CHALMERS
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Dimensioning Groundwater levels

A case study of the TK Geo method

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

IDA NORDBERG

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Engineering Geology
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30
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Examensarbete ACEX30
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ABSTRACT

Dimensioning groundwater level is a term that is used within the area of geo-construction and infrastructure projects. The level is used to calculate the water pressure that an underground construction should resist. The concept of dimensioning groundwater levels is implemented in Eurocode and governing documents from the Swedish Transport Administration (Trafikverket) and it implies a similar treatment as other loads to the construction in terms of safety. Groundwater levels fluctuate resulting in difficulties deciding on a single value as a dimensioning groundwater level. It is not only the evaluation method that arise questions within the industry. It has also arisen questions of who is responsible for these assessments and how should the levels be dealt with in large infrastructure projects where the whole landscape is affected, and the hydrogeological conditions are changed fundamentally? There is no simple answer to these questions but in an attempt to contribute to the industry, this master thesis aims to perform a case study where one common evaluation method for dimensioning groundwater levels is tested and compared to a statistical analysis. The master's thesis project also includes a literature study that describes the fundamentals about groundwater level fluctuation. The literature study also gives an overview of how loads and groundwater levels are treated according to Eurocode and Swedish regulations. The tested evaluation method for dimensioning groundwater levels in the case study is the method presented by the Swedish Transport Administration in their governing document, TK Geo. The method is developed by Chester Svensson and Göran Sällfors in the 1980s and is an easy way to establish dimensioning groundwater levels for construction sites mainly. The method is notated the *TK Geo method* in this report. The TK Geo method uses measurement series from a reference well to estimate groundwater levels at a site. In this thesis project, the TK Geo method is used to estimate the dimensioning groundwater levels at two case study sites. The results are then compared to statistical analysis of measurement series from the case study sites. The results show that the TK Geo method can predict dimensioning groundwater levels with reasonable accuracy if the reference well is representative for the case study site. The case study is too limited to enable a general conclusion about the accuracy of the method, but the results indicates that there are risks associated with the hydrogeological conceptualization and that there are possible improvements to the description given in TK Geo.

Keywords: Groundwater levels, Dimensioning groundwater levels, TK Geo, Hydrogeological conceptualization, Measurement series

Dimensionerande grundvattennivåer

En fallstudie av TK Geo-metoden

Examensarbete inom masterprogrammet Infrastruktur och miljöteknik

IDA NORDBERG

Institutionen för arkitektur och samhällsbyggnadsteknik
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SAMMANFATTNING

Dimensionerande grundvattennivåer är ett vanligt förekommande begrepp inom anläggningsbranschen. Nivån används för att beräkna det tryck som en konstruktion under mark ska motstå. Konceptet med dimensionerande nivåer återfinns även i Eurocode och Trafikverkets styrande dokument och konceptet förutsätter liknande hantering av grundvatten jämfört med andra laster som en konstruktion kan utsättas för. Problemet är dock att grundvattennivåer fluktuerar och att ansätta ett dimensionerande värde är svårt. Men det är inte bara utvärderingen av dimensionerande nivåer som skapar frågetecken i branschen. Även vem som ska vara ansvarig för utredningarna och hur frågan ska hanteras i stora projekt där hela landskapet omvandlas och de hydrogeologiska förutsättningarna förändras totalt är oklart. Det finns inga enkla lösningar till dessa frågor, men i ett försök att bidra till branschen är syftet med denna masteruppsats att genomföra en fallstudie där en utvärderingsmetod för dimensionerande grundvattennivåer testas och jämförs med statistisk analys. Masteruppsatsen inkluderar också en litteraturstudie som beskriver grunderna för grundvattennivåers fluktuerande. Litteraturstudien ger också en överblick kring hur laster och grundvattennivåer behandlas i Eurocode och svenska styrande dokument. Den testade utvärderingsmetoden för dimensionerande grundvattennivåer kommer från styrande dokument från Trafikverket, kallade TK Geo. Metoden är från början utvecklad av Chester Svensson och Göran Sällfors under 1980-talet och är en simpel metod för att ansätta dimensionerande grundvattennivåer för byggplatser. Metoden kallas för *TK Geo-metoden* i denna rapport. TK Geo-metoden är en referensrörsmetod som ansätter grundvattennivåer på en specifik plats utifrån mätserier från närliggande referensrör. I detta projekt används TK Geo metoden för att uppskatta dimensionerande grundvattennivåer för två observationsplatser. Resultaten jämförs sedan med statistisk analys av mätserier från observationsplatserna. Resultaten visar att TK Geo-metoden kan ansätta dimensionerande grundvattennivåer med tillräcklig precision om referensröret är representativt för observationsplatsen. Fallstudien är dock för begränsad för att några generella slutsatser ska kunna dras, men resultatet visar på risker kopplade till den hydrogeologiska konceptualiseringen och att potential till förbättring av beskrivningen av metoden i TK Geo finns.

