase. For groundwater flow systems, conceptual models are developed (Fetter, 2014) and they are used to analyse the real processes, even though a full description of the actual conditions is not feasible.

In particular, numerical groundwater models start from the flow equation and solve it for the head distribution throughout the aquifer. Fundamental information for the modeling process includes the geometry of the aquifer systems, boundary conditions and contacts between the aquifers and surface water systems. Further knowledge about stressing elements like extracting or injecting wells, irrigation run-off and recharge basins are useful to refine the models.

MODFLOW (first publication in 1984) is among the modeling softwares one of the most internationally recognized and used. It was developed by the USGS (United States Geological Survey) and it is based on the finite difference approach to solve the partial differential equations describing groundwater flow. MODFLOW is also contained in the water modeling application GMS (Groundwater Modeling System, Aquaveo 2018), developed by AQUAVEO. With this platform the user has the possibility to simplify the input and output data to MODFLOW, using GMS as an interface to represent different complex distributions of hydrogeological features of the area, for example hydraulic conductivity and recharge rate.

1.1 Problem description

Lake Bolmen is located in south-western Sweden, precisely in the Småland region. It is the twelfth largest lake in Sweden and a resource of great importance for the society as it provides water to around 600 000 people in Scania. It is also of paramount relevance for the local economy due to the activities related to fishery and tourism in the area.

Over the last decades a phenomenon of brownification (Figure 1-2) has been taking place in the lake. Brownification is a change in colour of the lake's water (Graneli, 2012) possibly caused by an increase in organic matter content. This humic material tends to absorb the solar radiation more in the short wavelength part of the visible spectrum. Another possible cause of this phenomenon is an increase in iron content of the water. The presence of dissolved organic matter in water can lead to multiple issues, like reducing the penetration of solar radiation into the deeper strata of the lake and increasing the available substratum for bacterial and algae growth. Thus, reducing the free available oxygen and increasing carbon dioxide production (Graneli, 2012). Also, water containing more dissolved organic matter will require advanced treatments to make it potable and would reduce fish production in the area. One other ecosystem service that is conditioned by brownification is the outdoor experience and touristic activity in general, since recreational use is preferred where the water is clear (Graneli, 2012). The phenomenon has been observed mostly in northern lakes and boreal regions, due to the high presence of peat, a soil type containing a great amount of carbon (Hansson et al., 2019). Other drivers may involve the increase of average temperature, reduced acidic deposition and modification in land use (Borgström, 2020).

***Figure 1-2**: Photo of lake Bolmen taken in Bolmstad, a town located on the eastern coast of the lake. A visible brownish colour of the water is the consequence of brownification. In the background Råö Island is also observable (photo by Massimiliano Favaro).*

1.2 Objectives of the study

The main objective of this study is to acquire deeper knowledge of the physical process of groundwater flow between Bolmen's catchment and the lake. In particular, the modeling of the lake aims at:

- estimating the water balance in a sub-area of the catchment, meaning that the flux of water exchanged between the lake and the aquifer should be calculated;
- finding plausible values of parameters such as hydraulic conductivity, recharge rate, precipitation, evapotranspiration rates, permeability rates through lake- or river-bed sediments that approximate the real unknown heterogeneous values over the area;
- obtaining a three-dimensional groundwater flow model that can simulate the real hydrogeological processes taking place in the study area and that could serve as a prediction tool for future developments. In this sense a comparison between the results of the modelling and the actual field observation will be made.

2.Material and Methods

2.1 Study area and conceptual model

The investigated area (Figure 2-1 and Figure 2-2) is located in the Swedish region of Småland and intersects three counties (Kronoberg, Jönköping and Halland).

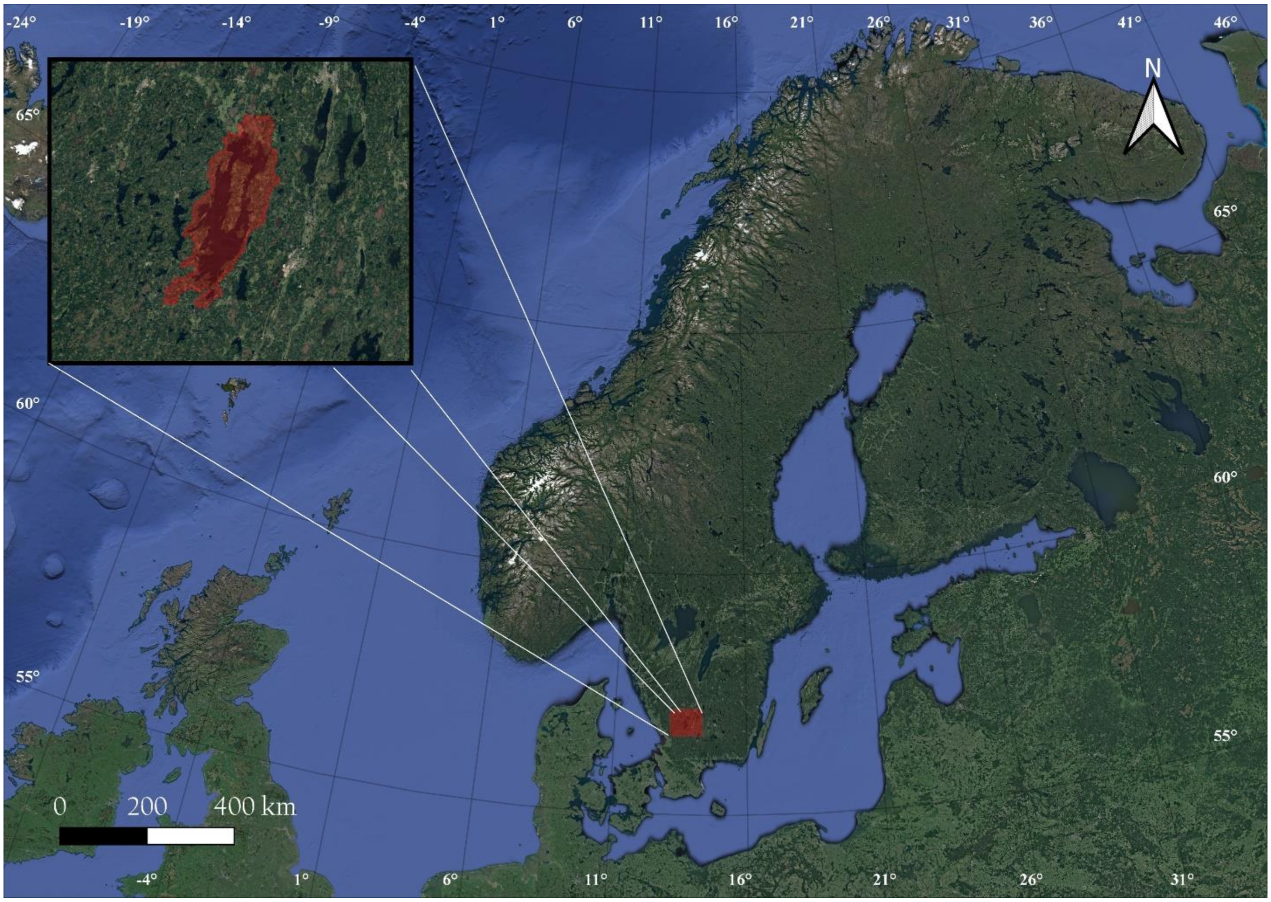

Figure 2-1: *Google Satellite image of Northern Europe and of the study area edited with QGIS. The study area is highlighted in red and it is magnified in the top-left corner of the figure. Map data ©2021 Google.*

The catchment area of Lake Bolmen (Figure 2-2) is approximately 1640 km^2 large, with the lake's extension being 30 km long from north to south and 10 km wide from east to west (Persson, 2011). The surface of the lake covers 183 km^2 (WISS, 2021) and the coastline is 330 km long. Bolmsö Island is the main island of the lake, located in the middle of it and covering 42 km^2 (estimated through QGIS analysis). Land cover in the catchment is dominated by forests (64.2%), then other relevant types of cover found are surface waters (lakes or streams, 15.2%), wetlands (8.5%), agricultural areas (7.7%) and urban areas (0.7%). Data is based on the SMHI (Swedish Meteorological and Hydrological Institute) S-Hype model.

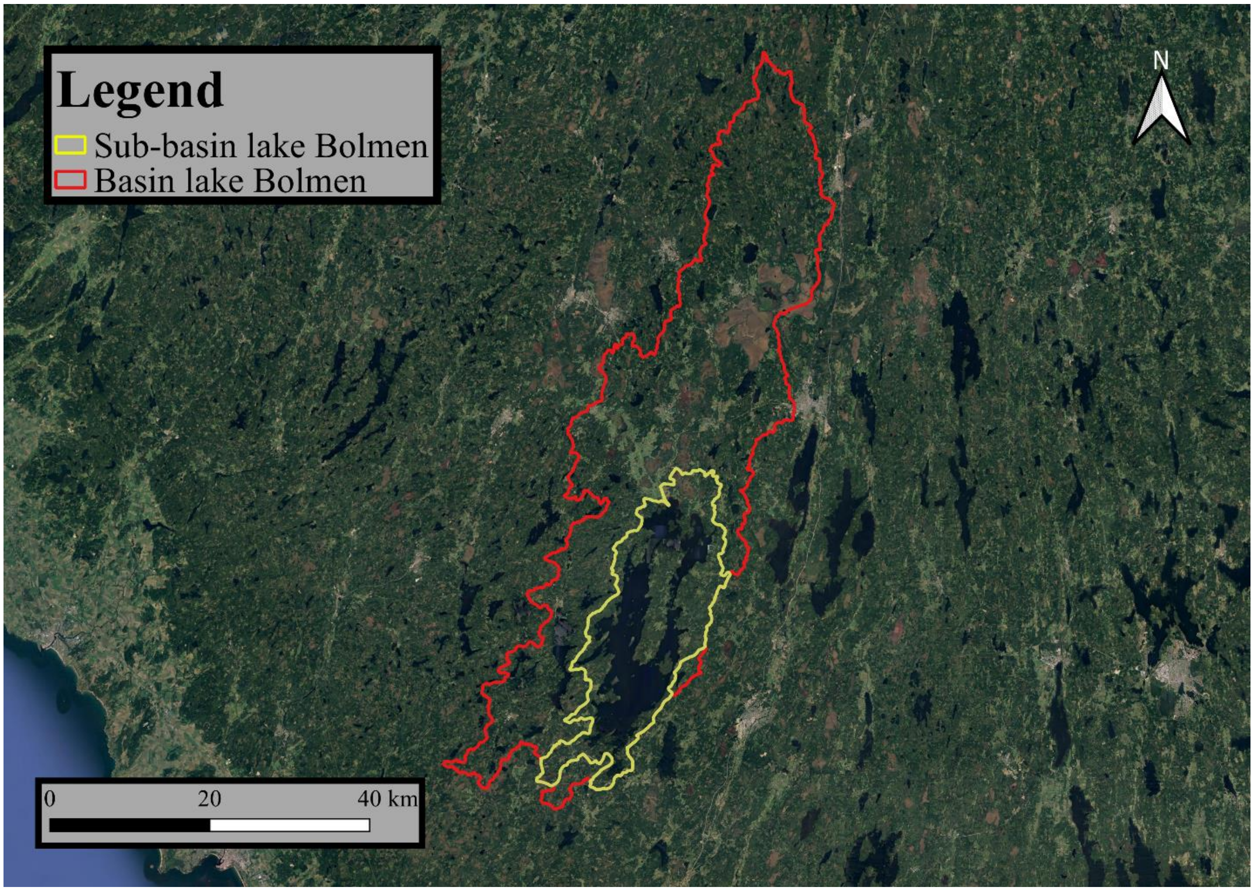

Figure 2-2*: Google Satellite image of main Bolmen basin edited with QGIS. Map data ©2021 Google.*

A particular focus in this work is the Quaternary deposits dominating the study area.

Two geological maps at a scale 1:50 000 describing the Quaternary deposits in the investigated area are available from the Swedish Geological Survey (SGU): map series Ae number 93 and number 80. Also, shapefiles from the institute are available online to observe the distribution of soil types at the ground surface (Figure 2-3).

Till, sandy till and glaciofluvial sediments are the main Quaternary deposits found in the investigated area. Till is the most common Quaternary sediment (Fredén, 1988) and it also generally underlies other types of Quaternary deposits. Its thickness ranges mostly between 5 to 20 m but it can even reach values of around 50 m. The morphology of till tends to reflect the shape of the bedrock. Among the different types of tills, the sandy till is the most widely spread but also gravelly till is present (see Appendix A for a description of different till types). The content of stones and boulders in the matrix is from low to medium. Glaciofluvial sediments appear mainly in the form of eskers, that are a typical geological formation found in Nordic regions dating back to the deglaciation period (approximately 12 400 years ago in the study area). Eskers are usually surrounded by hummocks and plains with gravel and sand and they are important aquifers and a main source of water for wells drilled in the area. Due to a generally higher effective porosity of glaciofluvial deposits with respect to the different types of tills, the latter can be considered relatively impermeable.

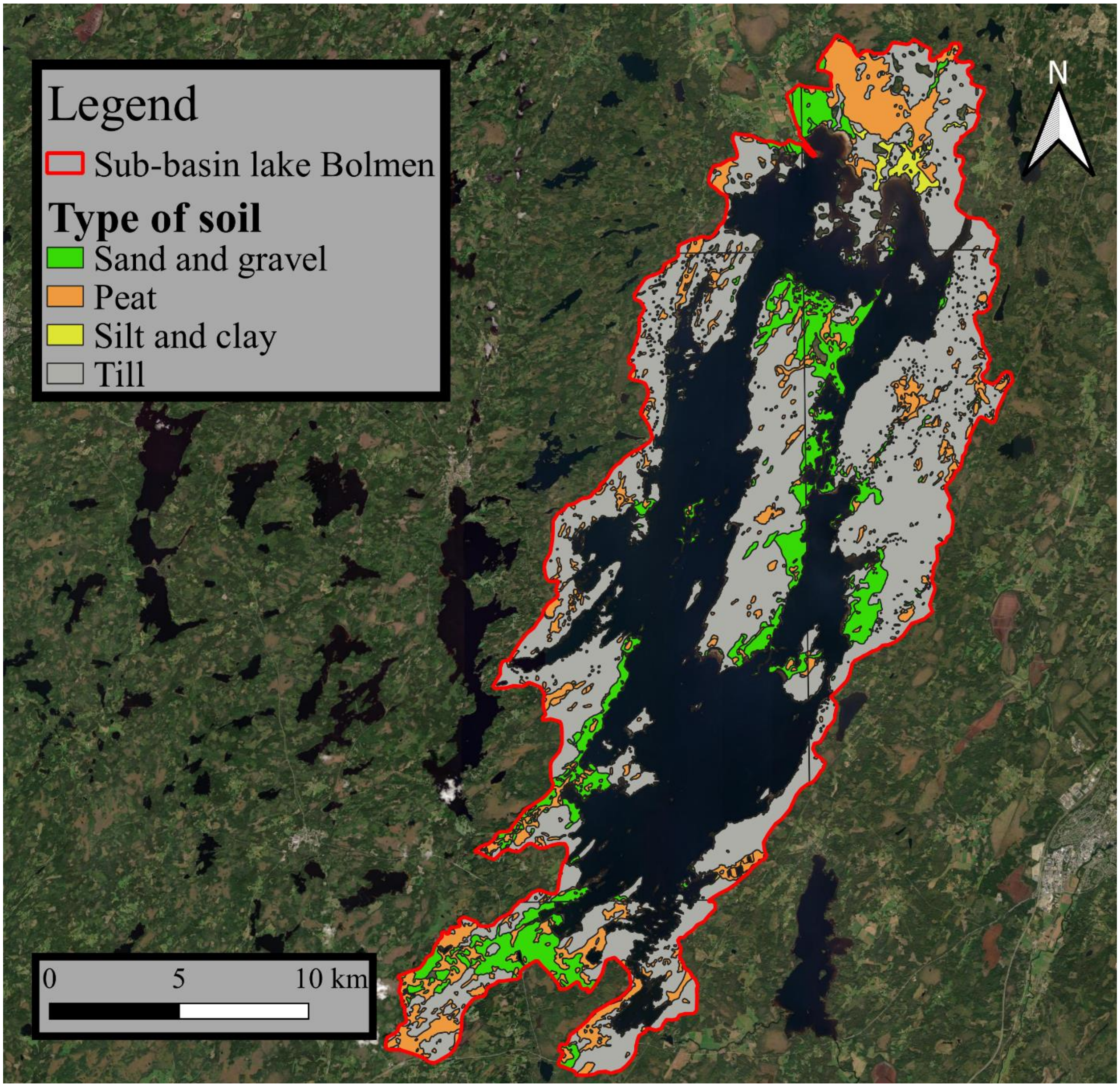

Figure 2-3: *ESRI satellite image of the study area with the Quaternary deposits at the ground surface. Edited in QGIS using data from SGU. Copyright: Esri, Geodatastyrelsen, NASA, NGA, USGS | SDFE, Esri, HERE, Garmin, METI/NASA, USGS | Earthstar Geographics*

Fine sand occurs as a glaciolacustrine sediment and often contains layers of coarse silt while glacial-fine grained sediments have a limited spatial occurrence. They are mostly overlain by fine sand, but varved clay with a thickness of 1.6 m has been encountered in Lake Bolmen. Postglacial sand appears around the lake and around some bogs, but the sediments are generally narrow and thin (around 1 m). Fluvial deposits, mainly sand and silt, are found along rivers. Peat and organic material are also widespread in the area and they are generally overlying till and glaciofluvial deposits. Bogs and fens are common, with bog peat having a thickness that can reach 5 m and fen peat of 1-2 m. Former lakes in which the water level has been lowered are the origin of the majority of current peat basins (Esko, 1986).

A current effect of the deglaciation phenomenon is the land uplift of less than 1 mm/y (Fredén, 1988).

A hydrogeological conceptual model has been developed to represent the study area of the sub-basin of lake Bolmen. The aquifer lying above the bedrock (assumed as totally impermeable) is represented, along with the lake, three main tributaries and the outflowing river (Figure 2-4) at Skeen. The modelled unconfined aquifer is considered to consist of tills, mainly of the sandy type, and glaciofluvial deposits according to the available information related to the spatial distribution of the different Quaternary deposits. Three islands are also included among which there is Bolmsö Island, the largest one found in lake Bolmen.

The hydraulic conductivity of sandy tills shows a great range of variability, between $4x10^{-4}$ to $2x10^{1}$ m/d (Lind and Lundin, 1990). Mean values for Scandinavian tills are around $2x10^{-1}$ m/d. The bedrock is the characteristic veined gneiss of the southwestern gneiss province of the Fennoscandian Shield and it is between 900 and 1700 million years old. Since gneisses can be characterized by an average hydraulic conductivity including fractures as low as $3x10^{-7}$ m/d (Bucher and Stober, 2007) and this value is several orders of magnitude lower than the Quaternary deposits, the bedrock is considered as impermeable. GIS layers identifying the different types of deposits have been extracted from the maps of the SGU (Swedish Geological Survey, 2020).

