Investigating the decrease of groundwater levels and the effect of fracture zone on recovery time: A case study of decrease in groundwater levels in a tunnel construction site in Vinsta, Stockholm

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Abstract

Groundwater is one of the main natural resources worldwide. Groundwater exists in aquifers below the earth surface and provides quantities of water for various purposes such as supply to households and businesses, public supply, drinking water supply, irrigation and agriculture. Sweden is also highly dependent on groundwater. As mentioned in the list of 16 Environmental Quality Objectives, that the Swedish Parliament established, "groundwater must assure a safe and sustainable supply of drinking water, as well as promoting viable habitats for plants and animals in lakes and watercourses". However, the protection of groundwater and generally the aquifer resources is prone to various human activities that are harmful in terms of volume and quality.

The present thesis aims to investigate the behavior of groundwater towards such human activities of large scales, like a tunnel construction, and small scale, like a construction of a geothermal plant. The area under study is investigated through spatial analysis, using ArcGIS; the groundwater levels are monitored and further statistically analyzed by implementing a Modified Double Mass Statistical Analysis; and further on a 3D numerical model is built in COMSOL Multiphysics in order to simulate possible drawdown caused by human intervention to the natural environment.

The created 3D model was used in order to evaluate the drawdown and different scenarios were implemented with the aim to determine the degree of sensitivity the model has towards fracture parameters. Since the occurrence of fractures in the rock mass is often connected to extended investigation and time/cost consuming techniques, the model contains an overall uncertainty concerning the location and properties of the fracture formations in the area. The different scenarios involve variation of fracture zone width and thus the behavior of the top soil layer is investigated in terms of recovery after drawdown.

The results indicated connection to human activities, with the statistical analysis to support this. Also, the numerical model showed that the fracture properties are connected to the recovery time of the groundwater levels after a drawdown is noticed. Wider fracture zone width implied more time needed for the groundwater levels to get to their initial values, under the perception that the source of recharge is precipitation. On the other hand, narrow fracture zone width was connected with greater drawdown, compared to the wider width scenario, and also earlier in time recovery of the groundwater levels.

The type of the soil layer and its vulnerability to human activities can vary greatly in terms of volume loss which can prove a hazard to existing infrastructure on the ground surface. The present study can prove useful in cases of prestudy of drilling projects of any scale. There is strong connection between fracture formations and recovery of groundwater levels and thus such kind of models can generate innovative techniques of planning before a project begins.

Keywords: Groundwater, spatial analysis, Modified Double Mass Statistical Analysis, 3D model, COMSOL Multiphysics, fracture zone, recovery time, soil layer
Sammanfattning

Grundvatten är en av de viktigaste naturresurserna världen över. Grundvatten finns i akviferer under jordytan och ger vatten för olika ändamål så som tillförsel till hushåll och företag, kommunalt bruk, dricksvattenförsörjning, bevattning och jordbruk. Även Sverige är mycket beroende av grundvatten. I en sammanställning av 16 nationella miljökvalitetsmål fastställde riksdagen bland annat att "grundvatten måste säkerställa ett säkert och hållbart utbud av dricksvatten samt att främja livskraftiga livsmiljöer för växter och djur i sjöar och vattendrag". Skyddet av grundvatten och de allmänna vattenresurserna är främst för att begränsa påverkan från olika mänskliga aktiviteter som är skadliga när det gäller volym och kvalitet.

Föreliggande uppsats syftar till att undersöka grundvattnets beteende till följd av storskaliga mänskliga aktiviteter, till exempel en tunnelkonstruktion, och mindre aktiviteter, till exempel byggnation av en geotermisk anläggning, och mindre aktiviteter, till exempel byggnation av en geotermisk anläggning. Det område som studeras undersöks genom rumslikt, med hjälp av ArcGIS; grundvattennivån övervakas och analyseras vidare statistiskt genom implementering av en statistisk analys av Modified Double Mass Statistical Analysis; en numerisk 3D-modell byggs i mjukvaran COMSOL Multiphysics för att simulera möjliga grundvattensänkning orsakad av mänsklig påverkan i den naturliga miljön.

3D-modellen användes för att utvärdera eventuellt grundvattensänkning och olika scenarier implementerades med syfte att bestämma graden av känslighet med avseende på sprickparameterer i modellen. Eftersom förekomst av sprickor i bergmassan ofta innebär ett behov av utökad undersökning och tid/kostnadsskävande tekniker innehåller modellen en övergripande osäkerhet om platsen samt egenskaper hos sprickorna i området. De olika scenarierna involverar variation av sprickzonsbredd och det övre jordskiktets beteende betraktas i termer av återhämtning efter avsänkt grundvattennivå.


Jordlagrets typ och dess känslighet för påverkan från mänskliga aktiviteter kan variera kraftigt i fråga om volymförlust vilket kan utgöra en fara för befintlig infrastruktur på markytan. Den aktuella studien kan vara användbar för förstudier till borprojekt av vilken skala som helst. Det finns stark koppling mellan sprickbildning och återhämtning av grundvattennivån, och sålunda denna typ av modeller generera innovativa planeringstekniker innan ett projekt börjar.

Nyckelord: Grundvatten, spatial analysis, Modified Double Mass Statistical Analysis, 3D-modell, COMSOL Multiphysics, sprickzon, återhämtningstid, jordlager
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1. Introduction

The Stockholm Bypass (Förbifart Stockholm) is planned to be a new route for the highway E4 to connect the northern to the southern parts of Stockholm. The bypass, when completed, will be 21 km long, out of which 18 km will be in tunnels. The construction of the bypass started in 2015 and it is estimated to finish in a time period of ten years (Trafikverket, 2015).

Apart from the utility that a road tunnel project has, there is an environmental impact that is connected to the tunnel excavation. In general excavation for tunnel constructions cause drawdown of the groundwater table and thus has a risk of surface and subsurface damages. The areas that are most sensitive to groundwater drainage are the ones that have the groundwater table linked to water-dependent vegetation and surface water. This sensitivity raises even more when the area of precipitation is of small size (Lindstrøm & Kveen, 2005).

The environmental impact that derives from large scale sub-surface infrastructures is mainly divided in two aspects. Firstly, the ground level surface that exists above such infrastructure has the tendency to collapse in a downwards. This is caused by the “need” the soil has to make up for the lost tubular cavity. The collapse can vary from slight to even severe in the surrounding surface (Thai, 2010). Secondly, there is an environmental impact linked to chemical residues. Sub-surface construction actions can have impact on the water quality disturbing the chemical balance of both the groundwater and the surface water. Concerning the groundwater, if there is dried sediments in the aquifer then the groundwater table can go through processes of erosion and oxidation. In turn, these processes lead to high concentration of ions, salts and various particles on the surface water (Lindstrøm & Kveen, 2005).

1.1. Problem definition and study area

The study area of the thesis is Vinsta. This area is planned to be part of the tunnel construction of Stockholm Bypass (Fig.1). In January 2016, a drop in the groundwater levels was noticed in most of the observation wells located in the area by the Swedish Transport Administration. The decrease was of around 1m. At that point that the decrease was noticed no construction works were taking place at the area. However, a drilling project was initiated in order to cover the need of a nearby geothermal plant. According to this project 61 boreholes were drilled in the area. Another factor that needs to be mentioned is the dry winter that was noticed on 2016, which can be translated to limited natural recharge to the aquifer.

The research question is focused on modelling and investigating the groundwater levels before and after the sharp drop in groundwater levels was noticed. A numerical model of the area is created and is used afterwards as a base for different scenarios. These scenarios are connecting different fracture zone properties to the time needed in order for the groundwater levels to recover up to their initial values, before the sharp decrease.
Vinsta is located within the division of Stockholm and more specifically in the Hässelby-Vällingby County. Vinsta has a total area of 1.67 km². Figure 2 shows the location of the study area with the reference to the city of Stockholm.
Further on, more details are given about both projects, the tunnel construction and the drilling project, as well as on the geological nature of the area under study. The observation wells along with their numerical groundwater measurements and their respective locations are presented in the following chapters.

2. Background

A large proportion of the earth’s surface is covered by hard rocks of low permeability. In the hydrogeology field these kinds of rocks are grouped under the term of “fractured rocks”. Fractured rocks are interesting to investigate since they are linked to groundwater supplies, contaminants’ movement, geothermal resources and geotechnical infrastructure as well as to storage capabilities (Singhal & Gupta, 2010). Moreover, the detailed investigation of such rocks offers a tool to firstly understanding their behavior and secondly planning sub-surface constructions in an optimal way. The changes in the groundwater flow can be predicted adequately when the properties of fractured rocks are known and investigated.

In order to have a better understanding of fractures and fractured rocks, it is useful to provide with terms and definitions of hydrogeology and subsurface water.