Nyckelord: Grundvattennivåer, dimensionerande grundvattennivåer, TK Geo, hydrogeologisk konceptualisering, mätserier

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Preface

This master's thesis is the completion of my civil engineering studies at Chalmers Technical University in Göteborg. This master's thesis would not have been possible without the interest and contribution from several people. Firstly, I want to thank Linn Ödlund Eriksson, my supervisor at Sweco in Göteborg, for the opportunity to do my master thesis at Sweco and for her genuine interest and supervision during the whole thesis project. I am very grateful for our discussions along the way and the time you have spent on this project. I also want to thank Ingvar Rehn at Sweco for his contribution to and opinions about the project. It has been an important part, especially regarding finding a suitable method.

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Finally, I want to thank everyone that have helped me staying motivated during the many weeks of working from home this incredibly special season.

Ida Nordberg, Göteborg, June 2020

1 Introduction

This master thesis covers the topic of dimensioning groundwater levels and the assessment of these within the framework of infrastructure projects. The thesis project consists of a literature study and a case study. The literature study explains the basic hydrogeological concepts that affects groundwater levels and the background to assessment of dimensioning levels within infrastructure projects. The case study focuses on testing and evaluation of one Swedish method for assessment of dimensioning groundwater levels.

1.1 Background

Hydrogeological issues associated with infrastructure projects has become an increasing part of the everyday work for hydrogeologists. The need for hydrogeological knowledge and understanding in infrastructure projects has increased together with the establishment of environmental legislation, increased awareness of the subject, harder competition between opposing interests, and increased complexity of the projects. This has led to more involvement of hydrogeologists in these projects. As a result, hydrogeologists, consultants, and experts from other disciplines such as geo-construction and geotechnics must collaborate to a greater extent than before since knowledge regarding groundwater level fluctuations has become more important for the design of geo-constructions. Groundwater has of course been managed in infrastructure projects even before hydrogeologists were involved to a greater extend, and it exists methods and instructions for hydrogeological issues in e.g. Eurocode 7 (Svensk Standard, 2009a, 2009b) and governing documents from the Swedish Transport Administration (Trafikverket) (Trafikverket, 2016a, 2016b). The hydrogeological regulations and standards described in these references, however, are written from other perspectives than hydrogeology and it has not been written by hydrogeologists. The lack of hydrogeological perspective in the standards and governing documents may lead to that risks connected to hydrogeology are missed out or underestimated in the planning process for new constructions. Hydrogeological risks could for example be the lack of understanding of how an excavation or underground construction affects groundwater levels, and the consequences of that may be that proper actions are not taken, and thus causes damage to the surroundings (and probably additional costs for the responsible actor). Another example could be the lack of understanding of wells, i.e. what a measured level in a well represents and how measurement series should be treated. The consequences may be incorrect handling of data that leads to inaccurate assessment of governing levels, which may be used for dimensioning of constructions.

Consultants working with the design of constructions and geo-constructions need input data in the form of groundwater level assessments to be able to design resilient and safe buildings and foundations. The groundwater level used in these calculations is referred to as dimensioning groundwater level. The concept of dimensioning groundwater levels is defined by Eurocode, but different ways of evaluating the parameter exist in various governing documents and standards. It is not only the evaluation of the parameter that confuses the industry, other questions also have arisen in large infrastructure projects (Forssberg, 2020). One common question is who should assess the dimensioning groundwater level? It is the client or the contractor or someone else? This question comes from the uncertainty regarding if dimensioning

levels is a precondition or something that is “constructed” to control the project. Together with that follow the question if dimensioning levels that are based on how it looks at the site before the start of the project are relevant at all? The whole surrounding landscape may be converted and the water flow directions and volumes in the ground changes entirely for big infrastructure projects, and a dimensioning level that was assessed regarding the conditions at the site before the project started may be irrelevant.

There are many questions and uncertainties connected to the concept of dimensioning groundwater levels and the various problems arise in different projects due to the conditions at the site and the type of project. This thesis project focuses on the evaluation of one common method (the TK Geo method) for assessment of dimensioning groundwater levels and thus try to make a minor contribution to the subject within the industry.