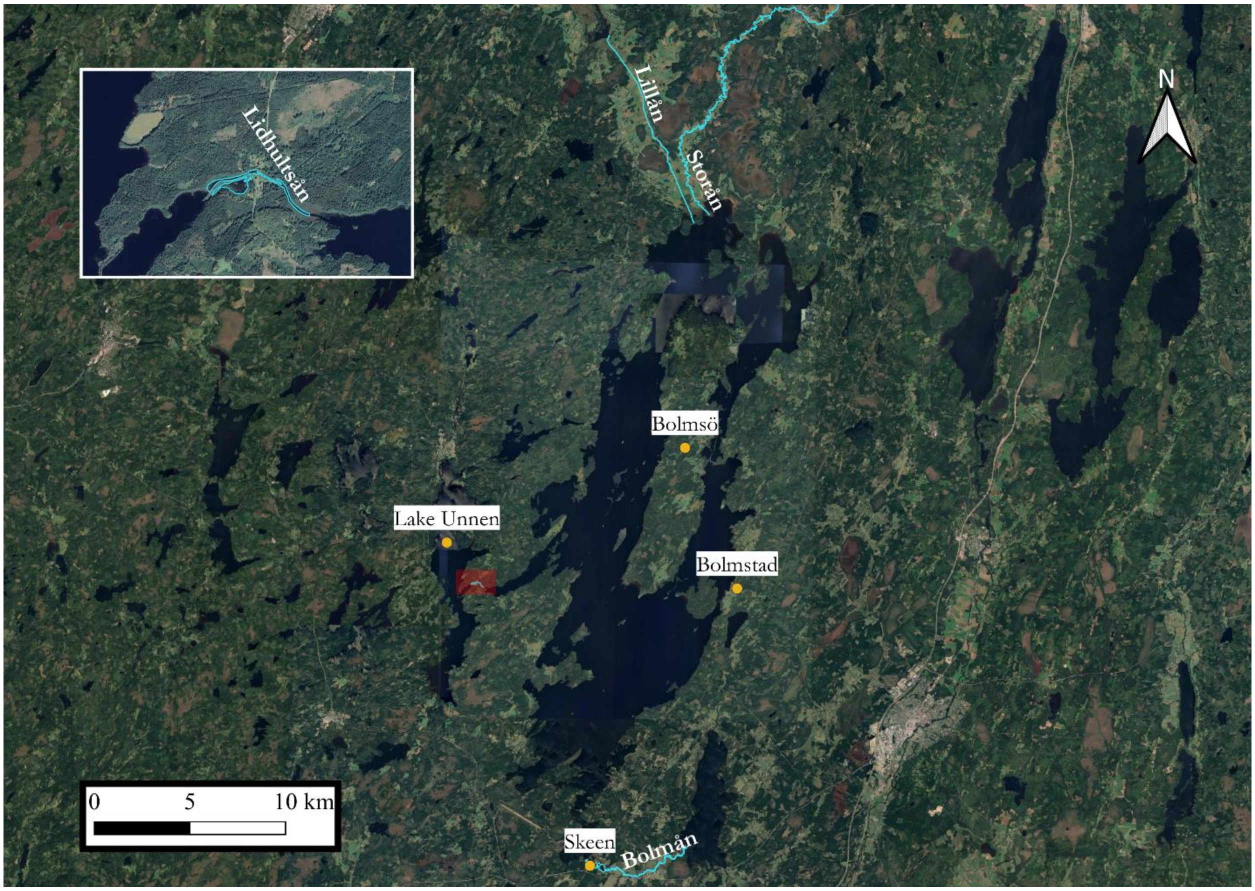

Figure 2-4: *Google Satellite image of the study area with tributary rivers Lillån, Storån and Lidhultsån and the outflowing river Bolmån. Due to the small length of Lidhultsån, the channel draining lake Unnen into lake Bolmen, it has been highlighted in red on the main map and magnified in the top left corner of the picture. Edited with QGIS. Map data ©2021 Google.*

Geological cross sections have been drawn to study the spatial distribution of the ground surface, the bedrock elevation and the thickness of the Quaternary deposits (Figure 2-5). These three datasets are strictly interconnected because the third one is the difference between the first two datasets. This relationship is valid for the aquifer surrounding lake Bolmen, while regarding the area covered by the lake a value of bedrock elevation is calculated subtracting the lake depth and the thickness of the deposits from the elevation of the lake's surface.

The operation has been conducted through the software QGIS. In positions where the thickness is near or less than 0 m (due to inaccuracies in the files), a minimum value of thickness equal to 10 m has been assigned in the cross-sections and also in the conceptual model. The specific value is chosen because a too low vertical dimension of the cell can lead to a non-convergence of the subsequent groundwater numerical model. The two cross sections are named AA' and BB' respectively. Cross section AA' (Figure 2-5) is drawn from north to south of the sub-basin of lake Bolmen, it is approximately 25 km long and intersects two islands: Bolmsö and another smaller one.

In blue (Figure 2-5b) the surface elevation referred to the mean sea level is shown: the maximum elevation of 162.78 m is found in Bolmsö while the minimum elevation coincides with lake Bolmen surface elevation, equal to 141.88 m. The minimum bedrock elevation is instead 126.55 m located in the southernmost end of the cross section where the maximum thickness of Quaternary deposits, around 21 m, is found. Regarding cross section BB' (Figure 2-5), it is drawn from west to east, its length is close to 14 km and it also intersects Bolmsö island. The eastern area of the sub-basin is the one having the higher surface and bedrock elevation: the maximum values are 195.30 m and 190.77 m respectively for the considered cross section (BB').

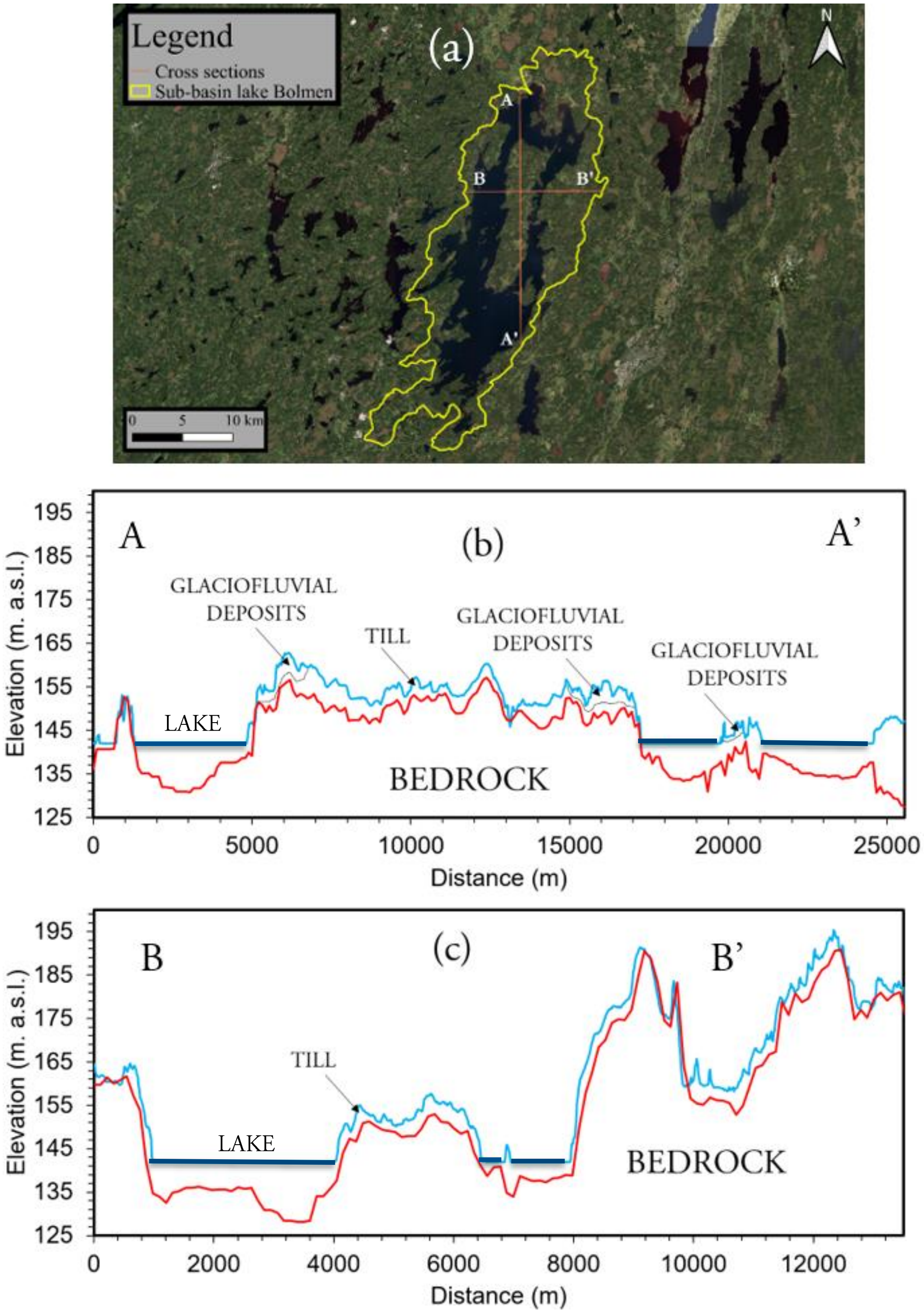

Figure 2-5*: (a) ESRI satellite image of the sub-basin with cross sections AA' and BB'. Copyright: Esri, Geodatastyrelsen, NASA, NGA, USGS | SDFE, Esri, HERE, Garmin, METI/NASA, USGS | Earthstar Geographics. (b) Cross section AA' from north to south with surface elevation (blue line) and bedrock elevation (red line). Units are in metre for the x-axis and metre above sea level for the y-axis. (c) Cross section BB' from west to east with surface elevation (blue line) and bedrock elevation (red line). Units are in metre for the x-axis and metre above sea level for the y-axis.*

2.2 Groundwater flow equation

The most general version of the flow equation is obtained by combining Darcy's law with the equation of mass conservation inside a volume of porous medium. It is valid for a wide range of cases: three-dimensional flow, heterogeneous and anisotropic porous media, fluids of variable density and unsaturated flow.

A general continuity equation for a fluid in a saturated medium reads (Han et al., 2020):

$$-\frac{\partial}{\partial t}(\rho\phi) = \nabla(\rho v) \tag{2.1}$$

meaning that the partial derivative in time of the fluid density ρ multiplied by the porosity ϕ of the medium equals the divergence of the density multiplied by the flow velocity v. The general meaning of the mass conservation equation is that the difference between the mass entering and the one exiting an elementary volume of soil equals the variation of mass in time inside that volume.

Darcy's law is an experimental equation that describes the flow of a fluid through a porous medium (Atangana, 2018). It was derived by the French engineer Henry Darcy back in 1856 by means of experiments with cylindrical sand columns (Figure 2-6).

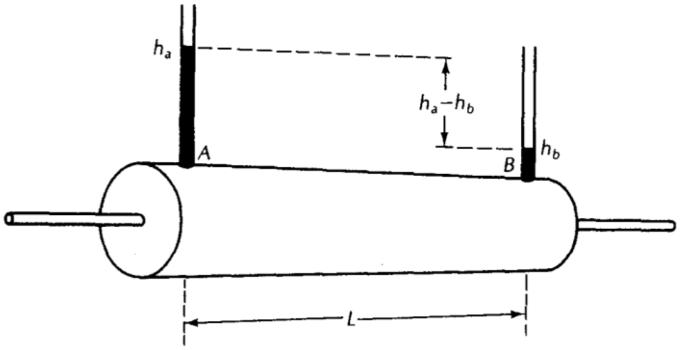

***Figure 2-6**: Darcy's experiment with a horizontal cylindrical column filled with sand (Fetter, 2014)*

It is analogous to other laws discovered in physics, such as Fourier's law of heat fluxes, Ohm's law for electrical current fluxes and Fick's law for diffusivity. In the field of hydrogeology, the most common application of Darcy's law is the estimation of flow through an aquifer, but it is employed also in the energy and oil industry to study the flow of other fluids than water like oil and gas. The simplest version of Darcy's law is for one-dimensional flow (Ge and Gorelick, 2015):

$$Q = -AK\frac{dh}{dx} \tag{2.2}$$

in which Q is the volumetric flow rate [L^3/T], A the cross-sectional area of the flow [L^2], K is the hydraulic conductivity [L/T] and the term $\frac{dh}{dx}$ [L/L] is generally called hydraulic gradient. This last term considers the variation of the hydraulic head h over a distance in the x direction. The hydraulic head is one of the most important parameters to describe the energetic configuration of a water system, being the sum of the elevation head with respect to a defined reference level (gravitational energy) and the pressure head (representing the fluid pore pressure) (Ge and Gorelick, 2015). Kinetic energy is negligible in groundwater problems due to the low velocity of water.

For a three-dimensional expression of the relationship of Darcy's law, K should be substituted with a tensor of nine terms denoting the hydraulic conductivities and the hydraulic gradient with a vector containing the values for the three principal directions (anisotropic condition). The negative sign in the right-hand side of the equation is explained by the fact that the flow direction is from higher to lower hydraulic heads.

The validity of Darcy's law is restricted to values of the Reynolds number (that expresses the ratio between inertial and viscous forces) for the flow field not higher than 10 (Atangana, 2018).

Combining Darcy's law with the general continuity equation, the following relationship describing the groundwater flow in a porous medium can be written (Konatar, 2017):

$$\frac{\partial}{\partial t}(\rho\phi) = -\nabla(\rho v) = \nabla(\rho \frac{k\rho g}{\mu} \nabla h) \tag{2.3}$$

taking into account the intrinsic permeability of the medium k, the fluid viscosity μ and the divergence of the hydraulic head h. Due to the presence of this last parameter the partial differential equation describing the groundwater flow is generally non-linear, but for confined aquifers and in absence of head-dependent boundaries the equation becomes linear (Hill, 1990).

2.3 Software MODFLOW

MODFLOW is a block-centred finite-difference model for simulations of groundwater flow (Fetter, 2014, see also chapter 1). A finite-difference model includes a finite-difference grid, in which approximate solutions to partial-differential equations are computed. In particular, equations are solved in the grid nodes and in the case of block-centered grids nodes are located in the centre of the grid cells. For mesh-centred grids, nodes are instead located in the intersections between the grid lines. The code MODFLOW has a modular structure, with a main program and several independent sub-routines named "packages" (Harbaugh, 2005). These last features have the purpose of simulating many possible characteristics of a hydrologic system such as streams, creeks, rivers, lakes, water reservoirs interacting with aquifers and man-made works as extraction or injection wells. Packages can also be solution methods of the groundwater flow equation. A more detailed description of the flowpath of MODFLOW can be found in Appendix B.

2.3.1 Geometrical modelling of the study area

The investigated area has been discretized in a grid made by squared cells with the dimension of 50x50 m^2 and a vertical dimension varying depending on the thickness of the Quaternary deposits. A unique vertical layer representing the unconfined aquifer has been considered. The final discretization is in one layer, 1000 rows and 607 columns for a total 607 000 cells in the grid.

Figure 2-7(a) illustrates the outcome of the interpolation of a raster file from SGU containing the surface elevation in the modelled area. This operation has been performed to assess the top elevation of the unconfined aquifer. Furthermore, the values of elevation in terms of meter above sea level (m.a.s.l.) are also coincident with the value of the first attempt assigned to the hydraulic heads in the MODFLOW simulations. Figure 2-7(b) depicts instead the bedrock elevation. This last one was obtained subtracting the thickness of the Quaternary deposits from the surface elevation and it coincides with the bottom elevation of the modelled unconfined aquifer in contact with lake Bolmen. The coordinate system in m for the two grids is the Universal Transverse Mercator (UTM), latitude zone number 33 and longitude band from 12°E to 18 °E.

All the external boundaries of the sub-basin model are at first conceptualized as no-flow boundaries. This has been initially done to avoid starting with a too complex model with many MODFLOW Packages applied together. Later, other attempts with different types of boundary conditions as general head boundaries are performed.

2.3.2 Hydraulic conductivity zones

The study area has been subdivided into a number of polygons according to the type of Quaternary deposits encountered at the ground surface (Figure 2-3). When the polygons are imported into MODFLOW from GMS, a value of hydraulic conductivity is assigned to the cells according to the overall value of the polygon that covers every sub-area of the model. In order to simplify the procedure, the only type of soils considered have been till, sand and gravel. Due to the very limited spatial occurrence of silt and clay and of the general small thickness of peat soils, these soil types have not been taken into account. In correspondence of bogs and fens the thickness can be larger, but the wetlands are not spatially extended in the study area. Since the till in the modelled area is mainly of the gravelly and sandy type, values assigned to the polygons are mostly relatively high. During the calibration procedure the values of hydraulic conductivity of the polygons are changed considering the model outcomes.

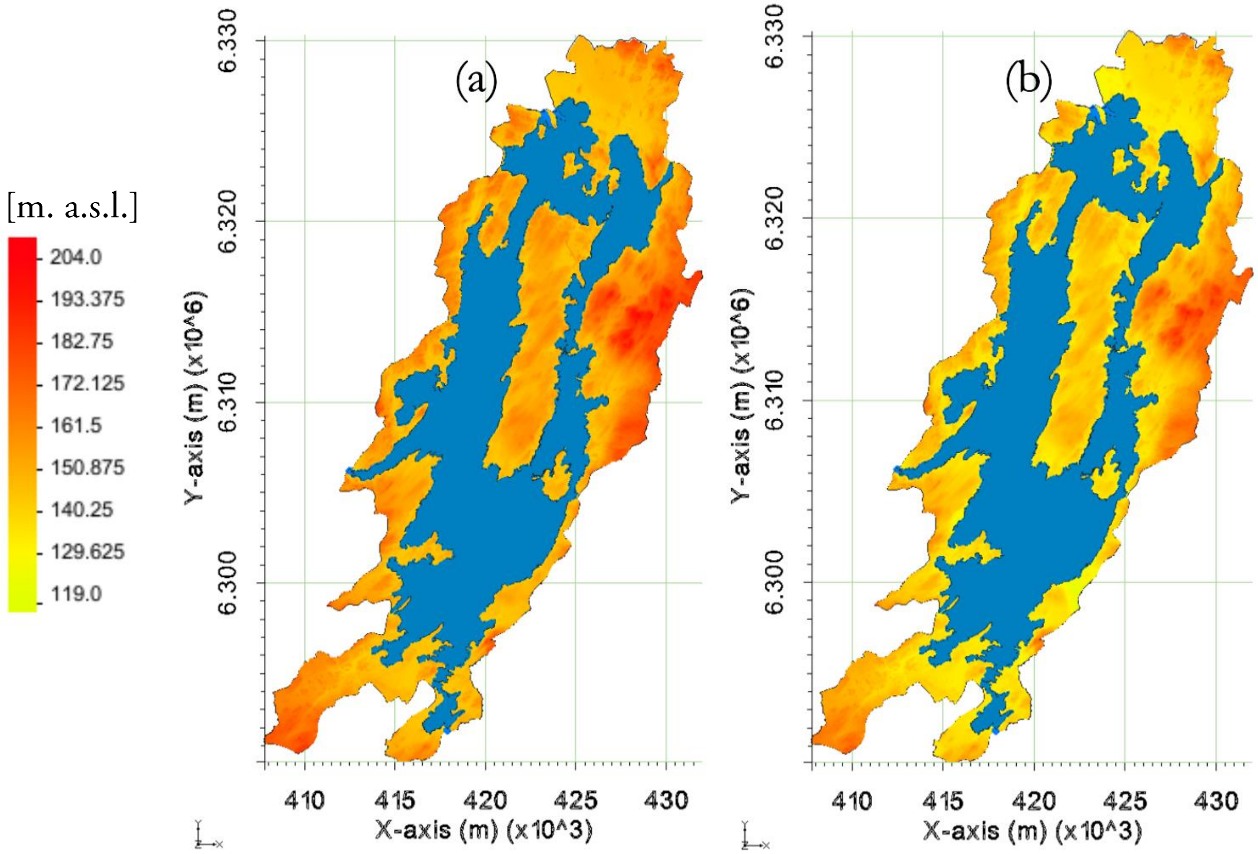

***Figure** 2-7: (a) Results of interpolation of surface elevation raster files on the model grid (m. a.s.l.). This coincides with the top elevation of the unconfined aquifer. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E. (b) Results of interpolation of bedrock elevation raster files on the model grid (m. a.s.l.). This coincides with the bottom elevation of the unconfined aquifer. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

2.3.3 Recharge Package

A first package integrated in MODFLOW for this study is the Recharge Package (RCH), needed to consider the rainfall infiltrating and percolating through the unsaturated zone as a contribution to the water budget of the area. This is due to the fact that the recharge rate [L/T] is rarely estimated on site and it is instead often derived from the amount of precipitation over a defined area. Usually a fraction of the total rainfall is considered to be contributing to the aquifer recharge on the basis of soil cover material, land use, vegetation type and surface topography.