2.1. Fractures and fractured zones

The above mentioned fractured rocks are interesting in terms of groundwater flow, porosity as well as permeability. However, there is quite limited knowledge of the fractures and such discontinuities due to the difficulty in investigation techniques, and the complexity of geological history of the area.

The general term that is used is “discontinuities”, but it includes fractures (or joints), bedding planes, rock foliation and cleavage, faults and shear zones and various other geological discontinuities (Fig.3). As Dippenaar and Van Rooy (2016) mention, discontinuities are connected to mechanical and sedimentary issues responsible for the separation of intact rock blocks that exist in the rock mass. In this study, consideration is based mainly on fractures.

Figure 3. Geological discontinuities and groundwater flow. Source: (Singhal & Gupta, 2010).

In general, by the term fractures are meant the planar cracks or breaks that have occurred in the rock mass without any noticed displacement. More analytically, fractures, or joints, are “the planes along which stress has caused partial loss of cohesion in the rock” (Singhal & Gupta, 2010). In other words, fractures have usually smooth surfaces along the plane, represent a geological weakness in the rock and there is no visible parallel to the surface movement. Typically, the extent of a fracture is limited and individually presents discontinuities along its plane. Fractured zones consist of narrow-spaced fractures that are interrelated. However, the extent and the lateral hydraulic properties of such zones can vary greatly in cases.
The main classification of fractures is based on its appearance. They are systematic and non-systematic (Fig.4). The systematic fractures are of regular form and distribution whereas the non-systematic ones meet but they do not cross other fractures. The latter ones are usually of curved form and their end is at the bedding surface while their formation takes place at the weathering zone (Singhal & Gupta, 2010).

![Systematic and non-systematic fractures](image)

**Figure 4. Systematic and non-systematic fractures. Source: (Singhal & Gupta, 2010)**

The systematic fractures are further classified depending on their geometric characteristics and their connection with the bedding. **Strike joints** are the ones with strike parallel to the strike of the rock. **Oblique or diagonal joints** are the ones that strike with angle the strike of the rocks. Lastly, the **bedding joints** are parallel to the bedding plane of the rock.

Based on the genetic characteristics of the systematic fractures, they are divided in three more categories. **Shear fractures** are the ones that appear with shear displacement and are developed in sets with specific angles. **Dilational fractures** are developed perpendicular to the bedding, they are open and they do not show displacement. **Hybrid fractures** are a combination of shear and dilational, meaning that they can develop in sets with angles, but they can also be open, partly filled with veins and even displacement (Singhal & Gupta, 2010).

### 2.2. Definitions and literature values

**Effective porosity ($\eta_e$):** is also termed as kinematic porosity and equals to the specific yield. The basis of effective porosity is that not all the pores of the rock take part in the flow. Grains of fine size and poor shorting are assigned a low value of effective porosity, whereas coarse grained materials are assigned higher one. This is due to the fact that greater retention is connected to intergranular forces. In fractured rocks, the size and the combination of fractures are the main parameters affecting effective porosity (Singhal & Gupta, 2010).

**Specific yield ($Sy$):** has the form of ratio between volume of water that can be released by an unconfined aquifer from the storage due to gravity, and the total volume of water that exist in fully saturated aquifer (Fig.5). The main variables that control the value of specific yield are the temperature, the duration of drainage, the composition of water in mineral terms and the grain size of the aquifer material (Singhal & Gupta, 2010).
Hydraulic conductivity ($K$): depends on the properties of the rock formation and on the properties of the fluid (Fig. 6). However, concerning fractured rocks, hydraulic conductivity depends also on the density, the size and the interconnection of fractures (Singhal & Gupta, 2010).

Storativity ($S$): is defined as the volume of water that is released by a vertical column of the aquifer of unit cross sectional area from the storage, while the average head in the column decreases by unit distance.

In confined aquifers, storativity is estimated by the equation $S = bS_s$ and typically varies from $10^{-3}$ to $10^{-6}$. $b$ is the aquifer thickness and $S_s$ is the specific storage. Specific storage is termed the amount of water that is released from a confined aquifer, due to both expansion of water and compression of aquifer, while the average head declines by unit (Singhal & Gupta, 2010).
In unconfined aquifers, storativity is calculated by the equation $S = S_y + bS_x$. The typical range of storativity in unconfined aquifers is 0.05 to 0.30.

It should be noted that $S_y$ is way greater in value compared to the $bS_x$. Thus, storativity in an unconfined aquifer can be safely regarded equal to the specific yield (or effective porosity as mentioned before).

**Hydraulic conductivity of fractured rock ($K_f$):** As mentioned before, there is difference between hydraulic conductivity of the rock matrix and the one of the fracture. Hydraulic conductivity of a fracture is controlled by the physical characteristics of the fracture, which mainly are aperture, spacing or frequency, stress and connectivity. In Figure 7 is presented the connection between fracture aperture and frequency to the hydraulic conductivity of the fracture (Singhal & Gupta, 2010).

![Figure 7. Schematic relationship between hydraulic conductivity and fracture aperture. Source: (Singhal & Gupta, 2010)](image)

### 2.3. Fractures and aquifers

The processes that lead to the creation of fractures are mainly stresses. Stress forces can be a result of tectonic deformation of rocks; contraction of cooling magma; glacier's movement or landslides; erosion; and weathering in terms of dilation (irregular cracks) and dissolution (widening of cavities) (Singhal & Gupta, 2010).

A single fracture is characterized by four parameters; the orientation (measurement of angle with the north and the horizontal level), the generic nature, the persistence (fracture length) and the aperture. However, there are eight, geometric and hydraulic, properties of fractures, according to Thörn and Fransson (Thörn & Fransson, 2013):

- Aperture, which is the perpendicular distance between the two surfaces of the fracture. The intervening void between the surfaces is either air or a water-saturated material (Singhal & Gupta, 2010).
- Contact area between the rock-walls.
- Roughness of the surfaces, which refers to the degree of coarse grains at the surfaces and the fitting they have.
- Matedness, which is the degree of matching between the two opposing surfaces of the fracture (Hakami, 1995).
- Spatial correlation, meaning the rate of aperture change from one point to another on the fracture surface (Hakami, 1995).
- Existing channels and their properties concerning their continuity and opening.
- Tortuosity, which reflects the non-straight flow paths.
- Stiffness of the surfaces, which indicates the amount of stress forces need to move the surfaces of the fracture one length unit closer to each other.

Concerning the aperture of the fracture, there is a strong interrelation with the flow rate within it. The hydraulic conductivity of the fracture is inversely related to typical stresses acting on the fracture and its depth, meaning that the typical stresses tend to reduce the fracture’s aperture and in turn to reduce the hydraulic conductivity. Also, fracture’s permeability is related to the temperature. The temperature increases moving from the surface to greater depth, the aperture of fracture is reduced and thus the permeability is reduced (Singhal & Gupta, 2010).

In general, as mentioned, fractures or faults can cause the bedding to be displaced, repeated or omitted. This, practically, means that it can locally affect the aquifer in the same way. A fracture can displace the beds in such way that the aquifer gets in contact with an impervious surface, affecting further the groundwater flow and distribution (Fig.8a). Another effect of the fractures can be the seepage of a surface and creation of springs along the fracture formation (Fig.8b). A fault can result in erosion of rock in higher elevations and further deposition at lower elevations. These deposits can act as good aquifers (Fig.8c). Also, dykes, veins or silicified fault zones can be barriers to the groundwater flow. However, this may produce new pathways for the groundwater across the barrier. Fractures and faults, also, tend to create linear zones of high secondary porosity resulting in creation of groundwater channels convenient for recharge and discharge from the aquifer. Lastly, due to thrust faulting an aquifer may get re-exposed to the surface for direct recharge (Fig.8d) (Singhal & Gupta, 2010).

Figure 8. Types of bed displacement. Source: (Singhal & Gupta, 2010)

It must be noted that the case of Vinsta can be sufficiently described as an aquifer created by processes of erosion due to fractures in the solid rock. The rock is eroded in higher elevations and the products of erosion are then slowly placed on the lower in elevation parts of the rock. The allocated erosion products turn to be aquifers for the groundwater flow.
2.4. Groundwater flow in fractured media

The groundwater flow in a fractured medium is defined as a function of fracture properties and intact rock properties (Dippenaar & Van Rooy, 2016).

Concerning the fractures rocks, the groundwater flows mainly through and along the discontinuities, like fractures or joints. Such kind of discontinuities if not filled with weathered or small parts of the rock are appropriate channels for groundwater. However, their permeability value decreases with filling of clayey material.