1.2 Aim

This master’s thesis aims to evaluate the method for calculating dimensioning groundwater levels presented in TK Geo by performing and comparing case studies. The thesis also aims to examine if there are any hydrogeological risks with the method and give some recommendations to further develop it.

1.3 Limitations

The thesis project focuses on dimensioning groundwater levels in soil aquifers. Many closely related questions exist but will not be included in this thesis project. These are:

- Definition and calculation methodology for characteristic groundwater levels
- Impact of climate change on dimensioning groundwater levels
- Climate factors impact on groundwater levels in different parts of the country
- Plants or installations effect on groundwater levels or how to calculate dimensioning groundwater levels when the ongoing human activity itself changes the groundwater conditions
- Already affected groundwater conditions by e.g. drinking water production or underground constructions
- Characteristic and dimensioning groundwater levels in rock.

1.4 Research questions

To achieve the aim the following questions must be assessed:

Literature study

- What is groundwater? What is an aquifer?
- How is groundwater recharged? Hydrogeological cycle? Water balance? Recharge and discharge areas?
- Which factors affect the natural groundwater level variations?

- What is hydrogeological characterization? How is hydrogeological characterization performed?
- What are characteristic and dimensioning values? How are groundwater levels treated within construction?
- How is dimensioning groundwater level treated in Eurocode and TK Geo?
- How does the calculation method for dimensioning groundwater levels in TK Geo works?

Case Study

- How accurately does the method in TK Geo predict the dimensioning groundwater level?
- How long measurement series is needed for the observation well and the reference well used in the TK Geo method?
- To which extent concerning hydrogeological aspects does the site where the observation well and reference well is located need to be conceptualized?
- How can a reference well that suites the observation well be found (needed for the TK Geo method calculations)?
- Are there any risks connected by using the method described in TK Geo as it is?
- In which ways can the method in TK Geo be developed to increase hydrogeological accuracy and the user-friendliness?

2 Literature Study

In the European Water Framework Directive groundwater is defined as: *"Groundwater means all water which is below the surface of the ground in the saturated zone and in direct contact with the ground or subsoil"* (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy [2000] OJ L 327/1). Groundwater is used for many different purposes in society, e.g. public supply of drinking water, irrigation, industrial use, and in the mining industry (Kresic, 2007). Groundwater also has an important part in the hydrologic cycle where it contributes to movements of water between atmosphere, land, and oceans. The hydrologic cycle, see Figure 1, shows how the water moves in space and between phases; ice (solid), liquid and vapours (gas).