The package will only assign a recharge value to the cells of the aquifer and it will not consider the precipitation over the lake surface (this fraction is instead considered in the LAK Package, see section 2.3.4). Data for precipitation are available in the sub-basin thanks to an active meteorological station located in Bakarebo (Figure 2-8). The station belongs to the Swedish Meteorological and Hydrological Institute (SMHI). Data are referred to the period in which the station has been active, that means from 1995 to 2021, but only validated data, available from 1995 to 2019, have been used to estimate the amount of recharge to the investigated area. Over these 24 years, the mean annual precipitation measured by the station equals 852.6 mm. The year with the highest amount of precipitation at the station was 2007, when a value of 1144 mm was registered, while the year with the least amount of precipitation was 2018 with 509 mm. Not all of this precipitation will eventually be a source of recharge to the aquifer since a part of it will be intercepted by plants and released through evapotranspiration. For southern Sweden, evapotranspiration can be assumed equal to 500 mm/y (Eriksson, 1981). The net precipitation can be estimated by subtracting the evapotranspiration from the precipitation, obtaining a value of 353 mm/y. This corresponds to 9.66×10^{-4} m/d. The value inserted in the model for the glaciofluvial deposits is lower, considering the possible presence of dunnian or hortonian surfaces where the amount of infiltration is reduced with respect to the net precipitation. Urban areas may also influence the amount of infiltration. For the sandy till, an even lower value should be introduced considering the lower infiltration capacity with respect to the glaciofluvial deposits. The recharge rate is in any case adjusted in the calibration phase according to outcomes of MODFLOW simulations. A procedure similar to the one for the hydraulic conductivity polygons has been followed to build polygons with different values of recharge rates.

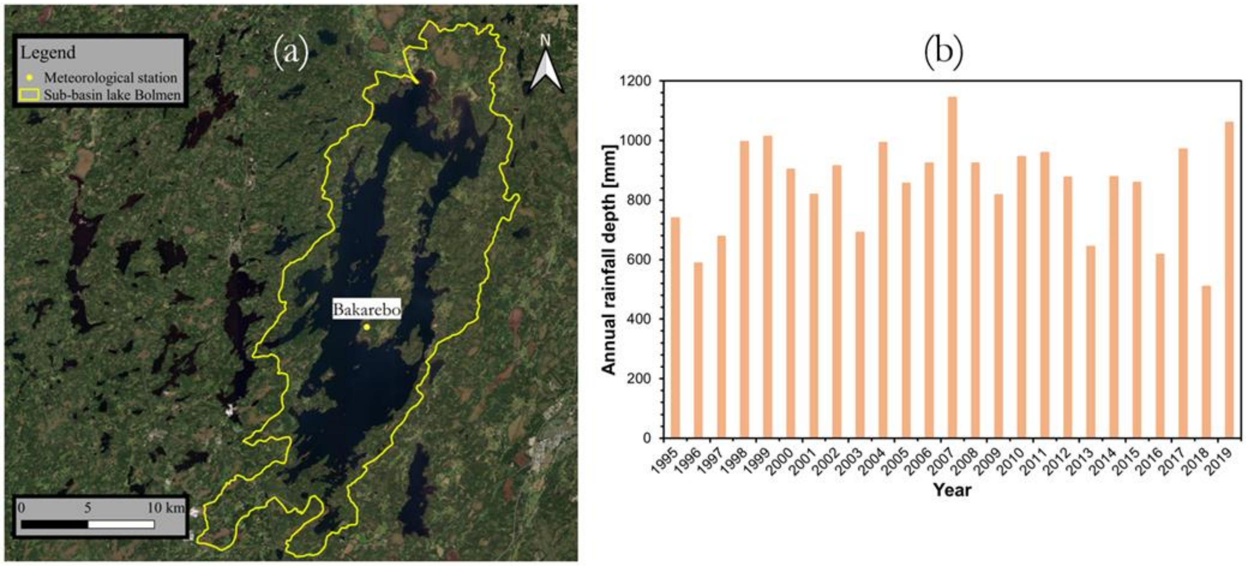

***Figure 2-8**: (a) ESRI satellite image with the meteorological station of Bakarebo. Copyright: Esri, Geodatastyrelsen, NASA, NGA, USGS | SDFE, Esri, HERE, Garmin, METI/NASA, USGS | Earthstar Geographics (b) Annual rainfall at Bakarebo station from 1995 to 2019. Data from SMHI.*

2.3.4 Lake Package

The Lake Package (LAK) was introduced into MODFLOW to properly model the interaction between an aquifer and a lake. It is based on the assumption that a surficial water reservoir exchanges a flux of water with the surrounding aquifer due to the head difference between the stage in the reservoir and the hydraulic head in the aquifer (Konikov and Merrit, 2000). This means that the flow is driven by Darcy's law, written as:

$$q = K\frac{h_l - h_a}{\Delta l} \tag{2.4}$$

where K [L/T] is the hydraulic conductivity of the lakebed sediments through which the flux takes place, h_l and h_a are the heads respectively in the lake and in the aquifer and Δl is the distance between the two points in which the flux is estimated. The stage in the lake depends on its geometry and on its water budget, that considers positive contributions as tributary streams, precipitation, surface runoff and negative contributions as outflowing streams, evaporation and artificial extraction for civil purposes. A very important note is that lake cells in MODFLOW are considered as inactive because they are just needed to identify the area of the lake. The feature that the LAK package models is the water budget of the entire reservoir and not of every single lake cell.

For a steady-state simulation in MODFLOW to determine the stage, the mathematical iterative method used is the Newton-Raphson method. This is commonly adopted to find the zeros of a function having a continuous derivative and it rapidly reaches convergence provided that the value of the first attempt of the lake stage is close to the solution. Instead, if the first guess stage is far from the solution, the Newton-Rapson may diverge. The method can be mathematically described as follows:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{2.5}$$

with x_n and x_{n+1}indicating the values of the lake stage at subsequent iterations and $f(x_n)$ and $f'(x_n)$ the function for which the zero has to be found and its derivative. $f(x_n)$ is normally expressed as (Konikov et al., 2000):

$$f(x_n) = f(h_l) = \frac{\Delta t}{A_s}\left[p - e + rnf - w + Q_{si} - Q_{so}(h_l) - \sum_m c_m(h_l - h_{am})\right] \tag{2.6}$$

where p takes into account the contribution of precipitation, e the evaporation, rnf the run-off, w the artificial withdrawal, Q_{si} the cumulated discharge of all tributaries, $Q_{so}(h_l)$ the cumulated discharge of the outflowing streams and $\sum_m c_m(h_l - h_{am})$ the seepage between the lake and the aquifer. Only the last two terms depend on h_l, so $f'(h_l)$ will depend only on them. The head-stage convergence criterion is of notable importance and it should be set considering the expected rate of seepage through the lake-bed sediments: if aquifer and lake are hydraulically well connected, then a smaller value is needed for the convergence criterion. Only cells of the grid in the coastline of the lake can transmit water to or from the aquifer because of the presence of one single layer in the vertical. The modeler has to indicate the maximum range of variability of the lake stage inserting the value of minimum stage, starting value of the stage and maximum stage. LAK also enables the possibility of subdivision of the lakes in minor reservoirs if the level decreases under a certain threshold.

Lake geometry

The Lake Package requires information about the three-dimensional geometry of the lake. A raster file containing the bathymetry of lake Bolmen has been imported in GMS and the elevations of the bottom of the lake have been interpolated to a triangular irregular network (TIN). The interpolation method that has been used is an inverse distance weighted method. The TIN is drawn automatically by the software considering the vertices of the coastline of the lake as nodes of triangles and it is then included into the LAK. Due to the high number of vertices of the GIS layer for the coastline of the lake, the number of drawn triangles building up the triangular irregular network is 2 374 801.

Leakance of lakebed sediments

Plausible values of leakance [T^{-1}] of lakebed sediments have been calculated assuming that the main materials that compose the sediments are clay, silt, silty sands and clayey sands. According to Fetter

(2014), the hydraulic conductivity values of these materials range from $8.64\text{x}10^{-7}$ to $8.64\text{x}10^{-2}$ m/d. The thickness of the sediments has been assumed as equal to 1 m, so that the leakance values range from $8.64\text{x}10^{-7}$ to $8.64\text{x}10^{-2}$ 1/d.

Withdrawal for the Bolmen tunnel

Sydvatten AB, the company managing drinking water resources in 17 municipalities of western Scania, extracts around 1.4 m^3/s from lake Bolmen for water supply. The value of 120 960 m^3/d has been inserted in the lake parameters to consider also this outflow from the lake. The water is diverted through the Bolmen tunnel, activated by Sydvatten AB in 1987 after 12 years of construction work (Persson, 2011), and is directed towards Ringsjöverket in Scania where it is treated to reach an acceptable drinking water quality. The tunnel has a cross sectional area of more than 9 m^2 and the flow is gravitational.

Precipitation and evaporation

The parameter considering rainfall intensity over lake Bolmen is obtained dividing the mean inflow due to precipitation, 4.7 m^3/s (406 080 m^3/d), by the area of the lake, that is 183 km^2. In daily units, precipitation over the body of water results as 0.0022 m/d. Regarding evaporation, the same procedure has been followed. The average value of evaporation is equal to 2.7 m^3/s (233 280 m^3/d), so the value of 0.0013 m/d has been inserted as a model input. Data for both precipitation and evaporation are from the flow model S-Hype (SMHI, 2020).

2.3.5 Streamflow-Routing Package

A river or channel can be modeled through the Streamflow-Routing Package (SFR2). The river, defined as a “segment”, is made of multiple reaches, that are cells in which SFR2 Package is active. It is of fundamental importance to assign the correct direction of flow to the segment to properly simulate the real hydrologic behaviour of the river. The software requires information about the elevation and geometry of the river or channel as input data. At least the elevation of the bottom of the channel in the first upstream and last downstream cells need to be assigned, then other information includes the thickness of the sediments representing the contact layer between the river and the aquifer, the depth of the water, the width of the channel and the roughness (Manning’s coefficient). MODFLOW is then programmed to linearly interpolate the streambed elevation from upstream to downstream.

The water balance in streams is based on the steady-state continuum equation calculated assuming that the inflow at the first reach of the stream is equal to the outflow minus all sources and sinks (Niswonger and Prudic, 2010). To simulate stream depth, the package gives four different options to the user (Banta et al., 2004), that are: a specified fixed value, the use of Manning's equation (either with a rectangular channel or with an eight-points cross section), a power law and a table where the different depths at different flow rates are indicated. The flow between a stream and an aquifer can be mathematically described as:

$$Q_L = \frac{KwL}{m}(h_s - h_a) \tag{2.7}$$

where $(h_s - h_a)$ is the difference between the head in the stream and the one in the aquifer and the term $\frac{KwL}{m}$ expresses the conductance of the streambed, being the product of hydraulic conductivity of the sediments, the width of the channel and the length of the stream divided by the thickness of the streambed.

MODFLOW allows to link lakes with tributaries and outflowing streams through the Streamflow-Routing Package (SFR2): for the tributaries a specified flow can be indicated by the user, while for the outflows either a specified flow is indicated or MODFLOW will establish the flow rate according to the head difference between the lake and the stream. The connection to the lake is indicated in the package by assigning the outflow (or inflow) of the tributary to the lake ID with a negative sign in front: in the case of modeling of lake Bolmen, being it the only lake in the grid, the value to be indicated is -1. This is due to the fact that streams are usually connected between each other and the connection is performed assigning a value of the ID of the tributary or outflowing river. Using a negative value for the ID means that the outflow (or inflow) is instead a lake.

Three main tributaries of lake Bolmen and one main outflow have been considered in the MODFLOW model (Figure 2-9). The most important inflow to lake Bolmen in terms of flow rate is represented by the river Storån with an annual average 9.4 m^3/s of discharge. Another considerable inflow comes from lake Unnen (Persson, 2011), via the Lidhultsån channel with a discharge of 3.2 m^3/s. The last contribution is given by river Lillån, having an average discharge of 2.5 m^3/s. The values of daily inflow to the lake due to these three rivers or channels are then respectively 812 160 m^3/d, 276 480 m^3/d and 216 000 m^3/d. The main river outflowing from lake Bolmen is the Bolmån, having an average discharge at the power station of Skeen of 21.4 m^3/s. This value is not introduced in the model since the flow rate of this river is calculated by MODFLOW considering the stage in the lake and the geometrical characteristics of the Bolmån.

Also the geometrical characteristics of the rivers have been considered (Table 1). HCOND1 and HCOND2 are the hydraulic conductivities of the river bed sediments at the upstream and downstream sections respectively. THICKM1, THICKM2, ELEVUP, ELEVDN, WIDTH1, WIDTH2, DEPTH1 and DEPTH2 are instead respectively the thickness of the sediments, the elevation of the bottom of the river, the width of the section and the depth of the water in the river or channel.

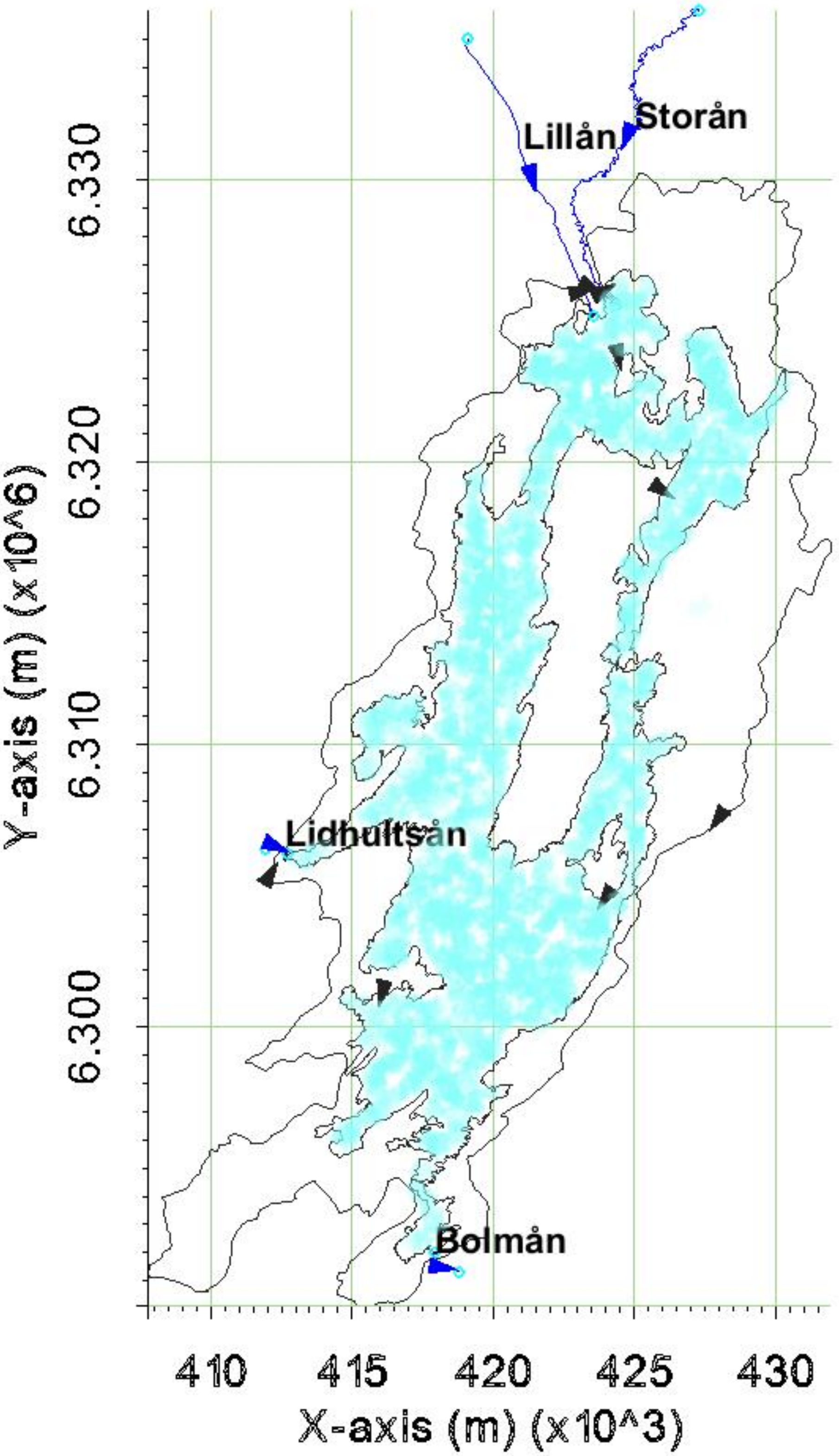

__Figure 2-9__: Reference system of the area in m (UTM zone 33, 12°E-18°E) with three tributaries (Lillån, Storån and Lidhultsån) and the outflowing river (Bolmån). In blue arc direction arrows indicating the flow direction are represented.

***Table 1**: Geometrical characteristics of the rivers and hydraulic conductivity of their bed sediments*

	HCOND1	THICKM1	ELEVUP	WIDTH1	DEPTH1
	[m/d]	[m]	[m]	[m]	[m]
Storån	60	1	144	20	0.9
Lidhultsån	60	1	143	10	0.9
Lillån	60	1	143	7	0.9
Bolmån	1	1	140	25	0

	HCOND2	THICKM2	ELEVDN	WIDTH2	DEPTH2
	[m/d]	[m]	[m]	[m]	[m]
Storån	60	1	142	20	0.9
Lidhultsån	60	1	141	10	0.9
Lillån	60	1	141	7	0.9
Bolmån	1	1	139	25	0

2.3.6 Preconditioned Conjugate-Gradient Package

MODFLOW is designed to solve equations describing the groundwater flow through a number of cells with a finite-difference approximation of the general partial-differential equation (Harbaugh, 2005):

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z}) + W = S_s\frac{\partial h}{\partial t} \qquad (2.8)$$

where K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities [L/T] along the three main axes x, y and z, h is the potentiometric head of water (sum of gravitational and pressure energy) [L], W is a term representing the stress factors (input and output fluxes of water) expressed as volumetric fluxes per unit volume [T^{-1}], S_s is the specific storage of the porous material and [L^{-1}] and t is the time [T]. The right-hand side term of the equation is equal to zero for simulations at steady-state, that is the case of this modeling of the area of lake Bolmen. A steady-state condition means that the sum of all contributions of inflows, outflows and external stresses for a cell must be equal to zero. This partial-differential equation is usually solved by numerical techniques, like the finite-difference method. In the finite-difference approximation, the continuous system is simplified through a series of discrete points and partial derivatives through differences in head values at specific points.