Depending on the values of porosity and permeability of a fracture, the rock formation can be classified in three categories; as purely fractured medium (Fig.9a); as double porosity medium (Fig.9b); as heterogeneous medium (Fig.9c). The purely fractured medium is characterized by interconnected fractures that control porosity and permeability whereas the matrix blocks are impermeable. In the double porosity medium, there is groundwater flow through both the fractures and the matrix but the main contributes to flow are the fractures. Lastly, the heterogeneous medium refers to fractures that are filled with clay or silt material and the according permeability of fracture is reduced (Singhal & Gupta, 2010).

Figure 9. Different categories of fractured media. Source: (Singhal & Gupta, 2010)

According to Lee and Farmer (1993) fractured rocks can be seen two porosity systems. The first one is called the matrix porosity ($\eta_m$), which refers to the intergranular void spaces, and the second one is the secondary porosity ($\eta_f$), which refers to the fracture and the solution cavities. The total porosity of the fractured rock is computed as the sum of matrix porosity and secondary porosity.

Literature has shown that secondary porosity is greatly less than the matrix porosity. Matrix porosity varies from 0.1% to 8%, while the secondary porosity of the fracture varies from 0.001% to 0.01% (Lee & Farmer, 1993). In the case of the present study, the secondary porosity is of most interest when referring to the fracture zone and is the one approximating the value of effective porosity.

2.5. Darcy’s Law

Darcy’s law states that the rate of flow ($Q$) is directly proportional to the cross-sectional area ($A$) and head decrease ($h$); and inversely proportional to the length of the flow path ($L$) (Singhal & Gupta, 2010).

Combining the above with a proportional constant ($K$) derives the Darcy’s equation as:

$$Q = KA \frac{dh}{dl}$$

or

$$Q = KA \frac{h}{L}$$

where $K$ is the hydraulic conductivity of the porous media.

From the latter equation, the specific discharge, or Darcy’s velocity, can be estimated as:

$$q = V = \frac{Q}{A} = K \frac{dh}{dl}$$

The equation of specific discharge indicates the amount of water per unit time through a unit cross-sectional area, to the same direction of flow. However, in natural conditions the flow does not cover
the entire cross-sectional area of an aquifer but only the pores (Singhal & Gupta, 2010). Thus, the average velocity through the pores can be calculated by the equation:

\[ \bar{V}_d = \frac{Q}{\eta A} = \frac{q}{\eta}, \]

where \( \eta \) is the total porosity of the media, or

\[ \bar{V}_d = \frac{q}{\eta_e} = K \frac{dh}{dt}, \]

where \( \eta_e \) is the effective porosity.

From past experiments it is shown that Darcy’s law has validity only in cases of laminar flow through porous media and is strongly connected with the Reynolds number, meaning that Darcy’s law is valid when Reynolds number is between 1 and 10. Furthermore, since Re is usually less than 1, Darcy’s law is generally applicable to groundwater flow apart from situations where there are steep gradients, like springs or pumping wells, or large cavities, like karst rocks (Singhal & Gupta, 2010).

2.5.1. General Flow Equation

Darcy’s law can be written also with the form of:

\[ V = -K \frac{dh}{ds}, \]

where \( s \) is the distance along the direction of flow (Singhal & Gupta, 2010).

If a material is assumed with dimensions \( dx, dy, dz \), then the velocity can be expressed for each one of the dimensions as:

\[ V_x = -K_x \frac{0h}{0x}, \quad V_y = -K_y \frac{0h}{0y}, \quad V_z = -K_z \frac{0h}{0z}, \]

where \( h \) is the total head referring to steady state, and \( K_x, K_y, K_z \) are the coefficients of hydraulic conductivity in x, y and z direction respectively.

The equation of continuity is also applicable. The conservation of mass implies that the net inward flux through an element equals the rate of matter accumulation within it (Singhal & Gupta, 2010). Thus:

\[ \frac{\theta (\rho V_x)}{\theta x} + \frac{\theta (\rho V_y)}{\theta y} + \frac{\theta (\rho V_z)}{\theta z} + N = \rho S_S \frac{0h}{0t} \]

where \( \rho \) is the density of fluid, \( N \) is the source/sink and \( S_S \) is the specific storage.

Assuming an incompressible fluid, \( \rho \) can be eliminated from both sides, and the flow equation for transient state and anisotropic medium turns to:

\[ \frac{\theta}{\theta x} \left( K_x \frac{0h}{0x} \right) + \frac{\theta}{\theta y} \left( K_y \frac{0h}{0y} \right) + \frac{\theta}{\theta z} \left( K_z \frac{0h}{0z} \right) = W = S_S \frac{0h}{0t}, \]

where \( W \) is the volume of flux per unit volume.

Assuming, again, a homogeneous and isotropic porous media, the above equation can be written as:

\[ \frac{\theta^2 h}{\theta x^2} + \frac{\theta^2 h}{\theta y^2} + \frac{\theta^2 h}{\theta z^2} = S_S \frac{0h}{0t} \]

For a horizontal confined aquifer of specific thickness \( b \), storage coefficient \( S = S_S b \), and \( T = Kb \), the equation becomes:

\[ \frac{\theta^2 h}{\theta x^2} + \frac{\theta^2 h}{\theta y^2} + \frac{\theta^2 h}{\theta z^2} = S \frac{0h}{0t} \]

For the steady state, velocity and pressure distribution have no variance in time and thus \( \frac{0h}{0t} = 0 \). The porous media is assumed homogeneous and isotropic. The flow equation is expressed as:

\[ \frac{\theta^2 h}{\theta x^2} + \frac{\theta^2 h}{\theta y^2} + \frac{\theta^2 h}{\theta z^2} = 0 \]

For non-steady state with radial flow to wells in confined aquifer, the differential equation is:
\[
\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = 0,
\]
where \( r \) is the radial distance from the well to the observation point.

### 2.6. Statistical Analysis

In this thesis, a statistical analysis method was used in order to check inconsistencies in the measured groundwater levels. By inconsistencies is meant the deviation from the normal behavior, i.e. a trend line of various observations. The Double Mass analysis is based on the idea that various hydrological data (precipitation, groundwater levels etc.) of an observation point can be compared to the data of another observation point or to a pattern created from more than one such points. The Double Mass Curve is actually a graph, created by plotting the cumulative figures of a variable from an observation point against the cumulative figures of another observation point or the cumulative figures of a variable from an observation point against the cumulative figures of the same variable at a different time (Searcy & Hardison, 1960). An example is given in Figure 10, for precipitation data.

![Figure 10. Example of Double Mass analysis. The cumulative values of precipitation of individual stations are plotted against the cumulative values of a pattern. Source: (Searcy & Hardison, 1960)](image)

The result of the Double Mass Curve can indicate a fixed ratio between the variables or breaks in the line. For the case of fixed ratio the graph line is straight, meaning that the data is proportional. The slope of the line equals the constant of proportionality between the two variables. The breaks in the line reflect changes in the relation between the two variables. Such changes can derive from either physical changes in the data of the two variables or faults in the data collection. Practically, the breaks show either a change in the proportionality constant, or that the proportionality constant is not the same for all rates of cumulation. The breaks in the Double Mass Curve are helpful in the analysis since they stand for the specific time that a change happened in the relation between the two variables (Searcy & Hardison, 1960).

For further analysis, the Double Mass Curve can appear helpful since the difference in the slope, and thus the proportionality constant, in the two sides of a break in the line equals the degree of change in the relation of the variables.

The main prerequisites for the implementation of the Double Mass analysis are, firstly, an area that is of small size and, secondly, data records for more than five years. The small area is connected to
the factor of weather. If the area is small enough then there is same effect from the weather conditions across it. Records that are longer than five years are connected to the factor of chance. Year-to-year breaks in the curve can be a result of chance. Breaks that persist for more than five years are more likely to be a result of real change rather than chance (Searcy & Hardison, 1960).

3. Methodology

The present study is a sum of various theoretical, statistical and numerical processes. The steps that were followed were the delineation of the watershed along with the spatial determination of the land uses and the soil types covering the surface; the statistical analysis implemented by the Modified Double Mass Curves in order to define changes in specific time; the numerical model built in COMSOL Multiphysics. The numerical model involves a main scenario built with assumptions in order to represent the effect of drilling, calibration of the scenario in order to be comparable with the real observations, and then implementation of two more scenarios so as to determine the link between the fracture zone width and the time needed for the groundwater levels to recover. The three models, simulating different width of the fracture zone, aim to determine (numerically and visually) the sensitivity of the constructed model to this parameter.

3.1. Watershed delineation

Since the current case is a hydrological study concerning groundwater levels, drawdown and infiltration, the related watershed needs to be delineated.