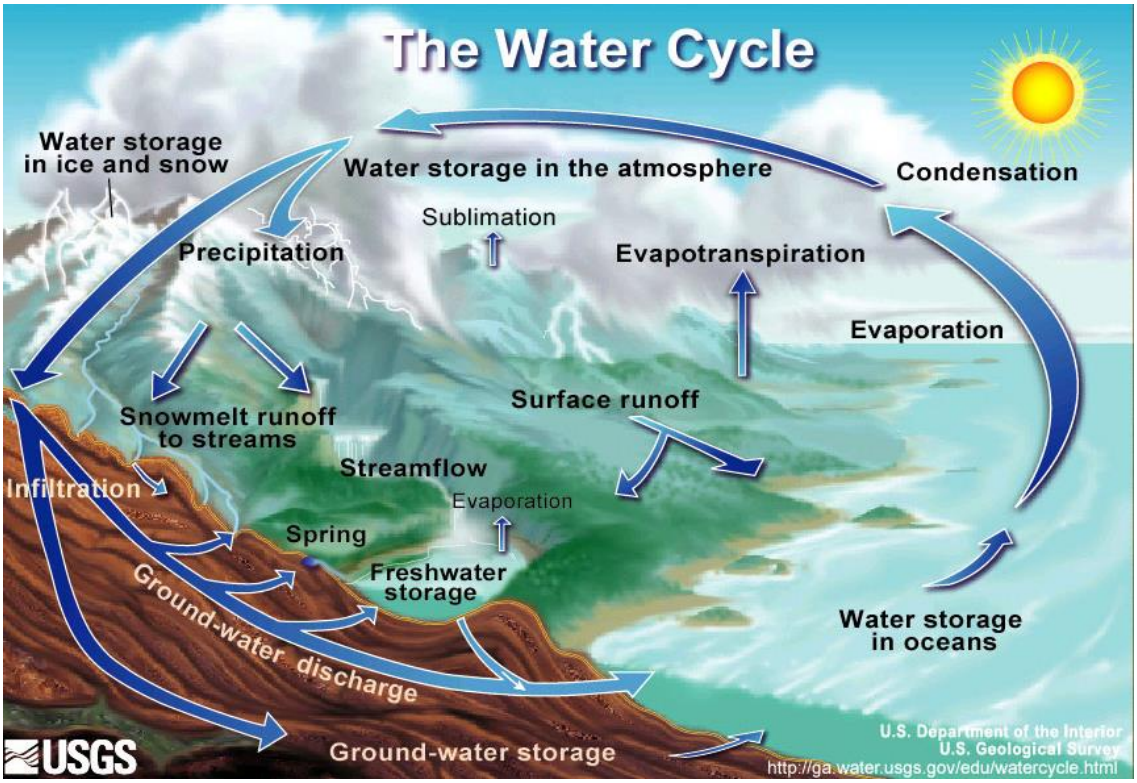

Figure 1: Hydrological cycle (U.S.G.S, 2005). *PD.*

Groundwater per definition can occur in any soil strata from very fine clay particles to coarse gravel and in bedrock fractures and pores. The different types of soil have very different hydraulic conductivity (Fetter, 2014), from as high as 0.1 m/s for well-sorted gravel to as low as 10^{-12} m/s for some clays (Carlsson & Gustafsson, 1997). The possibility to extract groundwater from the geologic formations follows in general variations in the hydraulic conductivity (low hydraulic conductivity, low extraction possibilities). A geologic formation that can store and transmit significant quantities of potable groundwater (e.g. to a well) is called an aquifer (Kresic, 2007).

2.1 Aquifers

Groundwater can occur in both soil and rock. There are two main types of aquifers; confined and unconfined. A confined aquifer is overlaid by a confining layer, a layer with very low hydraulic conductivity, and thus can the hydraulic head be above the upper boundary of the aquifer (Fetter, 2014). A confined aquifer may be an artesian aquifer if the water head is above the ground surface. An unconfined aquifer, also called a water-table aquifer, has the upper boundary at the water table where the pressure always is at the atmospheric level. An intermediate type of aquifer is leaky aquifers which is an aquifer that is over or underlaid of a layer with low hydraulic conductivity that still can transmit water to or from the aquifer (Carlsson & Gustafsson, 1997). The most common types of aquifers are shown in Figure 2. Groundwater in rock occur in fractures that form a system where water can flow (Kresic, 2007). Aquifers in rock are outside the scope of this thesis and will not be given any further considerations.

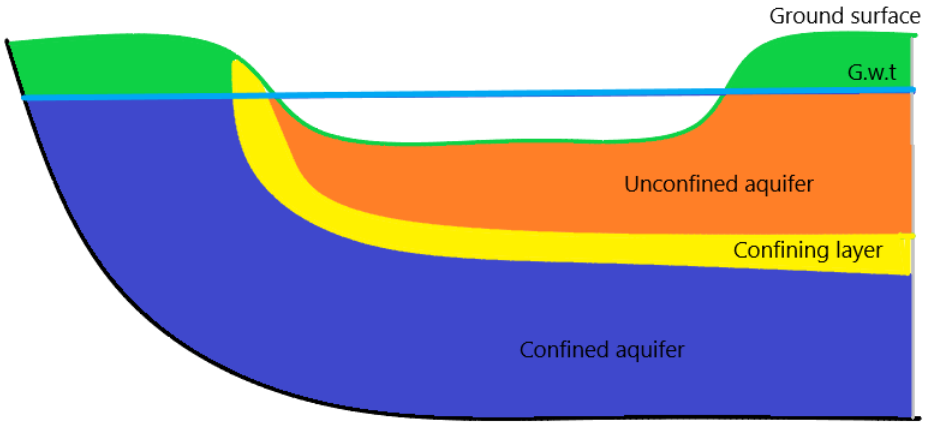

Figure 2: Different types of aquifers.

An aquifer can be divided into several features which also relates to the water flows in the aquifer (Kresic, 2007). The aquifer extent is the surface projection of the boundaries of the aquifer. For an unconfined aquifer, see example in Figure 3, the aquifer extent is simple to derive but for a confined aquifer it can be more difficult. The recharge area is the land surface where the aquifer receives water by percolation of precipitation, surface runoff, and maybe also directly from surface water bodies such as lakes and rivers. In simple cases, the aquifer extent and recharge area are the same, but for more complex situations (e.g. confined aquifers) they may be different. A confined aquifer is usually recharged at the edge where the water-bearing layer reaches the ground while an unconfined aquifer is recharged by percolation over the whole area. The recharge area for a confined aquifer can be a quite small part of the aquifer extent compared to an unconfined aquifer where the two features are represented by the same area. The drainage area is the area from which surface runoff will recharge the aquifer (if the water is not evapotranspirated). The drainage area is sometimes also called the contributing area. The water leaves the aquifer through the discharge area, such as via streams, lakes, wetlands, or oceans or via springs. The different key features of a simple unconfined aquifer can be seen in Figure 3.