The flow between two adjacent cells is described here. In computer codes, for three-dimensional simulations, three letters are used to indicate the position of a cell in the grid. Usually i is employed to indicate the specific row, j to indicate the column and k to indicate the layer. If one node is then denoted as node i, j, k and the other $i, j-1, k$, a schematic representation (Figure 2-10) of the system can be the following one (Harbaugh, 2005):

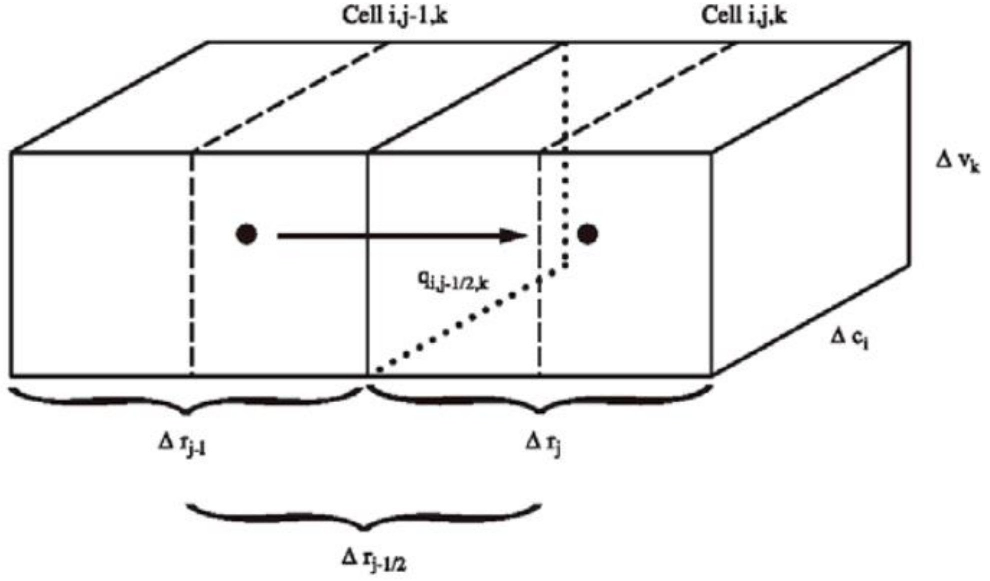

Figure 2-10*: Flow between adjacent cells (Harbaugh, 2005)*

The groundwater flow between two nodes is determined by Darcy's law written as:

$$q_{i,j-1/2,k} = KR_{i,j-1/2,k}\Delta c_i \Delta v_k \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta r_{j-1/2}} = CR_{i,j-1/2,k}(h_{i,j-1,k} - h_{i,j,k}) \tag{2.9}$$

where $q_{i,j-1/2,k}$ expresses the flow rate of water, $KR_{i,j-1/2,k}$ the hydraulic conductivity along the two nodes, the product $\Delta c_i \Delta v_k$ is the cross sectional area of the cells, $h_{i,j-1,k}$ and $h_{i,j,k}$ the hydraulic heads in the two nodes and $\Delta r_{j-1/2}$ the distance between the grid nodes. The term $CR_{i,j-1/2,k}$ is defined as conductance and it is useful to combine grid terms (geometry) and hydraulic conductivity in just a single constant. The subscript $j - 1/2$ refers to the region of space between the two nodes. A harmonic mean is usually employed to define an average value of hydraulic conductivity. The procedure described to compute the flow is followed for the other three facies of a cell in case of a single vertical layer (while it has to be performed for five facies in case of multiple vertical layers). A similar procedure is applied if external stress factors as rivers are adjacent to a cell.

Practically, the solution for the hydraulic head is calculated for every cell in the grid except for the boundary cells: these last ones can have either a constant head in time or they can be cells of the grid through which no flow is admitted. MODFLOW assigns the condition of no-flow cells automatically to all the cells of the grid's boundary. All other cells are referred to as "variable-head" cells in which the value of head can freely vary. The condition of a cell is classified according to a variable called

IBOUND: a value less than zero means a constant head cell, a value equal to zero a no-flow cell and a value greater than zero is assigned to variable head cells. Lake cells have an IBOUND equal to zero.

The Preconditioned Conjugate-Gradient (PCG) Package pertains to the category of MODFLOW packages defined as "solvers". It is a code designed to solve the matrix equations describing the finite-difference approximation of groundwater flow (Hill, 1990). The solution is searched through an iterative method, more useful than the direct method for large problems and applicable in cases in which the matrix is symmetric and positive-definite. Iterations, whose number is specified according to the complexity of the model (depending on cell numbers and non-linearities), are stopped either when the convergence criterion is met or when the maximum number of iterations is reached. Two types of iterations are used by the solver: inner and outer iterations. If round-off errors in the computations would not be present, just inner iterations would be sufficient for linear problems but this is not the actual case. In outer iterations head-dependent non-linear terms change on the basis of the heads computed in the previous iteration, while in inner iterations accuracy is improved without changing the non-linear terms (Harbaugh, 2005). The convergence criterion is based on the change in hydraulic head between two subsequent iterations: when the difference between the new head and the prior head is less than a user-specified value, convergence is reached.

500 outer iterations and 250 inner iterations have been chosen for the modelling of the lake sub-basin. The head change criterion has been set equal to 10^{-3} m, a common value for this type of problems. This is due to the fact that the actual solution of the flow equation is not known and for this reason the convergence criteria can not be the closeness to an exact solution.

As a starting value for the hydraulic head in each cell, a value equal to the ground surface elevation has been inserted. The initial guess value of hydraulic head usually does not have influence on the solution of the steady-state equation, but it could affect the number of iterations needed to reach it.

Final estimated values of the heads in the aquifer need to be interpreted as an approximation of the field condition due to uncertainties related to the hydrologic boundaries and the hydrogeological parameters (Harbaugh, 2005).

2.4 Calibration procedure

Model calibration is a procedure to estimate the appropriate parameters of the model in order for it to simulate the real hydrological behaviour of the catchment (Jackson et al., 2010), in particular computing heads and flow rates that are in accordance with the ones observed. The calibration on the basis of heads and flow rates is preferred because usually more accessible information related to these parameters is found, rather than the distribution of aquifer parameters or recharge rates (Fetter, 2014). The process can be either manually performed by the modeler or automatically done by MODFLOW through the use of additional packages. In the first case, a trial-and-error procedure is followed, with the user adjusting the parameters (selected inside acceptable ranges) after every run of the model to achieve a satisfactory fit with the observed values of head. In the latter case, models can be calibrated through parameter estimation techniques like nonlinear regressions. A good correspondence between the observed and simulated values is a necessary aspect of a good model, but it is not sufficient (Harbaugh and Reilly, 2004). As a matter of fact, a correct conceptualization of the study area and the integration of all key hydrological aspects and phenomena are equally important. This is due to the fact that there are potentially infinite possible combinations of hydrogeological parameters that provide the same model result (non-uniqueness problem). The quality of the results in terms of hydraulic heads values can be visually analysed through a series of calibration bars located in correspondence of the position of the observation wells. GMS will graphically show bars (Figure 2-11) with three different colours that depend on the settings defined by the user during the calibration procedure, in particular regarding the range of uncertainty of the observed value in the well. This interval is summed to the observed value in the well to obtain the highest value in the target, while the lowest value in the target is calculated by subtracting the interval from the observed value. A green colour of the calibration bar will indicate that the simulated value of the hydraulic head falls into the range, so the error with respect to the observed value is less than 100%. A yellow bar means that the simulated value does not fall into the range defined by the observed value plus and minus the interval and the error is between 100% and 200%. A red bar means that the error is greater than 200%. The position of the coloured bar in the interval indicates if the simulated value is higher or lower than the field observation.

To obtain a satisfying calibration, mainly the following parameters are to be adjusted: hydraulic conductivity of different zones of the aquifer, recharge rates and also leakage from lake- and river-bed sediments. For the hydraulic conductivity, a raise in the hydraulic head can be achieved by decreasing the value of the hydrological parameter in a cell, while vice versa a hydraulic head can be lowered by increasing the value of the conductivity. Regarding recharge rates, the situation is reversed. An increase in head can be obtained by increasing the recharge rate in a cell, whereas a lowering of head is obtained by decreasing the value of recharge rate.

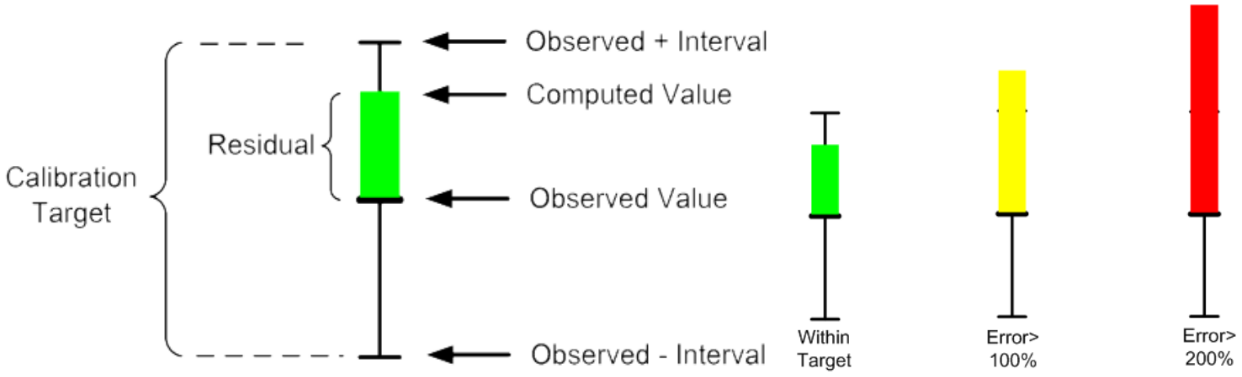

Figure 2-11*: Calibration bars in GMS*

2.4.1 Flow budget

The volumetric budget is the summary of all sources and sinks of water in the modeled area at the end of the simulation. While during the simulation the equation of groundwater flow is solved for each cell making the fundamental assumption of continuity in the cell itself, the program computes also independently a volumetric budget for the whole modeled area. This is because the continuity condition should hold also for the entire model and not only for a single cell. A complete independent flow budget is, in addition to the observed hydraulic heads in the area, a further check that the modeler can make to verify the validity of the results (Harbaugh, 2005). It is important to highlight that the total flow budget does not account for the volumetric flow between single cells of the grid, but only for instance flow to or from creeks, rivers or lakes, flow coming from or directed to constant-head cells or flow extracted or injected by wells. This means also that the flow rate of a river that does not interact with the aquifer due to a very low conductivity of its bed sediments will not appear in the budget. All packages describing hydrogeological features compute their own flow budget.

The percentage error visualized in the flow budget is an additional indicator of the quality of the simulation. It is another expression of the difference between the total inflow and total outflow:

$$D\ (\%) = \frac{100(IN - OUT)}{(IN + OUT)/2} \tag{2.10}$$

denoting as D the percentage error. Generally, a small value of D indicates a correct solution of the model equations. Another possibility in MODFLOW is to compute the flow budget of a group of cells.

2.4.2 Well selection

104 wells for which a value of groundwater table distance from the ground surface are registered in the study area. These wells are in most cases private wells, drilled in the bedrock and information are available about the depth of the well, the depth of the Quaternary deposits, the distance of the groundwater table from the surface at the moment in which the well was drilled, the length of the casing, well design parameters, the well capacity and use. Different usage of the wells includes drinking water supply, energy wells for heating systems and wells to increase the water available for agricultural and livestock purposes. Data needs to be sent from the well drillers to SGU by law from 1976. The selected wells chosen for the calibration phase are those for which a value of groundwater table distance from the surface is available. A value of the groundwater level is then calculated subtracting the distance from the water table (m) from the top elevation of the cell containing the observation point (m. a.s.l.).

Furthermore, values collected after the year 2010 are considered for consistency so that after the selection the number of wells used as calibration points is 26.

2.5 Software GMS

Groundwater Modeling System (GMS; Aquaveo 2018) is a software developed to among others simplify the use of the MODFLOW code, in particular giving a graphical interface to the groundwater flow model. All different versions of the code are available in GMS (USG, LGR, NWT, 2005, 2000, 96, 88). GMS provides a user interface where the investigated area is visualized in either two or three dimensions. The possibility of developing a conceptual modeling, using GIS data polygons, points and arcs, can be introduced and their hydrogeological features can then be mapped to the grid. A full coupling between GIS data and the software MODFLOW is a characteristic feature of GMS, that also includes several interpolation methods to transfer geographical information into the model grid.

Another useful feature of GMS is the possibility to automatically plot a number of results, as the comparison between heads observed through wells in the field and the simulated heads in the model.

3.Results

The results of the modelling process are reported in this section. At first, the final subdivision of the study area into several different hydraulic conductivity and recharge zones is presented as one of the outcomes of the calibration process. Later, the solution of the groundwater flow equation in terms of hydraulic heads in the study area is reported. After that, a description of the zones affected by flooding as well as drying of cells is presented. Then results in terms of comparison between observed hydraulic heads in the wells drilled in the investigated area and heads simulated by the modelling software MODFLOW are shown. Finally, an analysis of the model flow budget is conducted along with a description of parameter sensitivity.

Simulations have been run in a condition of steady-state, meaning that a single time-step with a temporal length of one day has been considered. A time interval, in this case one day, is needed by MODFLOW just to compute the volume of the lake an in general the volumes of water entering the model, but no transitional or time-dependent effects are simulated. Furthermore, a single stress period (a time interval in which input model parameters are kept constant) is simulated.

3.1 Subdivision of the study area

The final subdivision of the study area into zones with different hydraulic conductivities and recharge rates is the outcome of the calibration process based on the knowledge about the distribution of soil types in the area and about the range of variation of their hydrogeological parameters. Also the refinement of the model has been based on the outcomes of different simulations in terms of hydraulic heads, meaning that acceptable values have been chosen inside the ranges according to the estimated hydraulic heads in MODFLOW. The final number of different polygons in which the study area has been divided in GMS is 97 for hydraulic conductivity and 95 for recharge rate. Polygons have then been mapped to MODFLOW in order to allow for a correct assignment of hydraulic conductivity and recharge rate values to every active cell.

A map with the different zones is shown in Figure 3-1. The highest values of hydraulic conductivity and recharge rates have been assigned to the areas where glaciofluvial deposits as sand and gravel are found, while the smaller values have been used for till soils. However, values for tills are still relatively high due to the characteristics of these glacial sediments that are mostly of the type sandy or gravelly. Indeed, minimum values for hydraulic conductivity of till are equal to 0.26 m/d, whereas the highest values are close to 10 m/d. The highest values for glaciofluvial deposits are equal to 86.4 m/d.

Regarding recharge rates, the adopted values range from 5×10^{-6} m/d for impermeable areas to around 10^{-3} m/d where the infiltration and the subsequent recharge of the aquifer is more effective (mostly corresponding to glaciofluvial deposits).

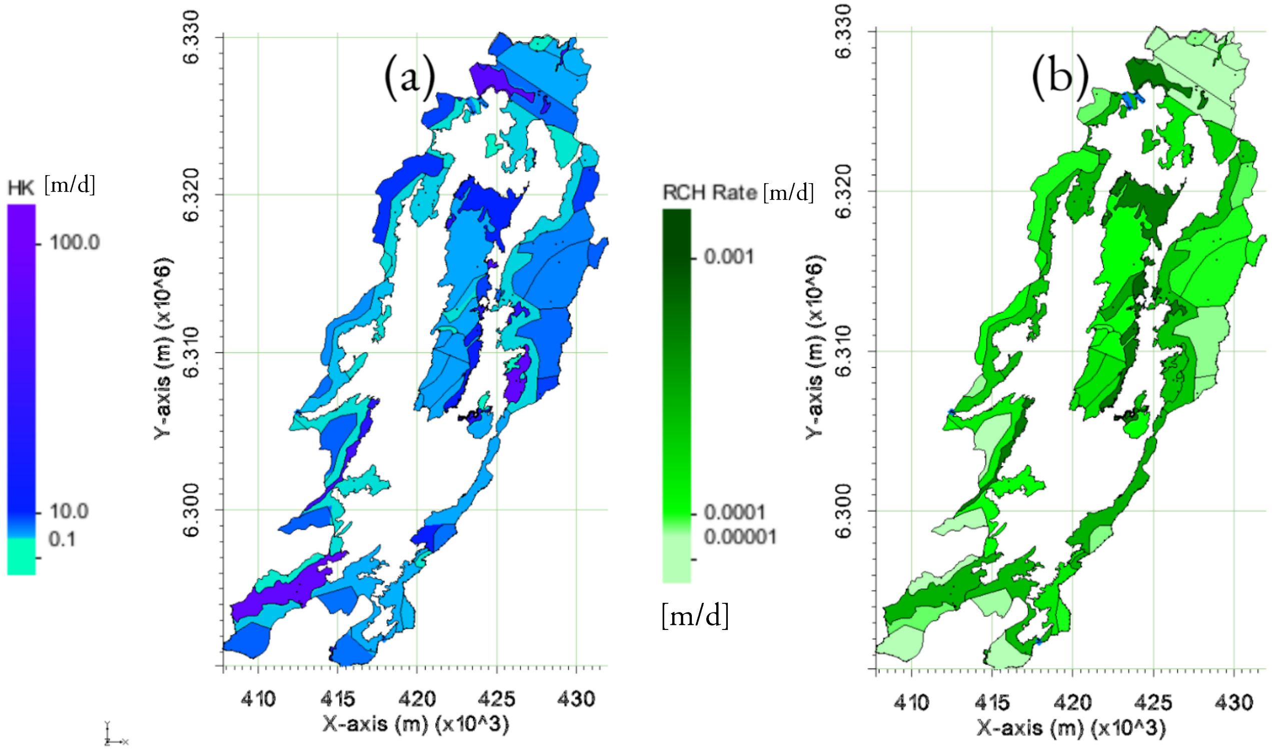

Figure 3-1: *(a) Results of subdivision of the model grid into different hydraulic conductivity zones (HK [m/d]) in the case of no-flow boundary. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E. (b) Results of subdivision of the model grid into different recharge rates zones (RCH Rate [m/d]) in the case of no-flow boundary. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

3.2 Map of lake Bolmen's sub-basin with simulated hydraulic heads

A map of the investigated area of lake Bolmen (Figure 3-2) with the hydraulic heads computed via MODFLOW has been extracted with GMS. It represents the value of the solution of the groundwater flow equation in each cell of the grid in terms of hydraulic heads with unit of measure in m. a.s.l. The reference system of the grid is the Universal Transverse Mercator (UTM zone 33, 12°E-18°E) with the x and y axes in m.

The highest values of hydraulic head occur in the eastern area of the model grid, where values above 180 m. a.s.l. are found, while the lowest values (around 140 m. a.s.l.) are found close to the coastline of lake Bolmen.

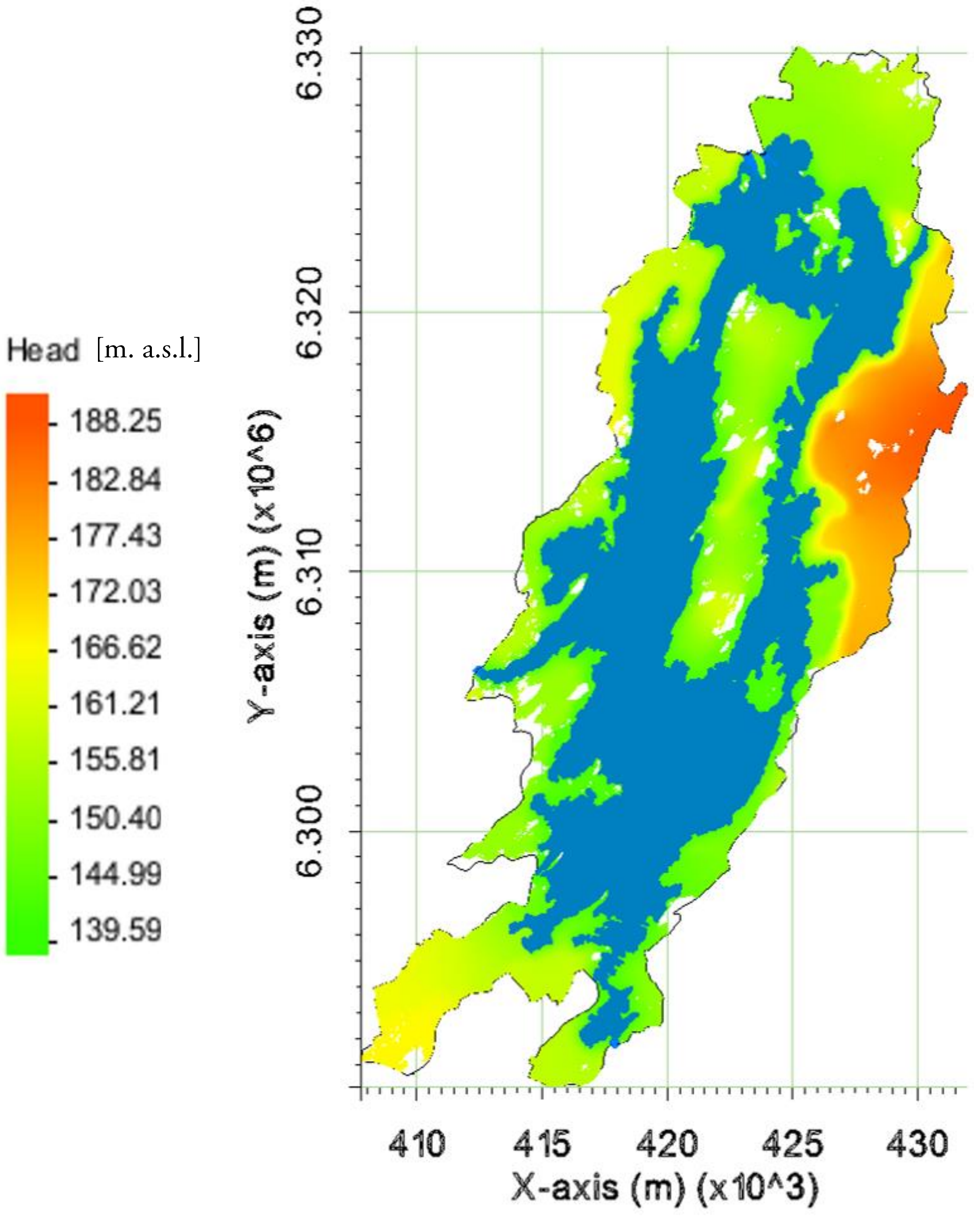

Figure 3-2: *Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.). Solutions are referred to the case with no-flow boundaries. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

3.3 Flooded cells and dry cells

A high number of flooded cells as well as dry cells are visualized in Figure 3-3. A flooded cell is a cell in which the simulated head is greater than the top elevation of the cell. The situation is possibly realistic only in the case of natural springs flowing in the investigated area or in case of smaller lakes or ponds fed by groundwater that in the modelling have been omitted. In lake Bolmen's sub-catchment no relevant springs are found, but a few small ponds are present. Also, a high number of dry cells results from the MODFLOW simulations. Dry cells are instead cells in which the hydraulic head drops under the bottom elevation during the simulations. The main difference between dry cells and flooded cells is that a value of hydraulic head is observable in the latter case, while for the first case the code automatically makes them inactive in the model grid so that they are excluded from the computations. But both flooded and dry cells identify areas in which the modelling needs to be improved.