The area of the watershed is estimated using ArcGIS and tools for watershed delineation. The watershed is defined as a “physically delineated area determined by the area upstream from a specified outlet point” (Trent University, 2017). The procedure followed in order to determine the watershed is divided in different steps. The initial data (DEM, soils, land-uses) is taken from Sveriges Geologiska Undersökning (SGU).

Firstly, a depressionless DEM (Digital Elevation Model) is created in order to remove the imperfections in the existing DEM and fill the “sinks”. As defined, a sink is a specific cell in the DEM which does not have an assigned drainage value and in turn results in inability to determine the flow direction in the area (Trent University, 2017). Then, the flow direction is created as a map layer and the whole drainage network of the area is made. Next step in the process is the flow accumulation which indicates the upstream cells that flow into a specific downslope cell based on the topography. Finally, the watershed is delineated based on user-defined pour points which are normally placed on high flow accumulation paths and act as natural outlets for the upstream cells.

For further processing of the watershed, the land-uses; the soil types; and the depth to the bedrock can be extracted based on the SGU data.

3.2. Modified Double Mass analysis

The available groundwater data are processed by a statistical method in order to define in time if there are deviations from the pattern of normal values between the observation wells. In order to check such kind of inconsistencies in the hydrological data, the method of Modified Double Mass statistical analysis is used. The method serves as a tool of creating cumulative graphs and defining ratios of wells and break points.

The chosen variable is the groundwater levels as measured from the Swedish Transport Administration. Various wells (testing wells), with their corresponding groundwater records are analyzed, cumulated and plotted against “reference” wells. As reference stations are defined the stations where the groundwater levels are unaffected by the cause of change but the rest external parameters, like precipitation and infiltration remain the same with the affected (Searcy & Hardison, 1960). In this case the reference wells are chosen with regard to the groundwater levels that remain quite stable in their values throughout the period of investigation.
In Table 1 are shown both the testing and the reference wells that are used to run the Double Mass analysis. In Figure 11 are shown the exact locations of the various wells as spread around the area under study.

Table 1. Observation and reference wells in the area used for the statistical analysis.

<table>
<thead>
<tr>
<th>Testing wells</th>
<th>Reference wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>08F535RU</td>
<td>08F522RU</td>
</tr>
<tr>
<td>08T610RU</td>
<td>R07VK10U</td>
</tr>
<tr>
<td>08W539</td>
<td></td>
</tr>
<tr>
<td>08W540</td>
<td></td>
</tr>
<tr>
<td>09F505RU</td>
<td></td>
</tr>
<tr>
<td>12A731RU</td>
<td></td>
</tr>
<tr>
<td>12s502RU</td>
<td></td>
</tr>
<tr>
<td>13A010RU</td>
<td></td>
</tr>
<tr>
<td>6244B185</td>
<td></td>
</tr>
<tr>
<td>GWGK560</td>
<td></td>
</tr>
<tr>
<td>R07VK11U</td>
<td></td>
</tr>
<tr>
<td>R07VK12U</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11. Location of the wells used in the statistical analysis. In red circles are the reference wells; in blue circles are the testing wells; the star represents the drilling spot.
The software that is used is called Groundwater Control Problem (GCP). The purpose of this software is to store and analyze the groundwater level data. The imported groundwater level data were reformed in order to assign to all the missing values the value -9999. The missing values in the record indicate the periods when the well has been observed dry. This actually means that the groundwater level can be much lower than the bottom of the well. (Olofsson, n.d.).

The analysis that is chosen in the software is the Modified Double Mass with interpolation of the records. The Modified Double Mass uses average values and thus it can magnify breaks that are not noticed by the Double Mass method, since the latter one has the tendency to smooth out the plotted curves (Searcy & Hardison, 1960). The interpolation that is used does not alter the initial records but only creates a temporary file with the wells to be assigned an interpolated reference value. This reference value derives by the user-defined number for days and thus, the value ranges between the original time lapse and the observation (Olofsson, n.d.).

The GCP software is modelling the Modified Double Mass Curves with 0.005 precision, 100 iterations, and 7 days maximum difference for the interpolation. The correlation coefficient is calculated for each of the testing wells and the according reference well. The result is a model of Modified Double Mass for each combination, depicting a curve relating the reference and the testing well.

3.3. Conceptual Model

In order to define the flows in the system, there is a need to estimate numerically the inflows and outflows from the system. The source of inflow is the effective precipitation, which is defined as the amount of precipitation after the value of evapotranspiration is removed. The amount of infiltration is estimated as a function of the existing landuses in the area. Below, the mentioned processes are described thoroughly.

3.3.1. Water balance

The method of Water Budget is used to describe the flow of water in terms of inflow and outflow from a water system. The basis of the method is the idea that precipitation (P) is falling in a specific watershed and part of it can be temporarily stored (S), another part can return to the atmosphere through evapotranspiration (ET) and a last one can be transported out of the system in the form of runoff (Q) to a certain outlet (SMHI, 2017).

Summing the above, recharge in the watershed is calculated as:

$$R = P - ET - Q - S$$

For the water balance of the watershed, the data needed is the value of annual average precipitation, the value of annual average runoff, the value of annual average evapotranspiration, the area of the watershed and the soil types in the watershed. It must be noted that in this study the storage variable is ignored.

The annual average values for precipitation, evapotranspiration and discharge are retrieved from the Swedish Meteorological and Hydrological Institute (SMHI) and more specific its Vattenwebb application which offers modelled data (SMHI, 2017). The mentioned data has derived from the HYDROLOGICAL Predictions for the Environment) (HY). This model refers to hydrological drainage areas and offers the ability to simulate surface water flows initiating from precipitation and ending to watershed outlets. The model actually utilizes variables of landuse, soil type and topography in order to create subdivisions and classes in the watershed. The available data on Vattenwebb is a result of calculations on water simulations either from observed daily values or from modelled ones.

According to SMHI the catchment that includes the watershed under study is called 61 Norrström and has its outlet at the Räckstraträsk Lake (Fig.12).
For the specific catchment the annual average values are long-term values calculated with reference to the years 1981-2010.

- Annual average precipitation is 587mm/yr
- Annual average evapotranspiration is 361mm/yr

The effective precipitation is calculated by the relation:

\[ P_{\text{eff}} = \text{annual average precipitation} - \text{annual average evapotranspiration} \]

The main landuses, as it will be shown in the results section, are forest, high built-up and low built-up areas. It can be assumed that the forest will infiltrate 70% of the amount of effective precipitation; the high built-up will not infiltrate any of the effective precipitation; and the low built-up will infiltrate 5% of the effective precipitation. The rest of the effective precipitation, that is not infiltrated, is removed by the stormwater system.

The recharge in the area under study is given by the following relation:

\[ R(\text{in}) = (70\% \text{ of effective precipitation} \times \text{forest area}) + (5\% \text{ of effective precipitation} \times \text{low built-up area}) \]

3.3.2. Boundary conditions

In order to approximate the boundary conditions, an interpolation function is used in ArcGIS, called Inverse Distance (IDW). In order to perform the function, the observation wells with their according groundwater levels for a specific day, are imported to ArcGIS. The initial coordinates in x,y are given by the Swedish Transport Administration in the coordinate system SWEREF99 18 00.

The function of IDW is an interpolation method from points. In this case the points are the observation wells. In Table 2 are shown the observation wells that are used as the points for the interpolation. The numerical values are the groundwater levels measured by the Swedish Transport Administration for the according wells on the 3rd of June 2015. The date was chosen with the aim to depict the situation before the sharp decrease on the groundwater levels. Since, the value of interpolation is the groundwater levels, it is important to set the outcrops as barriers to the groundwater flow. The IDW is run setting the maximum distance of effect at 280m.
Table 2. The groundwater measurements of the below presented observation wells are used as input to the IDW function.

<table>
<thead>
<tr>
<th>Observation Wells</th>
<th>GAGE Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>08T610RU</td>
<td>09F505RU</td>
</tr>
<tr>
<td>R07VK12U</td>
<td>08W539</td>
</tr>
<tr>
<td>6244B185</td>
<td>08W540</td>
</tr>
<tr>
<td>13A010RU</td>
<td>GWJ812</td>
</tr>
<tr>
<td>12A731RU</td>
<td>R07VK44U</td>
</tr>
<tr>
<td>08F535RU</td>
<td>GWGK48</td>
</tr>
<tr>
<td>R07VK11U</td>
<td>GWGK365</td>
</tr>
</tbody>
</table>

The result of IDW is a raster interpolated surface representing the groundwater surface as hydraulic heads in meter units. By superimposing the watershed polyline, the numerical boundary conditions can be determined in detail. The boundary conditions of the present study are regarded as constant heads.