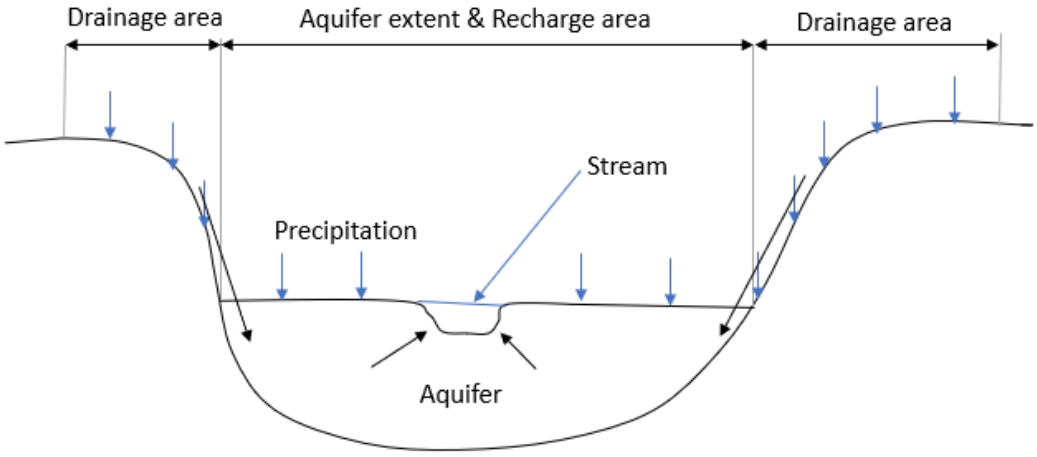

Figure 3: Key features of an unconfined aquifer.

The key features of the aquifer and the linked water flows are also important for the water balance of the system. A water balance is a summation of the water that enters and discharges a limited area during a given time (SMHI, n.d.-d). A water balance can be set up for a single aquifer or bigger systems. A water balance relates the key features (such as aquifer extent, recharge and discharge area etc.) to different flows of water that contribute to the whole system. The recharge area is the area where the water enters the aquifer and the discharge area where the water leaves the aquifer (Kresic, 2007). The drainage area answers the question where all water comes from and the aquifer extent says something about where it flows. The water balance can also be constructed as an equation, see Equation 1.

$$R = P - ET - \Delta S \quad (1)$$

Where:
R=Runoff
P=Precipitation
ET=Evapotranspiration
ΔS=Change in storage

Change in storage is the term in the equation that is directly related to the groundwater level since large storage corresponds to a high groundwater level and vice versa. The other terms are also indirectly related to the groundwater levels in an aquifer since it affects the amount of water that is available for recharge. Larger recharge leads to higher levels and the opposite leads to lower levels.
According to the equation, the change in storage (e.g. in an aquifer) can be estimated as the precipitation over the drainage area minus the evapotranspiration of water directly on the surface and through plants and the runoff (usually most as surface runoff).

2.1.1 Aquifer properties

A common method used for the evaluation of aquifers is test pumping. From test pumping results (drawdown in wells) it is possible to evaluate the transmissivity and storativity of the aquifer (Carlsson & Gustafsson, 1997). Transmissivity and storativity are the properties that are simplest to quantify for an aquifer since they are included in commonly used well-equations such as Theis and Thiems.

Transmissivity is defined as the water flow through a section of an aquifer that is one unit wide under a gradient of one (Carlsson & Gustafsson, 1997). The water's density and viscosity must be considered. Transmissivity is usually given in m^2/s. Transmissivity is linked to hydraulic conductivity. Hydraulic conductivity is a coefficient that describes at which rate water can move through a porous medium and is usually given in m/s (Fetter, 2014). Hydraulic conductivity is often seen as a material property of the granular material, even if density and viscosity of the water also must be considered. If the hydraulic conductivity is known the transmissivity can be found by multiplying the hydraulic conductivity with the saturated thickness of the aquifer.

Storativity is defined as the volume of water an aquifer takes to or releases from storage per unit surface area per unit change in head (Fetter, 2014). These changes depend on the volume change of the water and the grain orientation in a confined aquifer. The volume change in an unconfined aquifer is negligible and the storativity is equal to the specific yield. Specific yield is defined as the volume of water a saturated soil or rock will yield due to gravity drainage given as a ratio to the total volume of the soil or rock (Carlsson & Gustafsson, 1997).