Flooded cells are mostly concentrated in the northern, eastern and southern parts of the grid while the central part of the model around lake Bolmen and Bolmsö island as well as around the other two smaller islands is less affected by the problem. Dry cells are frequently observable close to the model boundaries.

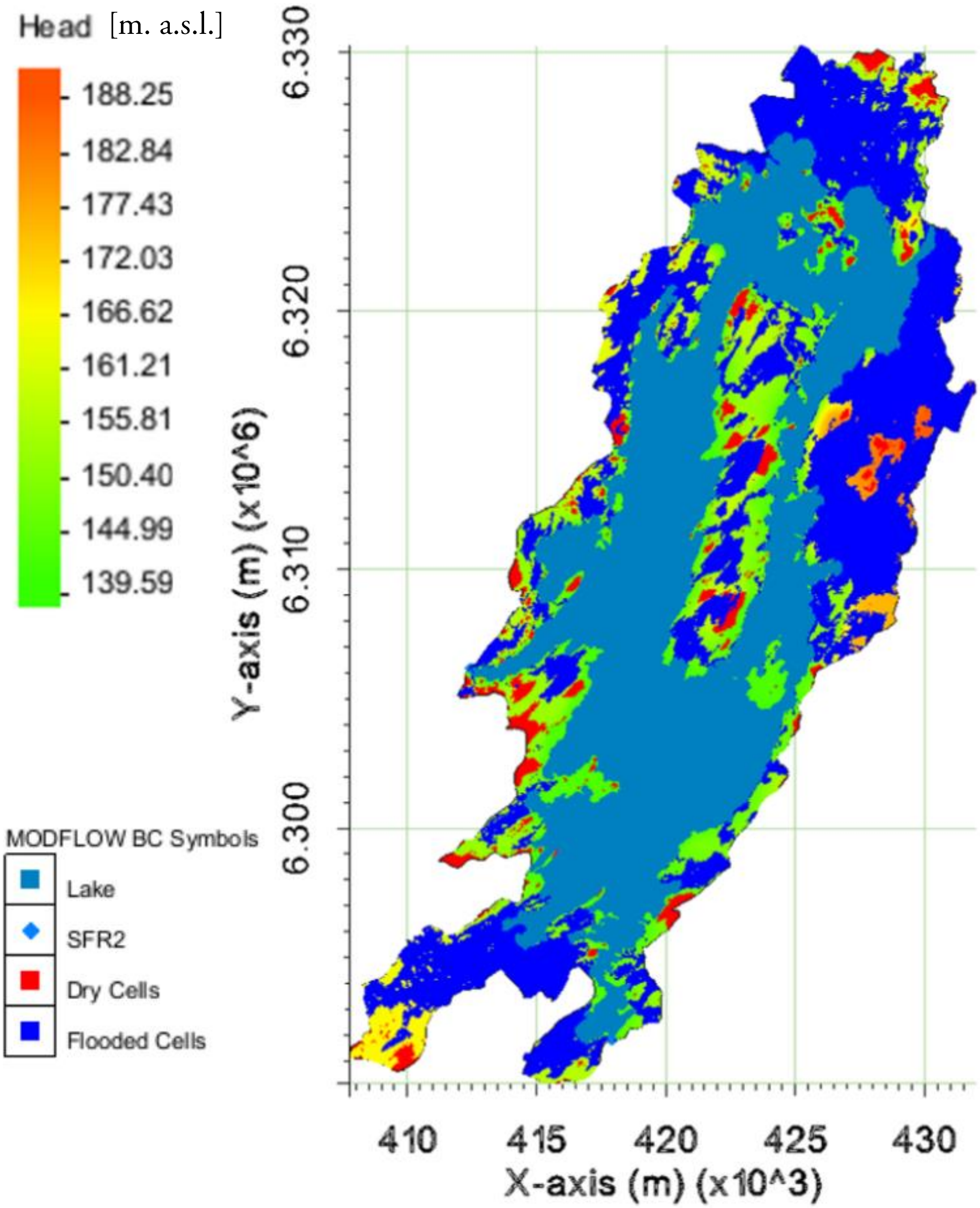

Figure 3-3: *Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.) including flooded (coloured in blue) and dry (coloured in red) cells. Solutions are referred to the case with no-flow boundaries. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

3.4 Comparison between computed heads and observed heads on site

In Figure 3-4 a map showing the study area with the 26 calibration bars referred to the observation points (water wells) is shown to analyse the quality of simulated heads in the cells in which a comparison is possible. Some bars may be missing due to the condition of the cell in which they are located. For instance, if a cell goes dry, MODFLOW makes it inactive and no hydraulic head value is computed for that cell. In Figure 3-5 a graph showing the comparison between computed heads and observed heads on site is presented. It is either possible to have the data plotted automatically by GMS or to plot the data found in the output files of MODFLOW. In this case the first way has been chosen to show the results. Also the residual values in comparison to the observed heads are graphically reported in Figure 3-6.

Among the 26 starting observation points, 25 of them are resulting in the map as calibration bars. This means that the cell corresponding to the remaining well has gone dry and then made inactive. Regarding the colour of the bars comparing observed and simulated values, 11 of them are green (error less than 100%), 5 are yellow (error between 100% and 200%) and 9 are red (error greater than 200%). The observation interval selected is equal to the observed value ±1.5 m. a.s.l., meaning that if the simulated value falls inside the interval the bar is printed in green, while if it falls between ±1.5 and ±3 m. a.s.l. the bar is printed in yellow. With distances from the observed value higher than ±3 m. a.s.l. the bar is red. The sum of the squared difference between observed and simulated values is equal to 1550 m. a.s.l.^{2}.

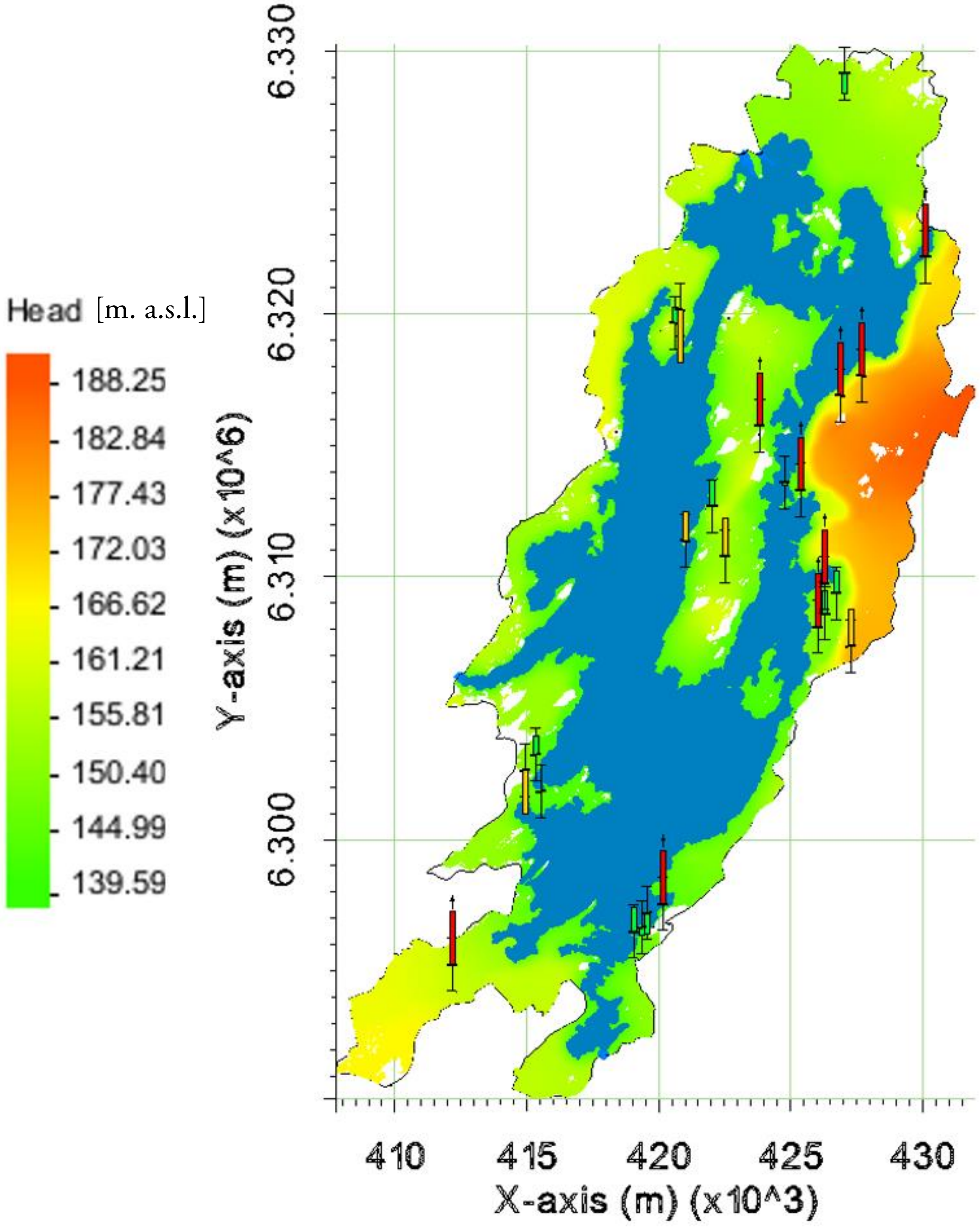

Figure 3-4: *Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.). Calibration bars for 26 observation points (water wells) produced by GMS comparing observed and computed groundwater levels are included. Solutions are referred to the case with no-flow boundaries. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

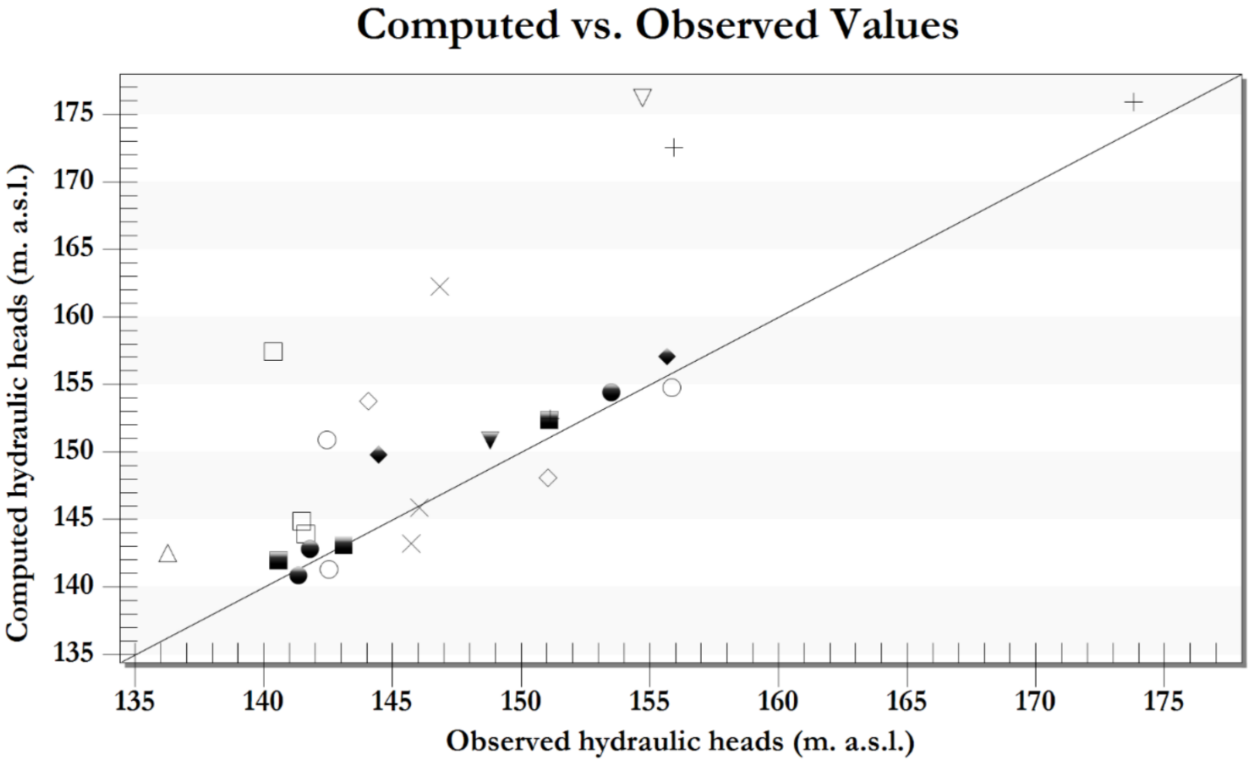

Figure 3-5: *Computed heads with MODFLOW (y axis) and observed heads in-situ (x axis). Unit of measure is m. a.s.l.*

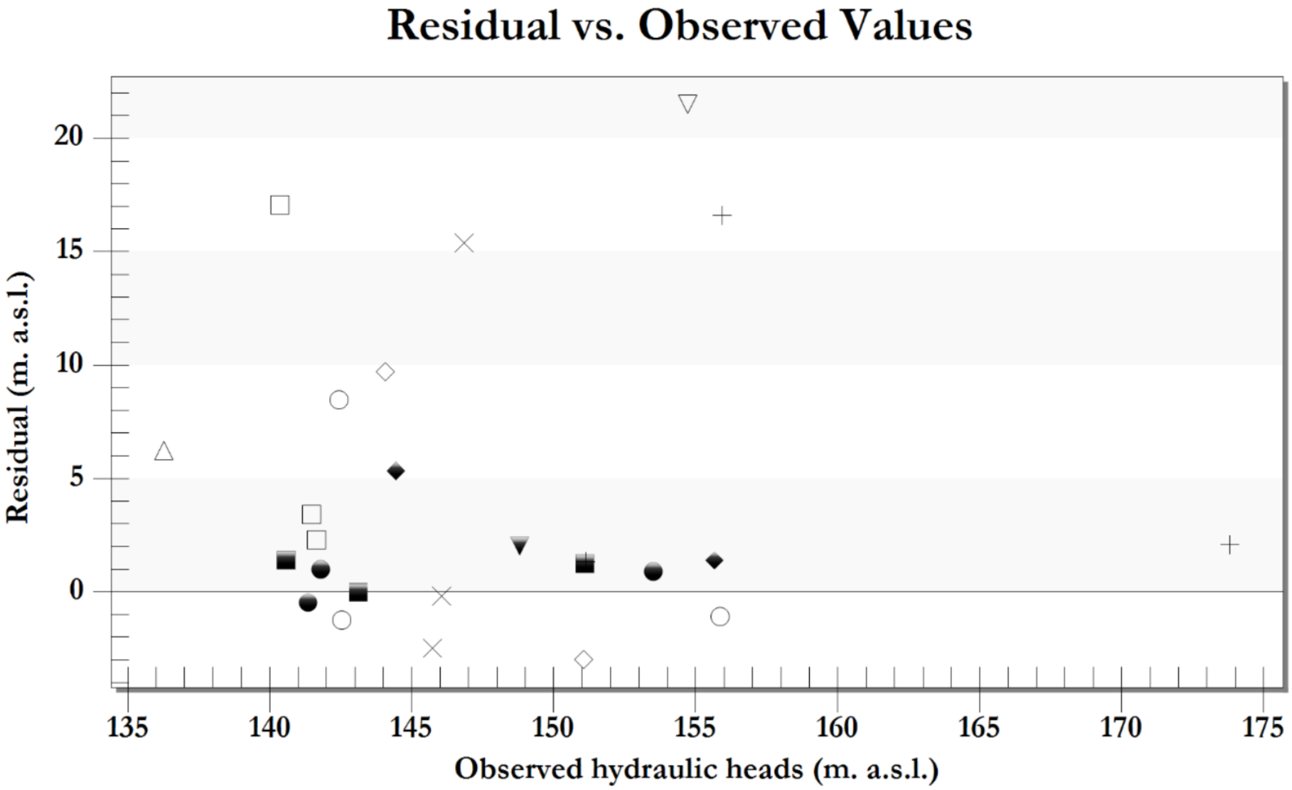

Figure 3-6: *Residual heads with MODFLOW (y axis) and observed heads in-situ (x axis). Unit of measure is m. a.s.l.*

3.5 Flow Budget

The flow budget of the simulation is found in the output files of MODFLOW. In particular, the budget (Table 2) is computed in terms of volumes as well as in terms of flow rates. Since the time-step is equal to one day and the temporal unit for the simulation is the day, no difference is found in the numerical values of Table 2.

The first two rows in the budget are related to the storage balance and the constant head inputs and outputs. Both these two are equal to 0 m^3 since the simulation is run at steady state (invariance of the storage) and no constant head is considered. This means that neither inflow nor output of groundwater is taking place from the model boundaries. The most relevant contribution of inflow to the model is given by recharge in the form of infiltrated and percolated precipitation, with a total amount of volume in the first and unique time step (1 day) equal to 57 101 m^3. Another smaller inflow of groundwater is due to the permeable sediments of the tributaries (stream leakage) that allow for a recharge of the unconfined aquifer, with a contribution close to 170 m^3. Lastly, an almost negligible contribution is given by the permeability of the lakebed sediments (lake seepage), that provide a recharge to the unconfined aquifer equal to 0.36 m^3. The total volume of water entering the active cells of the model is the sum of the three contributions and it is then equal to 57 272 m^3. This value does not take into account the water budget of the lake. Regarding the outputs from the model, the only terms different from zero are the stream leakage and the lake seepage. The stream leakage equals to 194 m^3 while the lake seepage is the dominant output of groundwater from the model, equal to 57 084 m^3. The total volume of water exiting the active cells of the model is the sum of the two contributions and it is then equal to 57 277 m^3. A possible evaluation of the quality of the solution from the numerical point of view can be obtained by calculating the difference between the sum of the inputs and the sum of the outputs. The result of this simple mathematical operation is -5.71 m^3. The percent discrepancy between inputs and outputs is equal to -0.01%.