Generally, the hydraulic head (h) is the sum of elevation (z) and pressure head \( p/\gamma \), with \( p \) being the gage pressure and \( \gamma \) the unit weight of water. The hydraulic head is the water level above datum, as observed in a well. Constant-head is a specific case of specified-head boundary conditions, meaning that the head can regarded as a function of position and time over a boundary, or a part of the boundary, of a groundwater surface. The term “constant” refers to a certain value uniform along the surface of the boundary and in time. In nature, the constant-head indicates the case when even if an aquifer is “drained”, the boundaries will continue to supply the required amount (Franke, Reilly, & Bennett, 1987).

### 3.4. Numerical model

In order to create the numerical model with COMSOL software, two surfaces are imported; the surface of elevation and the surface of the bedrock. It must be noted that the surface of the bedrock is created in ArcGIS by using the function of Raster Calculator and, in practice, reducing the DEM by the soil depth. These two surfaces are imported to AutoCAD Civil and projected to the coordinate system WGS84 - UTM 33N, in order for them to be in compatible format with COMSOL. A smaller area is extracted from the DEM and bedrock surface, for the modelling purposes.

The domains that are created by building up the geometry of the model are three; the bedrock, the soil material and the fracture zone. The bedrock according to the soil map, from SGU, is crystalline rock. The fracture is created with the perception that it runs the bedrock, and the parts of bedrock that come to the surface, but not the soil layer.

Concerning the soil material, the found types were clay and till. Till is usually met in the sides of the clay layer and is the soil type that allows the infiltration in the groundwater. However, in this case the till and clay layer are united and represented by one layer of clay, which is numerically approximated by setting the hydraulic conductivity value equal to the higher end of the clay range.

The recharge in the soil layer is computed and imported to the numerical model by the water balance. It is important to mention that the area that is modelled is not the whole watershed but only a smaller part of it. Thus, the water balance is recalculated, based on the paved surfaces and the landuses. The recharge is based on the perception that the forest will infiltrate 70% of the effective precipitation, the high built up will not infiltrate, and the construction sites will infiltrate a small amount of 5% of the effective precipitation. For modelling purposes the recharge is introduced evenly throughout the clay layer.

The boundary conditions are approximated again based on the groundwater surface created by the IDW, for the new smaller area. The groundwater flow is simulated by COMSOL by applying the equation of Darcy’s Law.
Concerning all the numerical models, there is an attached degree of uncertainty. The current model, although it includes a certain number of simplifications, is built to represent the reality. However, reality is a sum of properties which in the present study are the chosen values of hydraulic conductivity, storativity, effective porosity and fracture parameters. Each of these properties has a range of sensitivity and thus they inherit an overall uncertainty to the model.

3.4.1. Different scenarios on recovery of the groundwater levels

After the model is built, a transient state is studied. This is done by importing a time function in the model, which represents the start and the end date of the drilling. The drilling for the geothermal plant took place for 84 days. According to the report of the drilling project, the maximum capacity that was observed while drilling the wells was 10000l/h and thus this value is considered the case of pumping rate in the present modelling study. Since there were 61 drillings, a broader perception was formed with a cylinder, of 4.5 m radius, to represent all the drillings. Furthermore, due to the large area and long boundaries of the modelling area, it is considered safe to regard the boundaries as constant heads.

The transient state is calibrated by comparing the modelled groundwater levels to the ones as measured in reality from the observation wells R07VK11U (located on the upstream north of the drilling spot) and 08W540 (located on the downstream south of the drilling spot). It must be noted that the exact locations of the two observation wells, mentioned above, are approximated in the clay layer.

A simulation is run for a long future, based on the given fracture properties. This is done in order to determine the moment of recovery of the groundwater levels.

Another two different scenarios are run in order to examine the effect of the fracture zone width in the recovery of the groundwater levels. For this reason, keeping all the characteristics of the model the same, the width of the fracture zone is changed in order to represent a smaller (10 m) and a greater (30 m) width.
4. Results

4.1. Modified Double Mass Curves

The wells that were used in order to perform the Modified Double Mass analysis were in total 14, 12 of which are the testing wells and 2 are the reference wells. The according groundwater levels, given as timeseries for the broader period of 1/1/2013 to 3/5/2017, are presented in Figure 13.

Observing the groundwater levels, as measured for the wells above, there is a clear drop in the measurements for the majority of the wells. The reference wells (R07VK10U and 08F522RU) remain relatively in stable levels from the beginning of measurements until the present. The wells 6244B185 and 08F535RU seem to have a decreasing trend in their groundwater level measurements starting from around April 2015. They however show a sharper drop in the beginning of 2016. The same sharp drop is followed by the wells 12A731RU and R07VK12U as well. For the last two wells the lowest groundwater levels are reached around October 2016, whereas for the former two wells the drop slightly continues after this moment. After that the groundwater levels seem to follow an increasing trend but not reaching the same levels as before the decline.

The effect of precipitation on the groundwater levels was analysed by dividing the daily precipitation, given in mm, in two datasets and defining the respective trendlines. The first dataset is from 1st of June 2014 until 31st of December 2015 (Fig.14) and the second dataset is from 1st of January 2016 until 31st of May 2017 (Fig.15). For the second dataset, the extremes are more often but the overall precipitation levels are less than the ones in the first dataset.
The GCP software was run at first in iterations so as to correlate the testing wells to their according reference well. The correlation coefficients are shown in the Table 3.
Table 3. Correlation coefficients as calculated for all the testing wells against all the reference wells. In red are the highest match between testing and reference well.

<table>
<thead>
<tr>
<th>Testing Well</th>
<th>Reference Well</th>
<th>Iterations</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>08F535RU</td>
<td>08F522RU</td>
<td>68</td>
<td>Corr=.27</td>
</tr>
<tr>
<td>08F535RU</td>
<td>08F522RU</td>
<td>58</td>
<td>Corr=.13</td>
</tr>
<tr>
<td>08F610RU</td>
<td>08F522RU</td>
<td>50</td>
<td>Corr=.07</td>
</tr>
<tr>
<td>08F610RU</td>
<td>08F522RU</td>
<td>50</td>
<td>Corr=.01</td>
</tr>
<tr>
<td>08F539</td>
<td>08F522RU</td>
<td>67</td>
<td>Corr=.65</td>
</tr>
<tr>
<td>08V530</td>
<td>08V7K10U</td>
<td>67</td>
<td>Corr=.31</td>
</tr>
<tr>
<td>08V540</td>
<td>08F522RU</td>
<td>65</td>
<td>Corr=.33</td>
</tr>
<tr>
<td>08V540</td>
<td>08V7K10U</td>
<td>65</td>
<td>Corr=.13</td>
</tr>
<tr>
<td>03F53RU</td>
<td>08F522RU</td>
<td>66</td>
<td>Corr=.73</td>
</tr>
<tr>
<td>03F53RU</td>
<td>08F522RU</td>
<td>66</td>
<td>Corr=.41</td>
</tr>
<tr>
<td>12A731RU</td>
<td>08F522RU</td>
<td>37</td>
<td>Corr=.4</td>
</tr>
<tr>
<td>12A731RU</td>
<td>08F522RU</td>
<td>37</td>
<td>Corr=.47</td>
</tr>
<tr>
<td>12F529RU</td>
<td>08F522RU</td>
<td>54</td>
<td>Corr=.08</td>
</tr>
<tr>
<td>12G529RU</td>
<td>08F522RU</td>
<td>54</td>
<td>Corr=.45</td>
</tr>
<tr>
<td>13C016RU</td>
<td>08F522RU</td>
<td>29</td>
<td>Corr=.46</td>
</tr>
<tr>
<td>13C016RU</td>
<td>08F522RU</td>
<td>23</td>
<td>Corr=.34</td>
</tr>
<tr>
<td>5244B185</td>
<td>08F522RU</td>
<td>63</td>
<td>Corr=.45</td>
</tr>
<tr>
<td>5244B185</td>
<td>08F522RU</td>
<td>63</td>
<td>Corr=.28</td>
</tr>
<tr>
<td>GWGK560</td>
<td>08F522RU</td>
<td>63</td>
<td>Corr=.01</td>
</tr>
<tr>
<td>GWGK560</td>
<td>08F522RU</td>
<td>63</td>
<td>Corr=.58</td>
</tr>
<tr>
<td>R07V11U</td>
<td>08F522RU</td>
<td>65</td>
<td>Corr=.15</td>
</tr>
<tr>
<td>R07V11U</td>
<td>08F522RU</td>
<td>65</td>
<td>Corr=.75</td>
</tr>
<tr>
<td>R07V12J</td>
<td>08F522RU</td>
<td>50</td>
<td>Corr=.25</td>
</tr>
<tr>
<td>R07V12J</td>
<td>08F522RU</td>
<td>50</td>
<td>Corr=.25</td>
</tr>
</tbody>
</table>

It should be noted that where the correlation coefficient is relatively high (over 0.5) the results are more trustworthy; when the testing wells are at a great distance from the reference well then the correlation coefficient is exceptionally low and thus is not taken into consideration. Examples of the latter case are the testing well 08T610RU which is at a distance of 888m from the reference well 08F522RU; and the testing well GWGK560 which is at a distance of 935m from the same reference well.