Changes in transmissivity and storativity covaries, and a high transmissivity give a high storativity. Anyhow, the magnitudes of the values are different for confined and unconfined aquifers. To enable any conclusions if a specific aquifer has a high or low transmissivity or storativity the aquifer type must be known.

2.2 Groundwater recharge

Groundwater recharge is dependent on several factors but many of them are difficult to control or measure. Kresic (2007) lists some factors that affect the groundwater recharge. The first factor is the climate, thus whether the aquifer is located in a humid or arid region influences the groundwater recharge pattern and amount. In humid regions, groundwater recharge is usually dominated by precipitation infiltrating from a large drainage area and with the groundwater levels located close to the surface. Streams and lakes act as drainage areas to the aquifers and are gaining water. In arid regions, aquifer recharge is often concentrated to small areas, such as losing streams and deep water tables are common.

Recharge by infiltration is to a great extent controlled by the availability of water at land surface which is limited by climate factors such as precipitation and evapotranspiration (Kresic, 2007). The water balance equation (Equation 1) links the change in storage, which can be the change in groundwater storage for a specific aquifer, to the different climate factors, precipitation, runoff, and evapotranspiration. Precipitation is a crucial factor for groundwater recharge since larger amounts of

precipitation enable larger amounts of recharge, but not all precipitation recharges the groundwater aquifers. Part of the water is directly trapped by the vegetation and do not reach the ground; this is called interception. Some of the water runs off on the surface, in surface water bodies or groundwater streams close to the surface, and never creates deep groundwater recharge. The water that infiltrates to the unsaturated zone is either percolated further to the saturated zone and thus recharges the groundwater or is taken up by vegetation to facilitate photosynthesis. The latter process is called transpiration. Water can also evaporate directly from the ground. In the water balance equation, evaporation and transpiration is merged together to one factor and is then called evapotranspiration. The evapotranspiration is dependent on the climate (e.g. temperature and soil moisture) and it is important to distinguish between actual and potential evapotranspiration. Actual evapotranspiration is the evapotranspiration that occurs under the given climate conditions and potential evapotranspiration is the one that would occur in the given climate if the soil moisture were unlimited (Fetter, 2014). If the actual evapotranspiration is higher than the precipitation during a period, it leads to limited groundwater recharge and vice versa if the precipitation is higher than the actual evapotranspiration.

The second factor that Kresic (2007) lists are land-cover and land use. The infiltration of water into the ground is dependent on the land crusts permeability. Land covered with vegetation has usually higher permeability than bare soil since pores in bare soil more often becomes sealed due to accumulation of fine particles and thus, does not allow for infiltration. The land-use also effects infiltration of water, and urban and developed areas have, in general, lower infiltration rates than rural areas due to the high degree of more or less impermeable surfaces (such as asphalt).

The third factor that influences groundwater recharge according to Kresic (2007) is porosity and permeability of soil cover. This factor includes the transmission rate of water through the soil layers above the water table (the unsaturated zone), while the second factor only counts for the soil's crust. The fourth factor is the geologic and geomorphologic characteristics. This factor counts for bedrock characteristics which may have an important role for infiltration if the soil cover is thin or absent. For example, fractured bedrock will allow more infiltration than unfractured crystalline bedrock and steep slopes will increase the surface run-off and thus decrease the infiltration.

The fifth and last factor that Kresic (2007) list as a factor that influences groundwater recharge is depth to water table. In arid regions with deep water tables, the infiltration will end long before the wetting front reaches the water table. The water may then be evapotranspirated or stored in the unsaturated zone instead of recharging the groundwater. In general, increased thickness of the unsaturated zone leads to decreased groundwater recharge (Fetter, 2014).

The groundwater recharge is also affected by seasonal variations and when the precipitation falls during the year (Fetter, 2014). The groundwater is not recharged when the evapotranspiration is equal to or exceeds the amount of precipitation or when no precipitation falls at all. The evapotranspiration is high during the vegetational season and that also coincides with less precipitation in many temperate areas. In areas where the precipitation falls as snow during the winter, most of the groundwater recharge occurs during the snow melting (SGU, 2017a).