Furthermore, a specific hydrologic budget (Table 3) for lake Bolmen is an additional output of MODFLOW. The computations also include the estimated lake stage, equal to 140 m. a.s.l. Normally observed values are in the range between 141 m. a.s.l. and 142 m. a.s.l. (Sydvatten AB, 2016), but occasionally the stage can fall under 141 m. a.s.l., mostly due to low inflows of water in periods with low precipitation. The volume of water in the lake is calculated as a function of the model grid to determine the relationship between volume and area. Exactly 303 500 cells compose lake Bolmen, for a total volume of water of 9.52E+08 m^3. For transitional simulations also information about the change in water volumes through different time-steps would be available. Then also the total amount of precipitation over the lake surface is reported, equal to 3.74E+05 m^3, along with the evaporated volumes again from the surface of the lake, equal to 2.21E+05 m^3. Run-off volumes are null since they have been neglected from the modelling. In the following line the budgets related to groundwater and surface water and water use are printed. For groundwater, the inflow from the aquifer surrounding lake Bolmen towards the lake is the dominant fluid flux, equal to 5.71E+04 m^3/d. Instead the flow from lake Bolmen to the surrounding aquifer is 3.60E-01 m^3/d. Regarding surface water fluxes, the inflow from the three considered tributaries Storån, Lidhultsån and Lillån is equal to 1.33E+06 m^3/d, whereas the outflow through the river Bolmån is equal to 1.42E+06 m^3/d. Lastly, the fixed water withdrawal for civil purposes defined as “water use” is equal to 1.21E+05 m^3/d. Further information included in the following line is about the surface area of the lake, 1.70E+08 m^2, sum of the area of all lake cells.

Table 2: *Flow budget for the modelled area after the MODFLOW simulation*

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
            STORAGE =           0.0000               STORAGE =           0.0000
      CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
           RECHARGE =       57101.3750              RECHARGE =       57101.3750
     STREAM LEAKAGE =         169.9234        STREAM LEAKAGE =         169.9234
      LAKE  SEEPAGE =           0.3602         LAKE  SEEPAGE =           0.3602

           TOTAL IN =       57271.6562              TOTAL IN =       57271.6562

         OUT:                                     OUT:
         ----                                     ----
            STORAGE =           0.0000               STORAGE =           0.0000
      CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
           RECHARGE =           0.0000              RECHARGE =           0.0000
     STREAM LEAKAGE =         193.7493        STREAM LEAKAGE =         193.7493
      LAKE  SEEPAGE =       57083.6172         LAKE  SEEPAGE =       57083.6172

          TOTAL OUT =       57277.3672             TOTAL OUT =       57277.3672

           IN - OUT =          -5.7109              IN - OUT =          -5.7109

PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

Table 3: *Hydrologic budget for lake Bolmen after the MODFLOW simulation*

```
               HYDROLOGIC BUDGET SUMMARIES FOR SIMULATED LAKES
    (ALL FLUID FLUXES ARE VOLUMES ADDED TO THE LAKE DURING PRESENT TIME STEP)
    ------------------------------------------------------------------------------
LAKE     STAGE          VOLUME     VOL. CHANGE      PRECIP      EVAPORATION        RUNOFF
  1  1.404341E+02  9.519363E+08     N/A (SS)   3.740143E+05  2.210085E+05  0.000000E+00

          GROUND WATER            SURFACE WATER        WATER
LAKE     INFLOW      OUTFLOW      INFLOW      OUTFLOW       USE
  1  5.7084E+04  3.6017E-01  1.3319E+06  1.4210E+06  1.2096E+05

     CONNECTED LAKE    TIME-STEP         STAGE-CHANGE         PERCENT
LAKE     INFLUX       SURFACE AREA    TIME STEP  CUMULATIVE    DISCREPANCY
  1   0.0000E+00      1.7001E+08     N/A (SS)   N/A (SS)        0.000
--------------------------------------------------------------------------------
```

3.6 Parameter Sensitivity

The hydrogeological model of lake Bolmen and of the unconfined aquifer surrounding it proves to be highly sensitive to the parameters hydraulic conductivity, recharge rate and leakance through lakebed sediments. This latter has been set equal to 7.7×10^{-3} d^{-1}, but a modification of the parameter of the order of 10^{-4} d^{-1} resulted in certain cases to a non-convergence of the model.

Another decisive parameter for the convergence is the number of maximum iterations allowed to MODFLOW. A number of iterations equal to 500 for the outer iterations (named MXITER in the software) and to 250 for inner iterations (named ITER1) has resulted as sufficient to reach convergence. For the LAK Package a number of iterations equal to 200 has been enough for Newton-Rapson's method to find a solution regarding the lake stage.

4.Discussion

According to Baalousha (2015), groundwater modelling is a process that aims at simplifying the reality to understand phenomena and possibly predict future developments. This makes groundwater modelling an important tool to manage water resources, giving also the possibility to protect groundwater reservoirs and study the effects of remediation techniques in cases of contamination.

In light of the results of the modelling some considerations can be made.

4.1 Hydrological parameters

The model grid has been subdivided in a number of polygons with different values of hydraulic conductivity and recharge rate. In principle, the reason behind the differentiation of hydrological parameters over the study area is the need to achieve a calibrated model, that is one in which the measurements performed in the field are well reproduced by the calculations. For the modelling of lake Bolmen’s sub-catchment, the measurements are the groundwater levels estimated when water wells were drilled. The values assigned for the hydraulic conductivity and the recharge rate of each polygon (that is then interpolated from the GMS discretization to the MODFLOW grid) have been based on the type of soil found at the ground surface according to the information contained in the GIS layers of the Swedish Geological Survey. Apart from this trustworthy source about the material deposited on the ground surface, there is not an accurate connection between the values assigned to the cell of the model and the real values in the study area. Adopted values have been chosen inside acceptable ranges found in literature by a trial-and-error procedure, but in reality a proper estimation of hydrogeological parameters like the hydraulic conductivity of geological units as aquifers requires field testing. Among the techniques employed there are not only different types of drilling methods, but also hydraulic testing methods as pumping tests and slug tests. For recharge rates, other methods like the lysimeter method yield local values of the parameter (De Silva, 2004).

Uncertainties related to these two hydrological parameters can cause excessive deviations from the unknown real conditions of the study area. They can be partially solved only by performing local tests. Until the latter remain not easily available, the only way to give an estimate of the real parameters is to improve the calibration and achieve a good reproduction of the groundwater table distribution. But a risk using this procedure is to obtain an overfitted model working well with available observations and yet not able to accurately investigate future developments.

4.2 Solution of the groundwater flow equation

When the model reaches convergence, a solution of the groundwater flow equation (Eq. 2.8) for all the cells in the model grid is calculated. In the case of an estimated hydraulic head lower than the bottom elevation of the cell, the cell itself is excluded from the model as MODFLOW makes it inactive. The cell is classified as “dry”. For all other cells than the dry ones, a value of hydraulic head, that is the solution of the groundwater flow equation, can be read. The highest values computed with the calculations performed by the software for the sub-catchment of lake Bolmen appear in the eastern part of the area, where values are close to 190 m. a.s.l. This is expected since the area where the maximum values are computed is also the area where the maximum ground surface elevation is found. Indeed, often the water table follows the general shape of the topography (Fetter, 2014). Values of hydraulic head close to the minimum, around 140 m. a.s.l., are on the contrary mainly located close to the lake coastline, where also the lowest values of ground surface elevation appear.

Generally, the solutions of the equation for the cells in the grid overestimates the actual condition in the study area. This is easily understandable by observing the map that shows flooded and dry cells (Figure 3-3). An excessive number of cells in which the hydraulic head is above the ground surface is resulting mostly in the northern, eastern and southern part of the grid. A flooded cell may result for different reasons. Firstly, a too low value of hydraulic conductivity may have been assigned to the cells in a particular area of the model so that groundwater flow is limited by the parameter (Eq. 2.9). This incorrect reproduction of reality gives rise to the computation of too high values of hydraulic head. Secondly, a too high value of recharge rate may have been assigned to the cells, with a similar effect to the one of hydraulic conductivity, that means a too high hydraulic head. In the case of recharge rate the cause is that too much water recharges the aquifer with respect to the real phenomenon taking place in the catchment. The opposite reasoning can be followed to partially explain the resulting dry cells: a too high hydraulic conductivity or a too low recharge rate can be the causes.

One other reason for the high number of flooded and dry cells could be the type of boundary conditions employed. The no-flow boundary condition has been used for all external cells of the grid, with the possible consequence of neglecting potential inflows to the aquifer. These inflows are likely to exist mostly where the sub-catchment of lake Bolmen is in contact with the main Bolmen’s catchment, so in the northern and western part of the grid. This is why the assumption of having completely disconnected boundaries from the hydraulic point of view may not be entirely true. An attempt of modelling the boundaries through the General Head Boundary Package in MODFLOW is reported in Appendix C.

A factor that does not seem to substantially influence the flooding is instead the permeability of the lake-bed sediments because generally close to the coastline the flooding is less frequent than it is further away from the lake. That said, flooding can also be in certain areas a condition reflecting the reality. Indeed, the presence of some bogs and fens in the area can explain the value of the hydraulic head very close to the ground surface in their location.

Regarding the observation points, only in 11 out of 26 an acceptable error (less than 100%) is computed. An observed head interval of ±1.5 m. a.s.l. and a confidence on the observed value of the 95% have been considered in the analysis. It should be noted that measurements were taken at different periods of time, meaning that they are comparable only assuming that the stage of the lake is kept constant throughout the years and more generally assuming that no particular phenomenon is affecting the amount of water drained by the Bolmen's catchment. This may not be true if for instance dynamics of climate change are influencing the water balance. However, organizations managing water resources in the area have an interest in keeping the stage of the lake approximately fixed in time for drinking as well as for energy purposes.

Another significant point is that certain measurements may be affected by errors due to the fact that the ground surface has been interpolated from a raster file available from the Swedish Geological Survey to the MODFLOW grid. In the process of assigning the top elevation to each cell some parts of the grid may have resulted as having a slightly higher or smaller elevation than in the real situation. The error is propagated in the observation points when the observed head is estimated as the ground surface elevation minus the distance from the water table to the ground (that is the data available from SGU). Similarly, an error of interpolation, in this case mostly regarding the bottom elevation of the aquifer, may also be the reason for many cells in the grid to go dry. Indeed, the process of obtaining a spatially variable bottom elevation of the unconfined aquifer involved operations such as the subtraction of the thickness of the Quaternary deposits from the ground surface elevation. This procedure may have determined unrealistically low thicknesses of the aquifer in some parts of the model and so the groundwater level estimated by MODFLOW could easily fall below the bottom elevation of the cell. An attempt to solve the issue related to dry cells by modelling the grid with a constant bottom elevation is reported in Appendix C. Results related to this attempt suggest that with this condition the flooding is reduced and the drying of the cells is overcome, along with a relatively fast convergence with respect to the model with a heterogeneous bottom elevation of the aquifer.

Since a good calibration is achieved only in some areas of the model of Bolmen's sub-catchment, improvements shall be made before using it to predict future dynamics of water flow (see also chapter 5).

4.3 Water balance

The water budget calculated by MODFLOW at the end of the simulation can be interpreted to analyze the processes of groundwater flow taking place in the area. Almost all the rainfall infiltrating and recharging the unconfined aquifer flows as groundwater to lake Bolmen (Eq. 2.4), whereas the inverse process is negligible in terms of flow rates.

The positive contributions to the volume of the lake as the groundwater flow, the inflow from the tributaries and the precipitation over the surface of the lake are almost completely balanced by the negative contributions such as the evaporation, the water withdrawal for domestic and agricultural purposes and the drainage performed by the outflowing river. An assumption made on the water balance is that only the major rivers or channels have been considered, while other smaller streams or creeks flowing into lake Bolmen have been neglected. That said, most likely they would not notably affect results as the computed lake stage, the volume of water in the lake and the surface of the lake. As a consequence, also the processes of groundwater flow towards the lake should probably remain unaffected. On the other hand, the representation of the aquifer on the vertical direction with just one layer of grid cells implies that in this case there is no water transfer between the bottom of the lake and the underlying aquifer. With a multilayered configuration this problem could be overcome, but the computational requirements for running the software are increased and the operation may result as highly time-consuming. The same is valid for the discretization of the model grid in smaller cells, which leads to better accuracy in the results but also to longer times for the simulations to run.

4.4 Effects on brownification

Internal production by plankton and aquatic macrophytes as well as external inputs (terrestrial or derived by wetlands) are the two main sources of dissolved organic matter in inland waters (Graneli, 2012). Dissolved organic matter may be the cause of brownification of waters, along with an increase in iron content, reversed acidification, climate change, increase in precipitation and subsequent run-off, higher temperatures and changes in land use.

A first study on the consequence of groundwater inflow to lake Bolmen has been performed by Uwera (2020), with a balance of fluxes between the lake and Bolmsö Island. A result in that case is that groundwater flow in the island through more permeable deposits as glaciofluvial deposits and through soils rich in organic matter content as peat soils may be causing brownification. Similarly, also in the case of a groundwater model of the aquifer surrounding the lake considerations can be done on the consequences on brownification. The water budget of the model, in particular the value indicating the seepage of groundwater into the lake, can be used to derive terrestrial and wetland-related mass fluxes of dissolved organic matter into lake Bolmen. This can be achieved if further analysis on the organic fraction of soils is performed. A combination of the results of this modelling and of more knowledge on the composition of soils will allow for a more precise estimation of the inflow of dissolved organic matter into lake Bolmen.

5.Conclusion and Recommendations

This project aimed at establishing a groundwater-flow model of the sub-catchment of lake Bolmen. The model includes hydrological processes as the flow of groundwater through the top unconfined aquifer of the area, the contact between the aquifer and the lake, the connection between surficial water (river and channels) and the Bolmen reservoir, as well as other processes as precipitation, evaporation and artificial water withdrawal.

The results of the modelling performed with MODFLOW along with the aid of a user interface provided by GMS show how a successful convergence to a solution in terms of hydraulic heads is reached. However, the solution is proved to be accurate enough only in certain zones of the study area, whereas in other parts it is either overestimating or underestimating the level of groundwater in the aquifer. Regarding the direction of the flow, from the water budget of the model it can be read that the dominating flow is from the surrounding unconfined aquifer to lake Bolmen.

To achieve these results, a grid with spatially heterogeneous values of recharge rates and hydraulic conductivity has been created. The different values of these hydrogeological parameters have not been estimated in-situ since this was not the main purpose of the project but rather selected among acceptable ranges found in literature. For this reason, they are most likely not representing exactly the real values in the area. Therefore, improvements shall be made to the model before it is used to solve practical issues related to water management in the catchment, among which there is the estimation of mass inflow of dissolved organic matter from the basin possibly causing the brownification of the lake's water.

In light of the above, some recommendations can be given to gain more trustworthy results.

Firstly, the problem concerning the wide spatial occurrence of dry cells could be dealt with by adopting another version of MODFLOW called NWT. This other formulation of the software works well when it comes to unconfined layers and interactions between groundwater and surface water (Feinstein and Hunt, 2012). Cells are with this version not allowed to go abruptly dry but they are instead kept with a small saturated thickness. Convergence to the solution of the flow equation should also be considerably faster using MODFLOW-NWT, with a possible drawback being the larger number of modelling parameters required by this solver (meaning that experience with groundwater modelling is also recommended).

Secondly, reducing uncertainties related to field data would certainly help in determining if the results of the modelling are accurate. One of the main problems related to available data is that data have not been collected in close time ranges, but instead they were acquired in different periods. Field visits to a sufficiently large number of water wells in the area for measuring groundwater levels at the same moment represent a possible solution to this problem.

Thirdly, adopting a completely different approach in terms of modelling could be also a way to study lake Bolmen's basin. Indeed, with a finite element model (as for instance FEFLOW) the investigated area could be extended to include all the catchment of Bolmen and not only the last sub-catchment. Doing this with a finite element model would be less numerically and computationally demanding with respect to a finite difference model. Whether the modelling is instead continued with a finite difference grid, a possibility would be to refine the grid close to the lake. Boundary conditions regarding the spatial extension of the basin would certainly be more accurate, since they are generally well-known. However, a drawback in extending the grid is that further information is required on the areas that were previously not included.

Finally, if a sufficiently stable model is built, it would be feasible then to perform an automatic calibration of the parameters, instead of using a manual trial-and-error method. In MODFLOW the function is applied through the so-called PEST Package (Automatic Parameter Estimation). Furthermore, when simulations are completed the user has also the possibility of viewing a more detailed sensitivity analysis.

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Appendices

Appendix A - Till composition

Till is a material originating from the glaciation period (more than 10 000 years ago), when land ice eroded and transported both older soil layers and outcropping bedrocks (Fredén, 1988). When the ice melted, layers of unsorted soils were deposited on the land and formed these geological units typical of the northern regions. Till can contain basically particles and grains of any size, from clays to big boulders with the diameter of the order of a couple of metres. Fractions of grains smaller than 20 mm (that means from clay to gravel) make up the core of the till units and based on the composition of the matrix tills have different names. For instance, a gravelly-sandy till is dominated by gravel and sand. Tills with a clay content between 5% and 15% (always considering the material with a diameter smaller than 20 mm) are defined as clayey, while if the clay content exceeds the 15% they are named clay tills. Further subdivisions can be done. For example, another classification of tills is the one based on the frequency of boulders inside the matrix, that can be high, medium or low. This last one depends on the number of boulders found per surface area of the matrix (usually per 100 m^2).

In Figure A-1 a diagram showing the grain-size distribution in several types of tills is found. Also, a description of the dimension of the different composing materials is shown in the x axis. The y axis represents instead the percentage of weight of a particular grain size in the matrix.

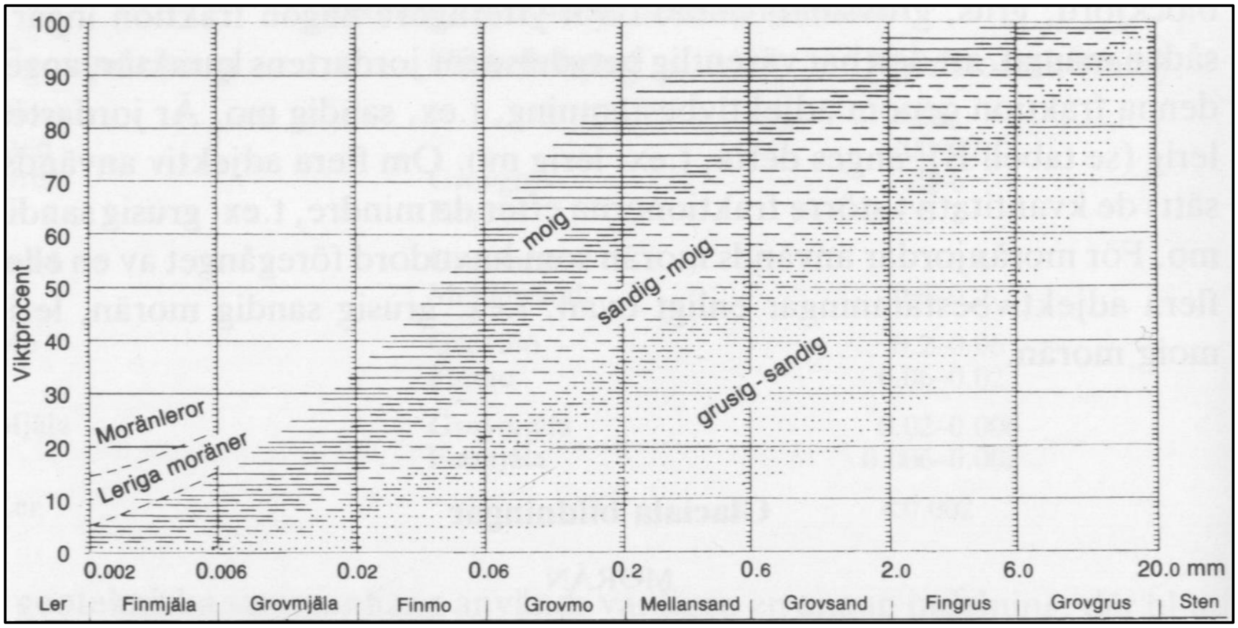


***Figure A-1**: Diagram showing the grain-size distribution of the matrix of different types of till (gravelly, sandy, silty to fine sandy, till with a clay content of 5-15% and clay till) (Fredén, 1988).*

Appendix B - MODFLOW flowchart

To find a solution to the groundwater flow equation for each active cell of the grid, the model follows the work path of Figure B-1. A simulation is divided into several “stress-periods”, while each of these periods (in which stress parameters are kept constant) is divided into a defined number of time-steps (Harbaugh, 2005). The systems of equations are solved for the heads on each node for every time-step, most likely needing more iterations to reach convergence. Three nested loops are included in the program: the first is the stress loop, within which a time-step loop is contained and this last one includes an iteration loop.