Below are analyzed the wells that have same or similar behavior. By behavior is meant the reaction the groundwater levels have against specific constructions or human activities taking place in certain places and moments. The rest of the wells, not mentioned below, appear with irregular behavior and not similar reaction, thus it is not easy to relate the changes in the Modified Double Mass Curves with certain moments.

- Testing well: 08F535RU

The timeseries of 08F535RU is plotted against the timeseries of the reference well 08F522RU (Fig.16). The distance between the wells is 578m and the correlation coefficient is 0.27.

Observing the Modified Double Mass Curve, the first brake is noticed on 4th December 2015 with a drop in the groundwater levels of 0.2m, while it remains like this until the 8th of January 2016. The second brake in the curve is noticed on the 5th of February 2016 with a total drop of 0.79m. The third brake is noticed on the 6th of February 2016 with a total drop of 0.88m and remains at this level until the 11th of March 2016. Another brake is noticed on the 8th of April 2016 with a drop of 0.96m and remains until the 11th of August 2016. On the 19th of August 2016 there is a further drop of 0.98m which remains until the 7th of September 2016. On the 14th of October 2016 the drop reaches 1.1m and on the 6th November 2016 the drop of groundwater levels becomes 1.21m, remaining like this until the present.
Figure 16. Double Mass Curve for the testing well 08F3535RU. In red is the moment that the drilling for the geothermal plant began.

- Testing well: 12A731RU

The timeseries of 12A731RU is plotted against the reference well R07VK10U (Fig.17). The distance between the two wells is 612m and the correlation coefficient is 0.47.

The first brake in the curve is noticed on the 5th of February 2016 with a drop of 1m. On the 6th of February the drop reaches 1.1m and remains until 16th of February. On the 17th of February 2016 the drop becomes 1.17m and remains until the 4th of May 2016. Another brake in the curve happens on the 3rd of June 2016 at 1.2m, while on the 9th of June the drop gets to 1.41m. On the 5th of August 2016 there is a drop of 1.55m in the groundwater levels. A rise is then noticed on the 16th of November 2016 where the groundwater levels reach again the 1.46m.

Figure 17. Double Mass Curve for the testing well 12A731RU. In red is the moment that the drilling for the geothermal plant began.
• Testing well: 12s502RU

The timeseries of 12s502RU is plotted against the reference well 08F522RU (Fig.18). The distance between the two wells is 884m and the correlation coefficient is 0.37.

The first brake in the Modified Double Mass Curve is noticed on the 4th of December 2015 with a drop of 0.23m and remains until the 7th of September 2016. The second brake is on the 14th of October with a drop of 0.39m, remaining until the present.

![Double Mass Curve for the testing well 12s502RU. In red is the moment that the drilling for the geothermal plant began.](image)

• Testing well: 6244B185

The timeseries of the well 6244B185 were plotted against the reference well 08F522RU (Fig.19). The distance between the two wells is 669m and the correlation coefficient is 0.46.

Observing the Modified Double Mass Curve, the first significant brake is noticed on the 2nd of September 2015 with a drop on the groundwater levels of 0.13m that remains until the 4th of December 2015. On the 8th of January 2016 the drop becomes greater at 0.18m, while on the 5th of February the drop reaches 1.1m. The next day, on the 6th of February the drop becomes 1.2m and remains until the 5th of March 2016. Another brake is noticed on the 11th of March 2016 with a further drop of 1.27m. A significant brake happens again on the 8th of April 2016 at the level of 1.42m. After that, the groundwater levels appear to drop constantly with the maximum drop to be on the 5th of August 2016 with a value of drop at 1.75m. On the 16th of November 2016 the groundwater levels start to rise and lastly on the 9th of December 2016 the drop has decreased in 1.44m up until the present.
Figure 19. Double Mass Curve for the testing well 6244B185. In red is the moment that the drilling for the geothermal plant began.

- Testing well: 08W539

The timeseries of 08W539 is plotted against the reference well 08F522RU (Fig.20). The distance between the wells is 498m and the correlation coefficient is 0.66.

The first brake in the Modified Double Mass Curve indicates a drop in the groundwater levels of 0.12m on the 4th of December 2015, which remains stable until 14th of January 2016. After that, on the 21st of January 2016 the drop becomes greater at 0.22m and remains at this level until the 11th of March 2016. Since the 8th of April 2016, up until the present the drop in the groundwater levels is at 0.27m.

Figure 20. Double Mass Curve for the testing well 08W539. In red is the moment that the drilling for the geothermal plant began.
4.2. Watershed Delineation and Water Balance

4.2.1. Watershed delineation

As mentioned in the methodology, the watersheds in the area were created based on user-defined outlet points. The watershed under consideration is “Watershed 4”. The calculated area of the watershed is 1.92km² (Fig. 21).

Figure 21. Watersheds in the area based on user-defined outlet points.

In Figure 22 are presented the different soil types found in the watershed. Analytically, these are the glacial clay, the outcrops, the post-glacial clay, the sandy till and the artificial material. The soil material mentioned as artificial material is considered as similar to silt.

The according extent of each soil type is:

- Glacial clay: 0.12km².
- Outcrops: 1.21km².
- Post-glacial clay: 0.013km².
- Sandy till: 0.086km².
- Artificial material: 0.50km².
4.2.2. Recharge

To the direction of estimating the recharge in the watershed under study, two resulting maps from ArcGIS were combined; the hillshade and the land-uses of the watershed.

The land-uses in the area as shown in Figure 23 are forest and built-up, which was further divided in high built-up and low built-up. The calculated areas of each land-use are:

- Forest: 0.90km$^2$.
- High built-up: 0.75km$^2$.
- Low built-up: 0.26km$^2$. 
The hillshade was created on the basis that an infinite illumination source spreads over a surface raster (Fig. 24). The angle of the source as well as the shadows creates a shaded relief of the area.

![Figure 24. Hillshade in the selected watershed.](image)

As it can be seen from Figure 24 almost 50% of the total area is paved surfaces whereas the other 50% is natural surfaces, i.e., forest. From the paved areas 75% is high built-up and approximately 25% is low built-up.

The recharge is estimated based on the perception that the natural surfaces (forest) and the low built-up will infiltrate a certain amount of the effective precipitation.

\[
P_{\text{eff}} = \text{annual average precipitation} - \text{annual average evapotranspiration} = 587 \text{ mm/yr} - 361 \text{ mm/yr} = 226 \text{ mm/yr}
\]

\[
R(\text{in}) = (70\% \times \text{effective precipitation} \times \text{forest area}) + (5\% \times \text{effective precipitation} \times \text{low built-up area}) = (70\% \times 0.226 \times (0.90 \times 10^6)) + (5\% \times 0.226 \times (0.26 \times 10^6)) = 145318 \text{ m}^3/\text{yr} = 4.61 \text{l/s}.
\]

4.2.3. Boundary Conditions

In Figure 25, the groundwater surface is seen as derived from the IDW function. The groundwater levels are retrieved from the observation wells for the date 3rd of June 2015, before the drilling began.
4.3. Model

In order to model the groundwater flow, a smaller area of the watershed was chosen (Fig. 26), estimated 0.3027 km$^2$. The landuses of the modelling area are: forest 0.0440 km$^2$; high built-up 0.2462 km$^2$; and construction area 0.0126 km$^2$ (Fig. 27).
The recharge was calculated again for the new area in order to serve as an input to the model. The basis was, again, that the forest infiltrates 70\% of the effective precipitation and the construction (or low-built up) area infiltrates 5\% of the effective precipitation. According to this, the recharge is:

\[ R(\text{in}) = (70\% \times \text{effective precipitation} \times \text{forest area}) + (5\% \times \text{effective precipitation} \times \text{construction area}) = (70\% \times 0.226 \times (0.0440 \times 10^6)) + (5\% \times 0.226 \times (0.0126 \times 10^6)) = 7093.562 \text{m}^3/\text{yr} = 0.2249 \text{l/s}. \]

The groundwater levels were fixed in a graph in order to represent the flow from north to south of the modelling area (Fig.28). The values of groundwater surface are the ones observed on the 4\textsuperscript{th} of April 2017.

The boundary conditions were approximated based on the IDW function. The groundwater levels that were taken as input to the function were for the 3\textsuperscript{rd} of June 2015, same as before (Fig.29).
The hydraulic properties of the three domains of the 3D model (bedrock, clay layer and fracture zone) were assigned to the different materials according to the literature values mentioned in the methodology.