2.2.1 Swedish conditions

The ground infiltration capacity is in general high, and therefore the groundwater recharge in Sweden is mostly dependent on other climate factors such as precipitation and evapotranspiration (SGU, 2017a). A rough estimation, that is valid for many locations is that the groundwater recharge can be calculated as the precipitation minus the evapotranspiration. This difference is also called the effective precipitation. Even if precipitation and evapotranspiration are the crucial factors for groundwater recharge in Sweden, the geology and land use also affect the infiltration capacity of the soil.

The climate varies throughout Sweden, and this has a large effect on when and to what extent groundwater recharge occurs in the different parts of the country (SGU, 2017a). In large parts of Sweden, the precipitation falls as snow during the winter and the groundwater recharge appears when the snow melts. This creates a peak in groundwater recharge during the spring for the northern parts of Sweden and the level then decreases during the vegetational period (summer). The recharge increases in general in all parts of the country in the autumn due to more precipitation, but it is more significant in the southern parts. During the winter, the groundwater recharge is nearly zero in the northern parts (as the precipitation is stored as snow) but some groundwater recharge occurs in the southern part of the country.

The amount of precipitation in Sweden is largest in the southwestern parts of the country and less on the east coast (SGU, 2017a). In the mountains, the precipitation varies a lot locally due to the topography with mountains and valleys. A lot of the precipitation falls during summer and autumn, but it varies between different parts of the country and the differences between the years are also significant. If the precipitation falls during the vegetational period (summer months, the length varies along the country) most of the water evapotranspirates and the recharge becomes practically zero.

2.3 Groundwater level variation

Groundwater levels in aquifers vary with seasons during the year but also between years (SGU, 2017a). The level increases during periods when the groundwater is recharged and falls when no precipitation occurs or when the evapotranspiration exceeds the precipitation (Fetter, 2014) as described in the sections above. The groundwater variation is not only dependent on recharge and discharge, it is also depending on the storage capacity in the actual aquifer (SGU, 2017a). The storage capacity is the amount of water that the geological formation can hold. The storage capacity is depending on the effective porosity (the connected pores that allow transmission of water). A geologic formation with high effective porosity has a high storage capacity since the void space that can be filled with water is large, and accordingly a geologic formation with low effective porosity has low storage capacity. The higher the effective porosity is the faster water can be transmitted in the pores (higher transmissivity and also storativity) but it also requires a larger volume of water to fill up the voids, consequently the material has a larger storage capacity (Svensson, 1984).

An unconfined aquifer with high storage capacity is less sensitive to periods with low or no recharge while unconfined aquifers with low storage capacity can have rapid level change when the recharge decreases or increases (SGU, 2017a). An unconfined aquifer with high storage capacity (large effective porosity) needs a large volume of waters to increase the groundwater level in the whole aquifer, and thus have smaller natural variations than an unconfined aquifer with low storage capacity (Svensson, 1984). In an unconfined aquifer with low storage capacity, the effective porosity rapidly gets filled with water after a precipitation event and the level rises, while during a dry period, the groundwater levels quickly gets lower. An unconfined aquifer with low storage capacity accordingly has larger fluctuations in groundwater levels during a year. A confined aquifer is characterised by the pressure level (that may be above the upper boundary of the water bearing material) and the volume of water that is needed to change the pressure level is not the same amount of water that is needed to rise the water table in an unconfined aquifer.

Within a watershed, higher locations in the terrain (recharge areas) in general shows larger groundwater variations than lower located areas (Svensson, 1984). Higher located areas often show a fast reaction to precipitation and dry periods, and sometimes wells in such locations become dry during long periods without precipitation.

The groundwater level is not only a subject for natural variation, it can also be affected by human activities such as extraction for drinking water production or for industrial activities or change due to leaking underground constructions. The effects caused by human activities may be much greater than natural variations in some aquifers.

The Geological Survey of Sweden (Sveriges geologiska undersökning, SGU) is the responsible authority for groundwater related issues in Sweden including measurements and assessments of levels. When SGU presents their assessments of the groundwater situation in Sweden they distinguish between small and large aquifers (SGU, n.d.-b). SGU defines small aquifers as all aquifers that has an area of 5 km^2 or less and accordingly, large aquifers are all aquifers that has an area that is larger than 5 km^2 (SGU, 2017b). Small aquifers react usually fast to changes in precipitation due to their limited storage capacity (SGU, 2017a). Changes can often be noticed as soon as just a couple of days after precipitation. In addition, aquifers with low storage capacity react rapidly to changes in precipitation even if the aquifers may have a big areal spreading. Such aquifers can be found in till and crystalline bedrock (materials with low effective porosity and thus a quick response to infiltration of surface water).