In general, the first step of the work path is named “Allocate and Read”, where the program determines the number of the grid cells. Furthermore, all hydrological options and the type of solver are defined and the needed memory for the simulation is allocated. Data that do not change over the stress periods are read, including cell dimensions, boundary conditions, initial heads, hydraulic properties of the aquifer and parameters related to the solver package. Subsequently, the three nested loops are started. Inside the stress loop the procedure called “Read and Prepare” reads the data related to a defined stress period (for instance well flow rates and recharge rates). The successive time-step loop for the modelling of lake Bolmen is performed just once, being the simulation at steady state. Inside the iteration loop the “Formulate” procedure defines the conductances for every node while the “Approximate” procedure approximates a solution of the system for the hydraulic head. The iteration loop is repeated until the head-change convergence criterion is met or until the number of iterations reaches a maximum value. At the end of the loop the procedure called “Output Control” is run to define which results are to be printed while the so-called “Water Budget” records the flow rate for all cells. With the “Output” procedure all the needed information is printed and finally memory is deallocated.

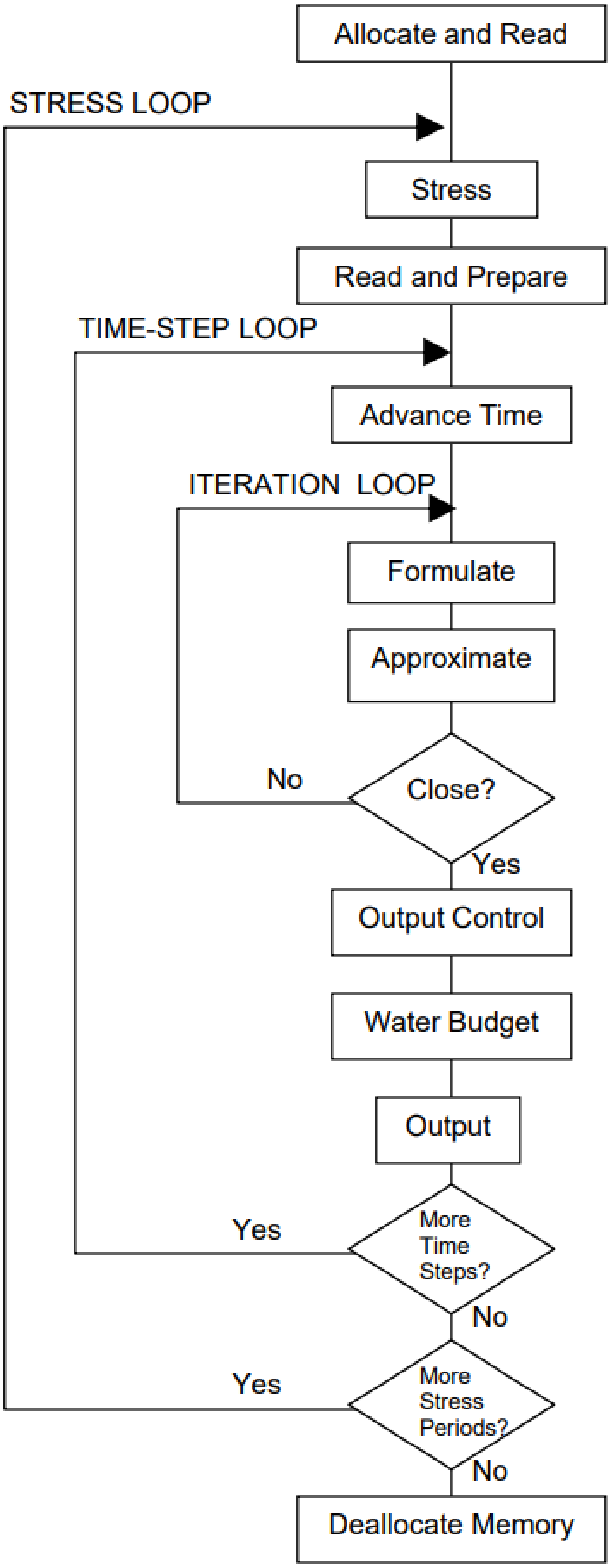


Figure B-1: *MODFLOW flowchart (Harbaugh, 2005)*

Appendix C - Additional results

General Head Boundary (GHB) MODFLOW Package

A strong assumption made in the modelling of lake Bolmen's sub-basin is the type of external boundaries. All of them, the lateral as well as the bottom boundary, have been considered as no-flow boundaries. Being the modelled area just a part of the more spatially extended Bolmen's catchment, with an areal dimension of 1640 km^2 (Figure 2-2), the contribution of groundwater flowing from the upstream catchment may be not negligible. Considering this, another approach could be followed to perform the modelling, that is changing the type of boundary condition using the General Head Boundary Package in MODFLOW. All the external boundaries of the model that are in contact with the main catchment of lake Bolmen can be given the possibility of having an inflow of groundwater. This is achieved by assigning the property of General Head to the cells in the appropriate zones and a fixed value of groundwater level to at least two of those cells. MODFLOW will interpolate automatically the values of hydraulic heads to all the other general head cells. Furthermore, a value of conductance should be assigned to the cells working as general heads. A risk arising with the use of this package is to model unrealistic inflows or outflows (Harbaugh, 2005), meaning that sufficient knowledge of the study area should be acquired before adopting the GHB Package.

The relationship to estimate the flow of water into or out from a boundary cell is the following (Harbaugh, 2005):

$$QB_n = CB_n(HB_n - h_{i,j,k}) \tag{C.1}$$

QB_n [L^3/T] expresses the flow through the boundary n, CB_n [L^2/T] the conductance of the block of porous material outside the model grid boundary, HB_n [L] the fixed head of the external source of groundwater and $h_{i,j,k}$ [L] the hydraulic head in the boundary cell. The process can be visually interpreted in Figure C-1. As in the usual case, the flow is proportional to the head difference between the cell and the fixed external constant-head source, but no mechanism or process is included to limit the flow in either of the two possible directions.

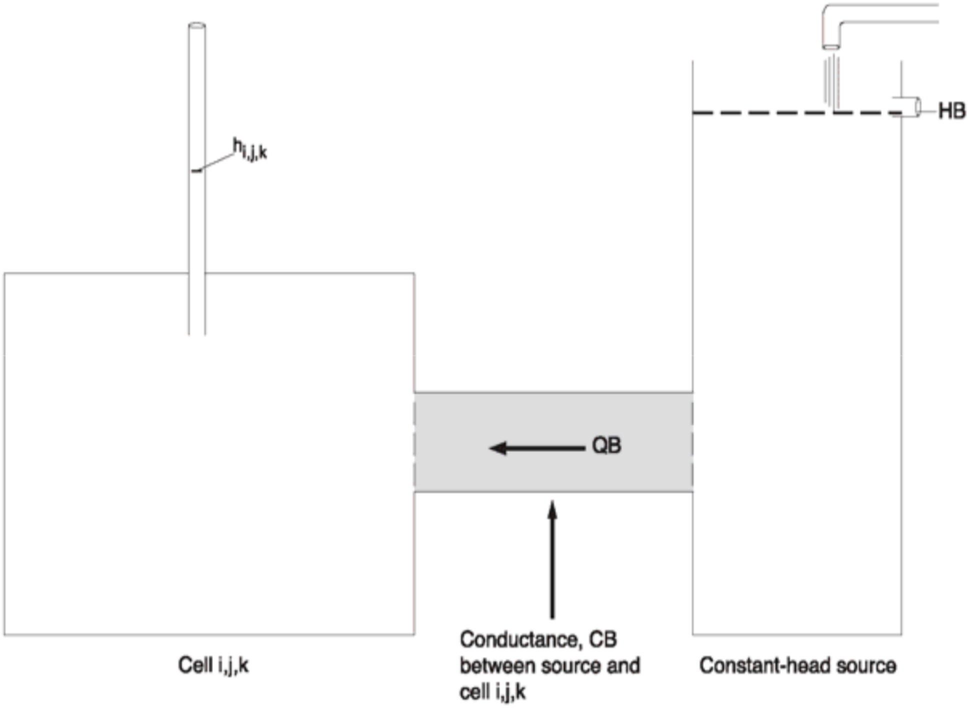


Figure C-1*: Process of groundwater flow through a general head boundary cell in MODFLOW (Harbaugh, 2005)*

For the modelling of lake Bolmen, the external source of groundwater would be the main catchment of Bolmen. A way to proceed in this case could be to make use of regional groundwater flow maps and to study the direction of groundwater flow to estimate which boundaries of the model are involved in an external groundwater contribution. Being these maps not readily available, another procedure has been followed to get a sense on how the model would perform with general head boundaries. Hydraulic head observations made in ten wells located close to the borders of lake Bolmen's sub-basin have been used to derive a groundwater table map of the study area (Figure C-2). This has been made using an inverse distance interpolation method in QGIS. From the obtained map values of hydraulic heads close to the boundary have been estimated and assigned to the external cells in MODFLOW's grid. The operation has been conducted with the aid of GMS by assigning a value of hydraulic head to the nodes of each arc representing the boundary of the sub-basin, then the program interpolates linearly and automatically the values of hydraulic head along two nodes.

Results of the modelling with a GHB package included in MODFLOW are reported in Figure C-3 and Figure C-4. From Figure C-4 it is possible to observe that a large spatial occurrence of flooded cells as well as dry cells results from the simulations. Furthermore, from Table 4 and Table 5 it is possible to read the flow budget as an output of MODFLOW. The flow is in some sections of the boundaries directed towards the unconfined aquifer, while for other sections the direction is the inverse, with a loss of water from the model.

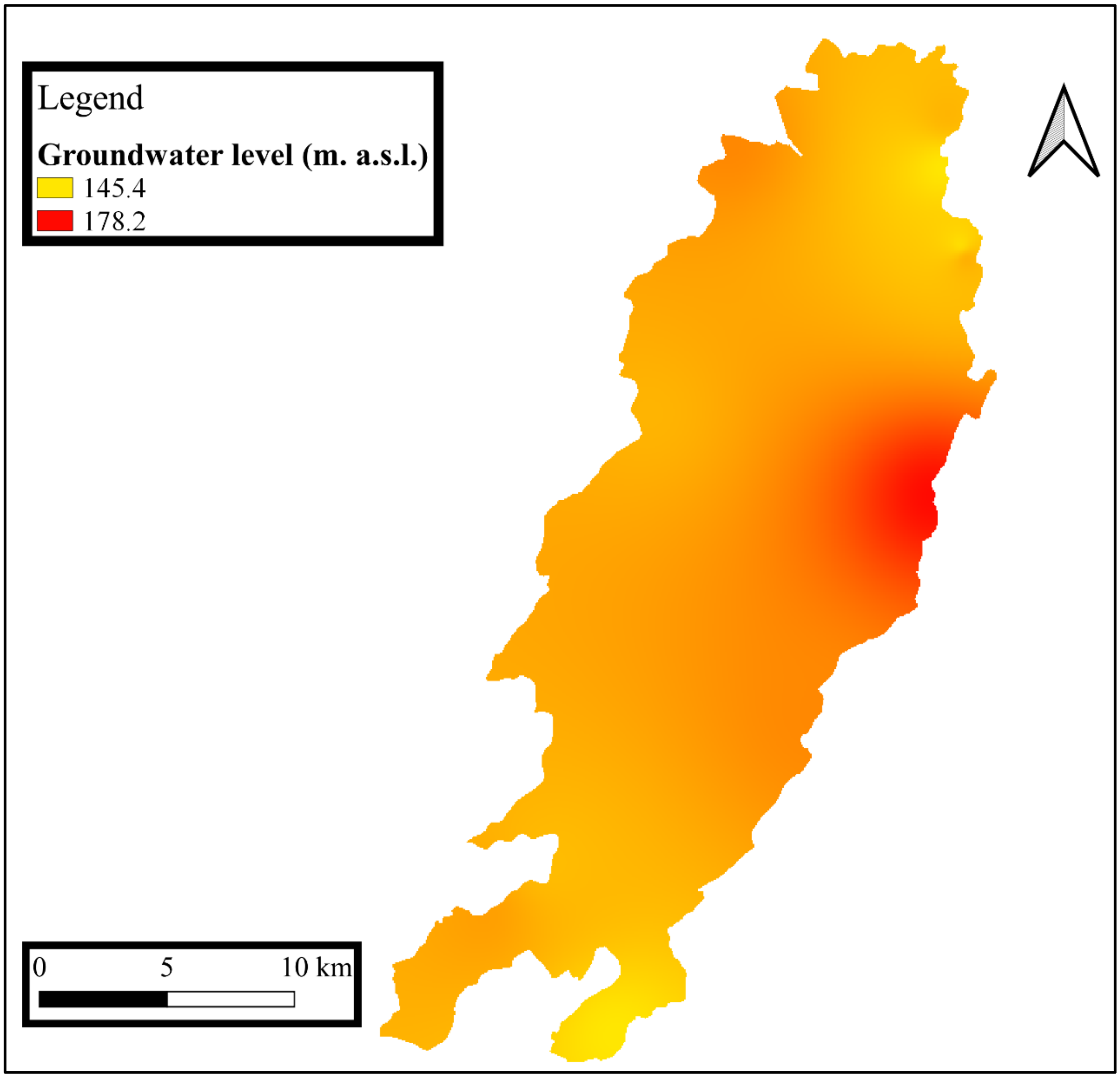


Figure C-2: *Map of groundwater levels in the study area derived from conducting a QGIS analysis on 10 water wells at the boundaries of the model. Values of groundwater level are interpolated on the sub-basin area.*

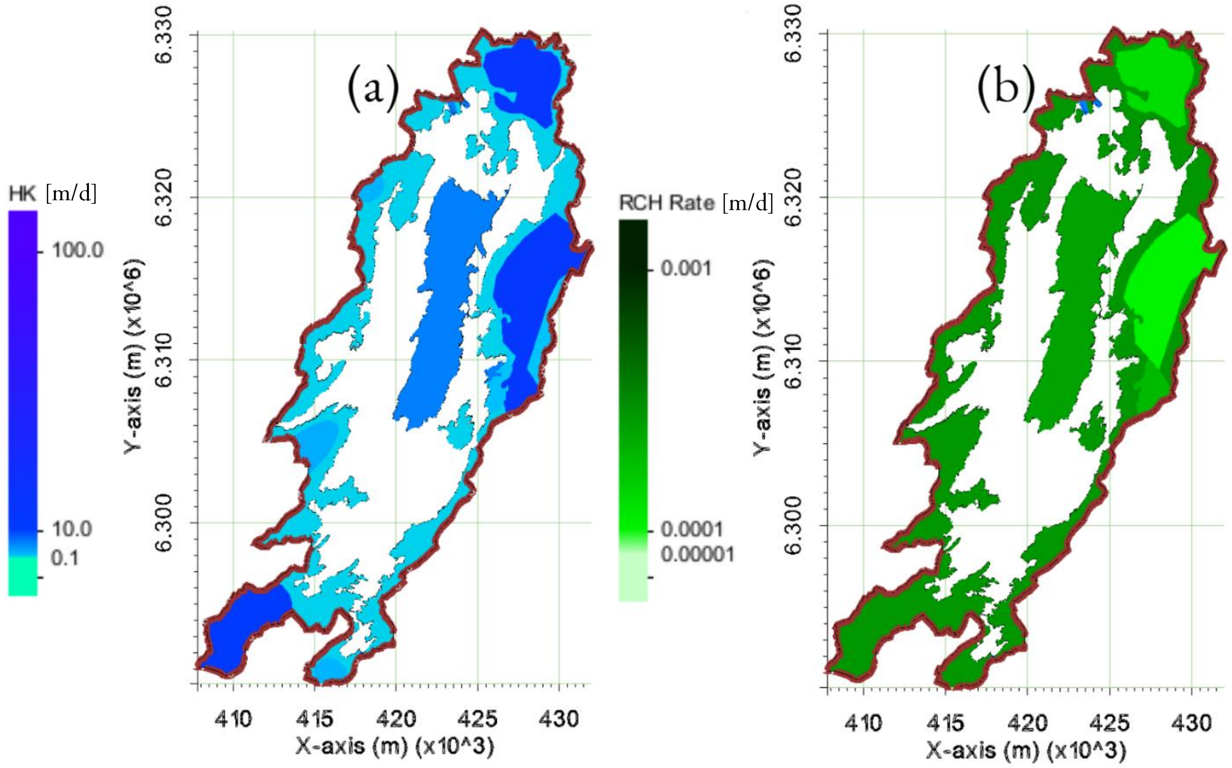


Figure C-3*: (a) Results of subdivision of the model grid into different hydraulic conductivity zones (HK [m/d]) in the case of GHB boundary. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E. (b) Results of subdivision of the model grid into different recharge rates zones (RCH Rate [m/d]) in the case of GHB boundary. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