As seen in Figure 30, there is a till (artificial material) layer below the clay. As mentioned above, the till and clay are approached as one individual layer in the numerical model for purposes of simplicity. Also, the width of the fracture zone is set to 20 m.
Below, in Table 4, are seen the analytical variables as used for building up the numerical model in COMSOL Multiphysics.

Table 4. Numerically expressed hydraulic properties for the model created in COMSOL Multiphysics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_inf</td>
<td>4 m/s</td>
<td>Infiltration to the forest and construction areas</td>
</tr>
<tr>
<td>K_c</td>
<td>9.5 m/s</td>
<td>Hydraulic conductivity of the clay layer</td>
</tr>
<tr>
<td>K_f</td>
<td>6.2 m/s</td>
<td>Hydraulic conductivity of the fracture zone</td>
</tr>
<tr>
<td>K_r</td>
<td>6 m/s</td>
<td>Hydraulic conductivity of the rock matrix</td>
</tr>
<tr>
<td>S_c</td>
<td>1.9 m^2</td>
<td>Storativity of the clay layer</td>
</tr>
<tr>
<td>S_f</td>
<td>5 m^3</td>
<td>Storativity of the fracture zone</td>
</tr>
<tr>
<td>S_r</td>
<td>2.9 m^3</td>
<td>Storativity of the rock matrix</td>
</tr>
<tr>
<td>n_c</td>
<td>1 m^2</td>
<td>Effective porosity of the clay layer</td>
</tr>
<tr>
<td>n_f</td>
<td>1 m^3</td>
<td>Effective porosity of the fracture zone</td>
</tr>
<tr>
<td>n_r</td>
<td>5 m^6</td>
<td>Effective porosity of the rock matrix</td>
</tr>
<tr>
<td>H_north</td>
<td>24 m</td>
<td>Boundary condition in the north</td>
</tr>
<tr>
<td>H_east</td>
<td>23 m</td>
<td>Boundary condition in the east</td>
</tr>
<tr>
<td>H_west</td>
<td>29 m</td>
<td>Boundary condition in the west</td>
</tr>
<tr>
<td>H_south</td>
<td>23 m</td>
<td>Boundary condition in the south</td>
</tr>
</tbody>
</table>

After the various parameters of the model are set, the steady state is simulated (Fig. 31).

Figure 31. Steady state of the model.

As seen from the steady state, there is a variation of the hydraulic head in the area, ranging from 23 m in the south, east and north boundary, to almost around 29 m, in the western part. As noticed, the groundwater flow is towards the southern boundary.
Below (Fig. 32), the clay layer is presented at the steady state.

The mass balance was then calculated, in terms of outflow and inflow over each of the surfaces of the 3D model. The fluxes were calculated as surface integration for each of the three domains. The mass balance was estimated on the basis that mass is entering the system with the form of precipitation.

Table 5. Fluxes calculated for each of the model domains.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Boundary Surface</th>
<th>Type of Boundary</th>
<th>Length (m)</th>
<th>Flow (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil layer (clay)</td>
<td>South</td>
<td>Constant Head</td>
<td>434</td>
<td>-0.021</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>Constant Head</td>
<td>246</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>Constant Head</td>
<td>780</td>
<td>-0.056</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>Constant Head</td>
<td>461</td>
<td>-0.047</td>
</tr>
<tr>
<td>Bedrock</td>
<td>South</td>
<td>Constant Head</td>
<td>436</td>
<td>-0.424</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>Constant Head</td>
<td>743</td>
<td>0.540</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>Constant Head</td>
<td>780</td>
<td>-0.475</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>Constant Head</td>
<td>460</td>
<td>-0.434</td>
</tr>
<tr>
<td>Fracture zone</td>
<td>South</td>
<td>Constant Head</td>
<td>24</td>
<td>-0.063</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>Constant Head</td>
<td>37</td>
<td>-0.0048</td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
<td></td>
<td></td>
<td>9.69E-01</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>8.04E-03</td>
</tr>
</tbody>
</table>
Then, the drilling that took place was introduced to the model with the form of a rectangular function. The function was formulated in order to represent the start date and the end date of the drilling. The aim is to determine visually the moment that the groundwater levels are getting back to the initial values measured before the drilling. As mentioned the drilling started at 1st of December 2015 and lasted until the 23rd of February 2016, i.e. 84 days.

The result of pumping, concerning the clay layer is shown below. The figures represent different times: the first day of pumping (Fig.33a); the last day of pumping (after 84 days of continuous pumping at 10000l/h) (Fig.33b); the first day after the pumping has stop (85th day) (Fig.33c); the 211th day (Fig.33d); the 520th day (Fig.33e); and the 4875th day (Fig.33f).
Figure 33. Different moments in time while and after pumping.
However, the effect of the pumping at the bottom of the pumping well can be seen in Figure 34. It must be noted that the pumping is through the bedrock and not the clay layer.

![Figure 34. The effect of pumping in the bedrock. (a) represents the first day of pumping and (b) the last day.](image)

The drawdown was then calculated for different spots on the clay (Fig.35) in order to define the subsidence in the soil layer (Fig.36).

![Figure 35. Different spots on the clay layer used to estimate the drawdown.](image)
The transient state was calibrated by comparing the modelled drawdown to observed drawdown from observation wells (Fig. 37 & Fig. 38). The drawdown is compared from the beginning of the drilling (23/2/2015) until the end of the available measured data (25/4/2017).

Figure 36. Drawdown in the soil layer based on the results of the 3D model.

Figure 37. Calibration of the transient state by comparing the modelled drawdown to the according observed drawdown. Comparison of D4 to the observation well R07VK11U.
It is shown from the model that, given the specific hydraulic conductivities and storativities of the different domains and fracture properties, there is a recovery of the groundwater levels in the clay layer after the pumping stops (Fig.39). With the term recovery is meant the groundwater to reach the initial levels as before the pumping.
For further analysis of the model, different scenarios are simulated in order to define the effect of the width of the fracture zone to the rate of recovery of the groundwater levels.

- **Scenario 1**: Fracture zone width greater than the initial, i.e. 30 m.

In Figure 40 are presented different moments of the transient state, with the width of the fracture zone being at 30 m.

![Figure 40](image)

Figure 40. Different times of the simulation with fracture zone width 30 m. (a) on the last day of pumping, 84th day; (b) on the 211th day.

The recovery of the groundwater levels after the pumping has stopped for the first scenario is shown in Figure 41.

![Figure 41](image)

Figure 41. Recovery of groundwater levels for the different spots on the clay layer, for fracture zone width 30 m.
- **Scenario 2**: Fracture zone width lesser than the initial, i.e. 10 m.

In Figure 42 are presented different moments of the transient state, with the width of the fracture zone being at 10 m.

![Figure 42. Different times of the simulation with fracture zone width 10 m. (a) on the last day of pumping, 84th day; (b) on the 211th day.](image)

The recovery of the groundwater levels after the pumping has stopped for the second scenario is shown in Figure 43.

![Figure 43. Recovery of groundwater levels for the different spots on the clay layer, for fracture zone width 10 m.](image)
5. Discussion

By relating the results from the Modified Double Mass statistical analysis, five wells were found to have the same trend. These five wells are 08F535RU; 12A731RU; 12S502RU, 6244B185; and 08W539. For these wells, the significant drop on the groundwater levels is observed on the 4th of December 2015. At this specific moment a drilling project took place in the area, where 61 boreholes were drilled in order to extract geothermal energy for heating purposes. The drilling lasted from 1st of December 2015 until 23rd of February 2016. Concerning the recovery of the groundwater levels, according to the Modified Double Mass, only the wells 6244B185 and 12A731RU appear to have a slight one, while the rest three of the wells show no clear evidence of recovery. It must be noted that the degree of effect on the reference wells is a factor of uncertainty on the results of the Modified Double Mass analysis.

According to the official report of the geothermal drilling company between the time interval of 23rd December 2015 and 3rd February 2016, 44 wells were drilled, a lot of which with high capacity. On the 4th and 5th of February 2016, two wells were drilled with medium capacity around 5000l/h. This coincides in time with a drop of 0.79m for the well 08F535RU, a drop of 1m for the well 12A731RU, and a drop of 1.1m for the well 6244B185. Also, between the 8th and the 16th of February 2016, nine wells were drilled, two of which with low capacity (500l/h), and seven wells with high capacity (1000-5000l/h). This can be related with a drop of 1.1m for the well 12A731RU. Between the interval 17th and 23rd of February, five more wells are drilled, one of which with very high capacity (10000l/h). Again it can be related with a further drop on the groundwater levels of 1.17m for the well 12A731RU.