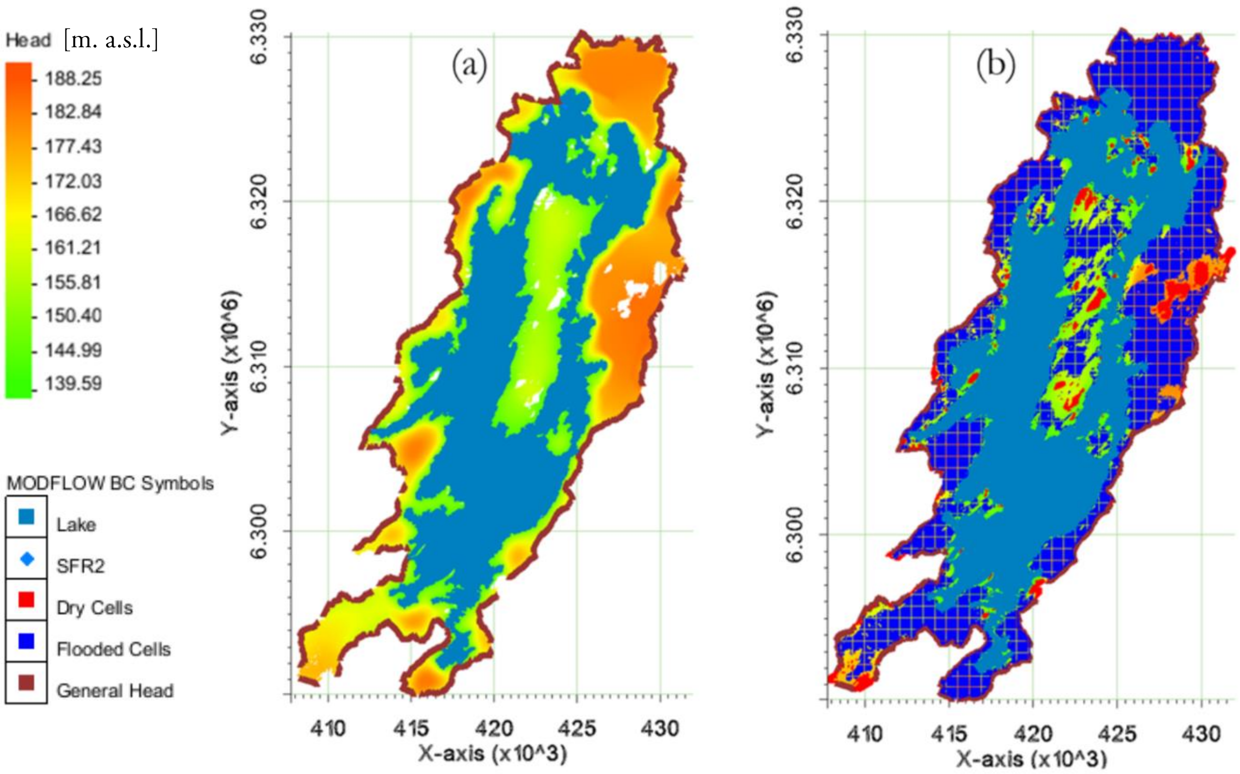
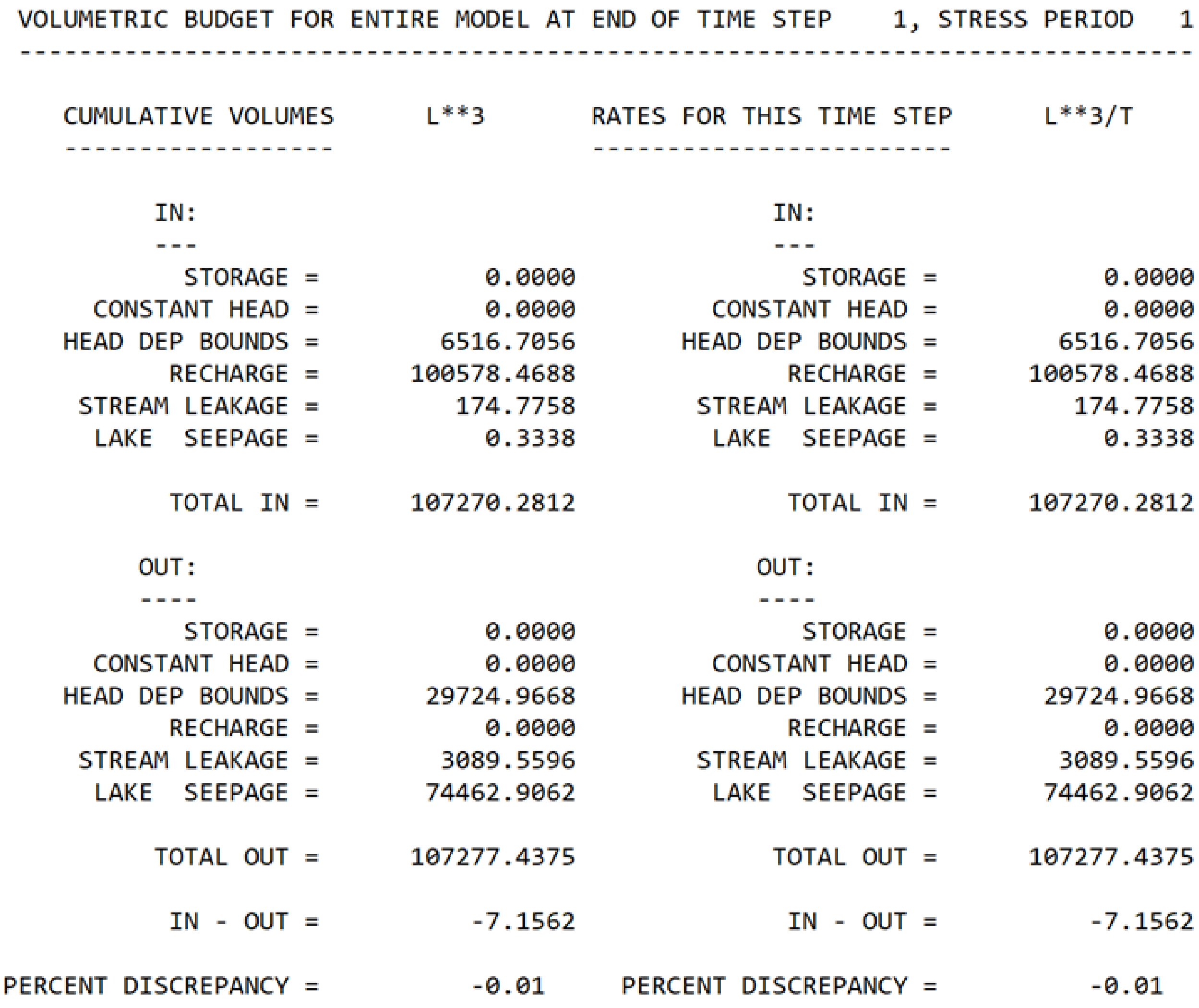


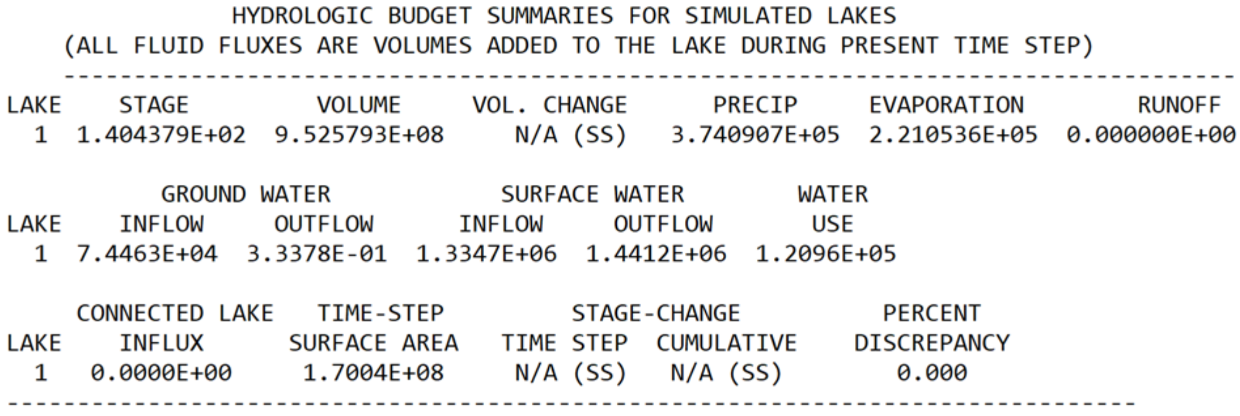
Figure C-4: *(a) Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.). Solutions are referred to the case with GHB boundaries. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18° E. (b) Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.) including flooded (coloured in blue) and dry (coloured in red) cells. Solutions are referred to the case with GHB boundaries. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

Table 4: *Flow budget for the modelled area after the MODFLOW simulation in case of modelling with GHB boundaries.*



```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
-------------------------------------------------------------------------------

   CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
   ------------------                 ------------------------

         IN:                                      IN:
         ---                                      ---
           STORAGE =           0.0000               STORAGE =           0.0000
     CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
   HEAD DEP BOUNDS =        6516.7056       HEAD DEP BOUNDS =        6516.7056
          RECHARGE =      100578.4688              RECHARGE =      100578.4688
    STREAM LEAKAGE =         174.7758        STREAM LEAKAGE =         174.7758
     LAKE  SEEPAGE =           0.3338         LAKE  SEEPAGE =           0.3338

          TOTAL IN =      107270.2812              TOTAL IN =      107270.2812

        OUT:                                     OUT:
        ----                                     ----
           STORAGE =           0.0000               STORAGE =           0.0000
     CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
   HEAD DEP BOUNDS =       29724.9668       HEAD DEP BOUNDS =       29724.9668
          RECHARGE =           0.0000              RECHARGE =           0.0000
    STREAM LEAKAGE =        3089.5596        STREAM LEAKAGE =        3089.5596
     LAKE  SEEPAGE =       74462.9062         LAKE  SEEPAGE =       74462.9062

         TOTAL OUT =      107277.4375             TOTAL OUT =      107277.4375

          IN - OUT =          -7.1562              IN - OUT =          -7.1562

PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

Table 5: *Hydrologic budget for lake Bolmen after the MODFLOW simulation in case of modelling with GHB boundaries.*



```
                HYDROLOGIC BUDGET SUMMARIES FOR SIMULATED LAKES
    (ALL FLUID FLUXES ARE VOLUMES ADDED TO THE LAKE DURING PRESENT TIME STEP)
    ------------------------------------------------------------------------------
LAKE     STAGE          VOLUME      VOL. CHANGE      PRECIP     EVAPORATION        RUNOFF
  1  1.404379E+02  9.525793E+08     N/A (SS)   3.740907E+05  2.210536E+05  0.000000E+00

          GROUND WATER            SURFACE WATER        WATER
LAKE     INFLOW      OUTFLOW      INFLOW     OUTFLOW      USE
  1  7.4463E+04  3.3378E-01  1.3347E+06  1.4412E+06  1.2096E+05

     CONNECTED LAKE    TIME-STEP         STAGE-CHANGE         PERCENT
LAKE     INFLUX       SURFACE AREA   TIME STEP  CUMULATIVE    DISCREPANCY
  1    0.0000E+00      1.7004E+08     N/A (SS)   N/A (SS)        0.000
-------------------------------------------------------------------------
```

Constant bottom elevation of the aquifer

A flaw of the model built with a bottom of the aquifer calculated as difference of ground surface elevation and thickness of Quaternary deposits is the large spatial distribution of flooded as well as dry grid cells. This problem is most likely to be due to uncertainties related to the actual thickness of the Quaternary deposits rather than to the elevation of the ground surface, because data related to this last parameter are usually more detailed and accurate. Techniques employed to analyse the ground surface elevation permit to acquire precise data for very extended surfaces without being particularly time-consuming. Examples of such techniques are LIDAR (Laser Imaging Detection and Ranging) and GPS (Global Positioning Systems). The thickness of the deposits is instead often determined through more local surveys, mostly vertical drilling, meaning that measurements are more sparsely distributed in space and uncertainties in building digital models are larger.

In light of this, simulations have been run also with a constant bottom elevation of the unconfined aquifer of 100 m. a.s.l., maintaining a spatially variable top elevation.

Among the results of these simulations there is the absence of dry cells. This means that the simulated hydraulic heads never fall below 100 m. a.s.l. (Figure C-5). Also, the absence of dry cells indicates that the areas where in other simulations dry cells appear are possibly affected by errors in the bottom elevation of the grid cells. Again, these errors are most likely due to uncertainties related to the thickness of the Quaternary deposits.

Another interesting result observed by running simulations with constant bottom of the unconfined aquifer is the relatively limited flooding (Figure C-5) with respect to the too high hydraulic heads estimated with the other employed methods.

Moreover, the convergence is generally reached in fewer iterations and then less time is needed to perform simulations after the adjustment of parameters.

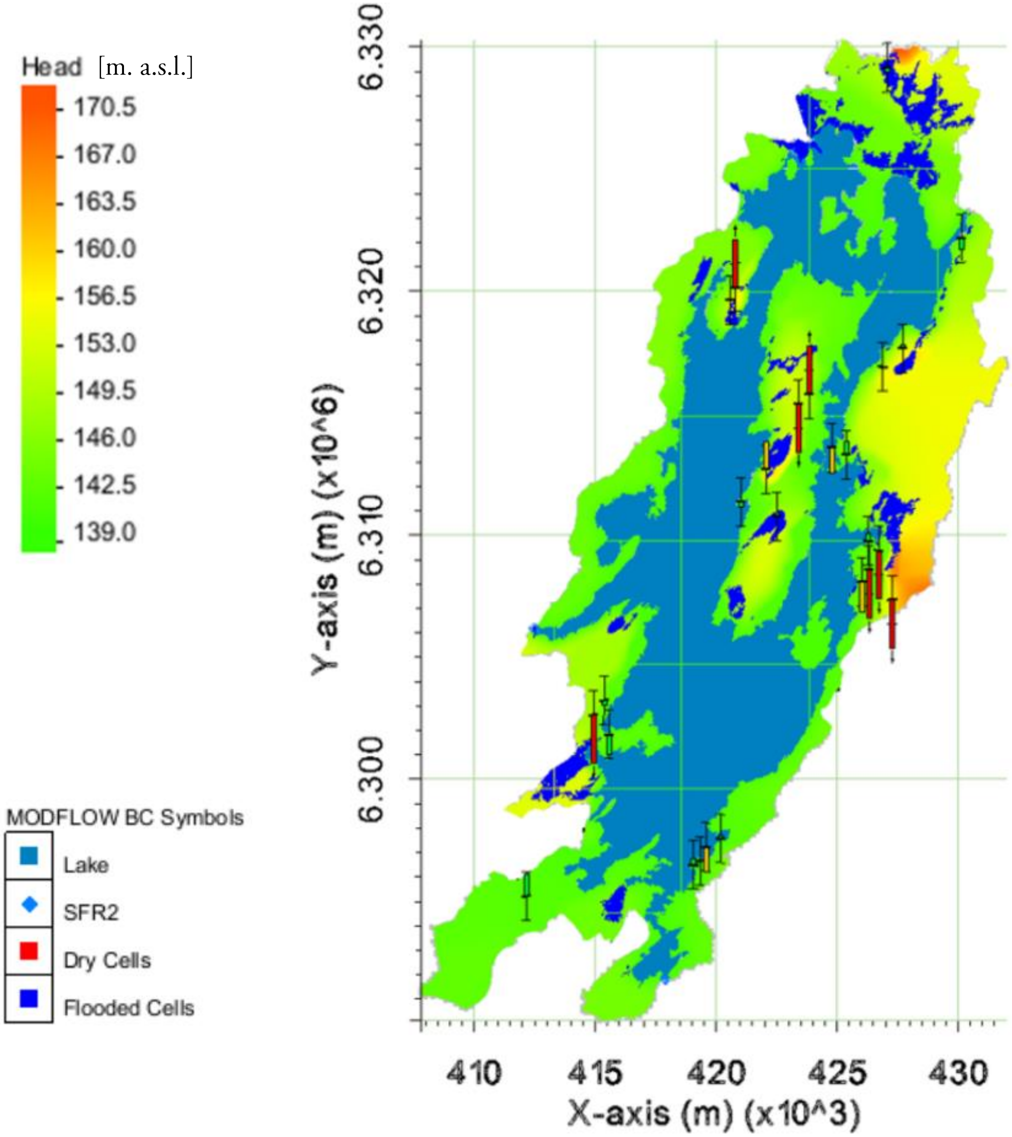


Figure C-5: *Map of the solutions of the groundwater flow equation for the study area in terms of hydraulic heads (m. a.s.l.). Solutions are referred to the case with constant bottom elevation. Calibration bars are found in correspondence of 26 water wells. Units of the x and y axes are m with reference system UTM zone 33, 12°E-18°E.*

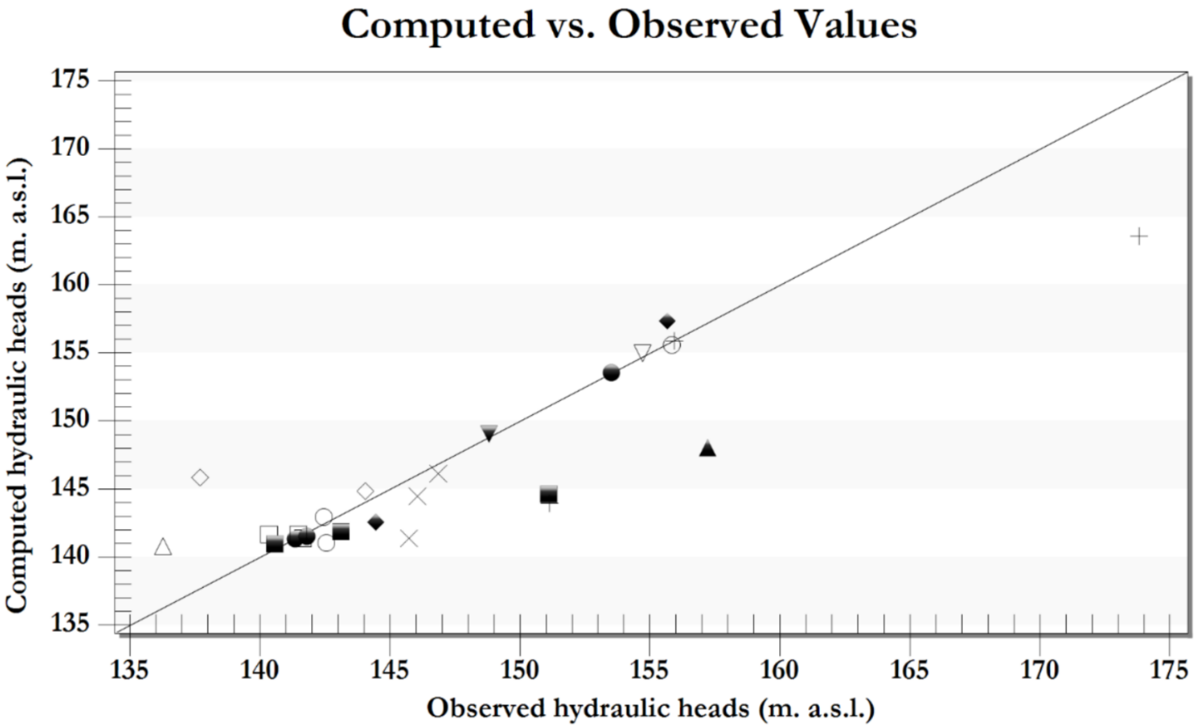


Figure C-6: *Computed heads with MODFLOW in the case of modelling with constant bottom elevation (y axis) and observed heads in-situ (x axis). Unit of measure is m. a.s.l.*

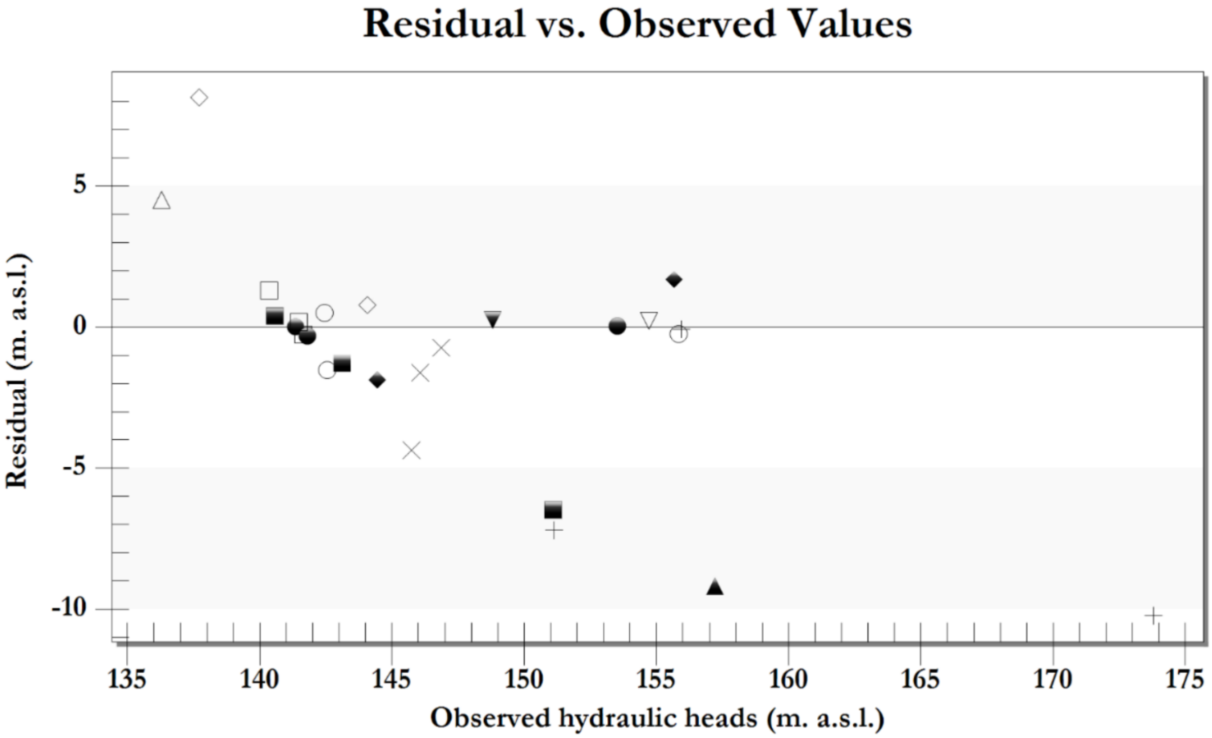


Figure C-7: *Residual heads with MODFLOW in the case of modelling with constant bottom elevation (y axis) and observed heads in-situ (x axis). Unit of measure is m. a.s.l.*