It should be mentioned that for the wells mentioned above, the correlation coefficient ranges between 0.27 and 0.66, meaning that there is correlation from low to average. The high value of a correlation coefficient indicates a smaller value of standard error. In this case, the poor correlation for some of the wells can be a matter of small-in-length available timeseries of groundwater levels. Furthermore, for the above results of the Modified Double Mass, the timeseries of the wells are mostly in a monthly basis and they become more intense only after the initial drop is noticed. This can exclude details and further changes for intervals less than a month.

Concerning the model as well as the different scenarios on the width of the fracture zone the results appear to be quite interesting.

For the main case of fracture zone width at 20m and pumping of 10000l/h, the calibration of the transient state showed differences from reality. The wells, that were located in the model and then were compared to observation wells in reality, represented different distances from the spot of pumping. The well namely D6, which is located on the fracture zone but closer to the southern boundary, remains unaffected during the pumping. The same behavior is noticed for the well D2. This behavior can be explained by the long distance between the wells and the pumping spot. Concerning the well D3, which is closer to the pumping appears to have change in the groundwater level. However, the decrease of almost 2m is not instant but is noticed only after 30 days after the pumping has started. The well D4, which is located directly upstream of the pumping shows great decrease of 10m instantly after the pumping starts. The well D5 on the downstream of pumping is less affected than the upstream, which is connected to the groundwater flow direction, with a decrease of 7m.

Comparing the results of the model with the observed values of groundwater levels there is divergence. By that is meant that for the case of D4 and R07VK11U, while the groundwater levels for both the modelled and the observed timeseries begin with the same value, the modelled one shows a drop of 10m more than the unaffected observed timeseries, while the pumping period. The lowest value is reached on the last day of pumping and the recovery starts directly after it. Since November 2016 both the timeseries follow the same trend with the modelled drawdown to divert around 0.3m less from the observed one. Comparing D5 and 08W540, the maximum difference is seen on the last day on pumping with the modelled drawdown diverts 6m from the observed. After the pumping stops the modelled timeseries follows an increasing trend and after November 2016, the difference
of the two timeseries becomes relatively constant with 2m. D4 seems to have more resemblance to the real measured conditions after the pumping, compared to D5.

The results of calibration can be explained by the fact that the timeseries that were compared are limited in time. Also, the wells that were located in the model are not in the same coordinates as the observation ones. Another important factor is the till layer that is not modelled individually while building the numerical model, but only approximated by incorporating it to the clay layer parameters. Thus, all these can affect the results of the calibration and explain some of the divergence in the groundwater levels. There is, also, clear connection between the effect and the distance from the pumping spot, since the wells in greater distance seem to be unaffected whereas the ones in closer distance are greatly influenced.

Examining the main scenario with the fracture width being at 20m, the results are:

For the point D4, which is located on the directly upstream of the pumping well, there is a drawdown of 11 m noticed on the 84th day. At the end of the simulation, after almost 14 years the groundwater levels divert from the initial values 0.05m. D5, which is located on the directly downstream of the pumping well, shows its minimum value on the 88th day with a drawdown of approximately 6.5m. On the 5000th day the values differ 0.05m from the initial groundwater levels. D3, which is located upstream of the pumping well but not on the fracture zone, shows its minimum value on the 186th day with a drawdown of 2.5m. D3 also follows a smoother curve to recovery, compared to the two points mentioned above. The groundwater values at the end of the simulation divert 0.04 from the initial ones. D2, which is higher up on the fracture zone, shows its minimum on the 250th day with a drawdown of 0.17 m. The difference from the initial values is 0.02m. D1, which is located closer to the pumping well but not on the fracture zone, gets its minimum value after 2.7 years with a drawdown of 0.4m. Finally, D6, which is located on the downstream part of the model area and still on the fracture zone, shows a drawdown of 0.17m on the 229th day, while the groundwater values at the end of the simulation divert from the initial ones 0.01m.

For the first scenario, with fracture zone width 30m, the numerical results are:

D4 shows its minimum level on the 84th day with a drawdown of 10m. The groundwater values at the end of the simulation divert from the initial ones 0.25m. D5 gets the minimum value on the 88th day with 6m drawdown. The difference between the groundwater levels in the beginning and end of simulation is 0.23m. D3 shows a drawdown of 2m on the 188th day of the simulation and the difference of the groundwater levels is 0.20m. D2 appears to have its maximum drawdown on the 301st day at 0.3m and the difference between the groundwater levels at the end of the simulation is 0.10m. D1 gets its minimum value after 3.04 years with a drawdown of 0.23m, and the values of the simulation differ 0.05m. Lastly, D6 shows the greatest drawdown on the 296th day at 0.27m. The divergence of the final groundwater levels from the initial ones is 0.04m.

For the second and last scenario, with width of fracture zone 10m, the numerical results are:

D4 has the greatest drawdown of 12m on the 84th day and the groundwater levels are fully recovered on the 2391st day or 6.5 years. D5 gets the minimum value on the 89th day with a drawdown of 6.5m, while the groundwater levels get to the initial values after 6.9 years. D3 shows the greatest drawdown on the 183rd day at 2.84m. The groundwater levels recover after 7.9 years. D2 is quite interesting since it follows an increasing trend throughout the pumping with an increase of 0.07m in the groundwater level. However the groundwater level seems to decrease after the pumping has stopped. D1 shows a drawdown of 0.24m at around 2.9 years while the groundwater level gets to the initial value after 11.7 years. Finally, D6 gets to the lowest value of groundwater level at around 2 years after with a drawdown of 0.07m. The recovery of the groundwater level is noticed after 5.5 years.

Combining all the above conclusions, for the main scenario of fracture width it can be seen that the more downstream parts of the fracture zone appear to have better recovery in time, meaning smaller deviations from the initial groundwater levels. The directly upstream of the pumping well is more affected compared to the downstream part. It appears to greater drawdown but faster recovery. The
spots that are not located on the fracture have lesser drawdown but are affected for greater amount of time. Also, these spots that are located not on the fracture but closer to it have smoother recovery. The full recovery of the modelled area in terms of groundwater levels seems to be slightly after the 5000 days (around 14 years) of the simulation with the deviations to range from 0.01m to 0.05m.

Comparing the main scenario to the one with the larger width, it is noticed that there is less recovery in the groundwater levels, meaning that there is deviation from the initial values approximately of 0.25m. However there is less drawdown from pumping in the upstream part and approximately of same magnitude in the downstream, compared to the main scenario. Again, further in distance from the pumping well, the effect of pumping is more extended in time. The full recovery of the groundwater values is expected to be long further than the 5000 days of the simulation.

Comparing the main scenario to the one with smaller width, it is seen that there is greater recovery, in terms of time. However, the drawdown that is observed is bigger than the one of the main scenario. The recovery of the groundwater levels is noticed sooner in time for the spots that are located closer to the pumping well, compared to those in further distances.

Regarding the model, as seen from the results, the topography seems to affect the visual representations. When it comes to 3D models that represent the surface and the bedrock surface, the result of the simulations is connected to the topological relationships. Also, the geometry of the fracture is another factor of uncertainty. The fracture zone in this model is presented as a linear cut in the bedrock. In reality, this is not the case and thus the results of the groundwater levels, both spatially and numerically, are prompted to divergence from the real situation. It is important to mention that the pumping rate is arbitrary set to 10000l/h, which is the maximum observed capacity of the drilling wells. Apart from that, the specific pumping rate is not constant throughout the 84 days, as taken in the model.
6. Conclusion

In conclusion, for the present thesis a 3D model was created in order to represent part of the reality as closely as possible. It must be highlighted that for the specific model various approximations and adjustments were made. Thus, there can be a divergence from reality. However, the attempt aimed to offer an understanding of the geological formations and how the different hydraulic properties affect the groundwater flow.

Groundwater is highly connected to the surface human activities. It is also important to have knowledge of the slow process that groundwater follows. Combining these two factors the results of the model are verified. Pumping from the groundwater indicates radical, and not only local, drop in the groundwater levels. If no artificial infiltration is introduced then the only recharge comes from precipitation. Thus, the recovery of groundwater levels based on the natural recharge needs time, which can prove crucial for the ground surface levels and human constructions.

It is well known that fractures in the bedrock are difficult to investigate and identify and require time consuming processes. However, the effect that the fracture properties, and in this case the width of the fracture zone, can have on the recovery of the groundwater levels is rather interesting. It is important to have knowledge of the geology as well as of the properties of each formation, in order to securely extract and use the groundwater and protect the aquifer resources.
References


Thai, G. (2010). *Predicting Subsidence Resulting from Tunnel Excavation*. Ontario, Canada: University of Waterloo.