Large aquifers react slowly to changes in precipitation. It can take weeks or months before a change can be observed (due to the large volume of water that is needed to fill the voids in the aquifer and thus raise the water level) (SGU, 2017a). Large aquifers are found in large sand and gravel formations such as eskers and deltas. A large aquifer is not as sensitive for shorter periods with less groundwater recharge as small aquifers, but if the recharge is limited over several years it may have a significant effect. If the groundwater levels decrease in a large aquifer it takes long time before it reaches its normal levels again. Large aquifers are important raw water sources for municipal drinking water production.

2.4 Hydrogeological conceptualization

Hydrogeological conceptualization of an aquifer is a way to describe the properties and interactions between surface- and groundwater bodies (Fulton et al., 2005). One way to describe the characteristics of an aquifer is to create a conceptual model of the system. The conceptual model should include all necessary information that is needed to understand the system, its connections to extern events and the problem considered, but not include unnecessary information. A conceptual model may contain information about climate parameters (e.g. precipitation, evapotranspiration), geology, topography, land use, hydrogeologic characteristics (e.g. groundwater recharge, flow directions) and water-quality parameters, but it depends on the purpose with the model and information available.

Which information that is relevant to include in a conceptual model depends on the local conditions at the site and the purpose with the model. Stejmar Eklund (2002) describes which factors to include in a model of a site with focus on Swedish conditions. According to Stejmar Eklund, a hydrogeologic environment can be described by two systems, a hydrogeologic system, and a parameter system. The hydrogeologic system should include information about the bedrock, soil, location of the site relative to the highest shoreline, stratigraphy, hydrology, and land use. If the site is located above or below the highest shoreline gives information about possible stratigraphic units underlaying the surface crust. Geological formations formed below the highest shoreline can include both glacial and postglacial clay layers and other postglacial sediments such as wave-washed sands and peat above the till and glaciofluvial sediments. Stratigraphic formed above the highest shoreline includes no clay layers above the layers with till and glaciofluvial sediments, but may be overlaid with peat or different types of sorted sediments such as wind sediments, see Figure 4. These two main stratigraphic are valid for most of Sweden, but the thickness of the layers can vary a lot, and all layers may not be represented at all sites.

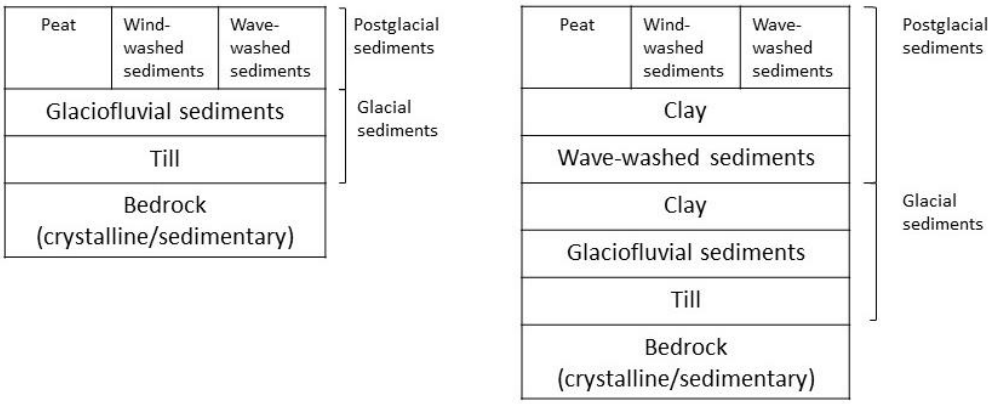

Figure 4: Main stratigraphy's in Sweden, above highest shoreline to the left and below highest shoreline to the right.

The parameter system should include data about groundwater recharge, groundwater level, hydraulic conductivity, porosity, storage capacity, field capacity, and the hydraulic gradient (Stejmar Eklund, 2002).

In some situations, a characterization of the environment around a specific well may be of interest. When characterizing a specific well, all factors that describe the whole system mentioned in the paragraphs above are of interest. Beside these facts, information about where in the aquifer the specific well and well screen is situated also are of interest since the water level in the well represents the pressure level at the well-screen location. Especially, information regarding which aquifer type (confined or unconfined) the well is situated in and if the well is in a recharge or discharge area is important.

2.5 Standards affecting geo-construction

It is crucial to have a proper foundation when building infrastructure such as roads, railways, bridges, tunnels, or pipes. The foundations should resist both the loads from the structure itself and loads associated with activities. The strength of a foundations is always dependent on the soil underneath and the geotechnical conditions at the site. The design of infrastructure constructions is affected by various standards and rules e.g. Eurocode. Eurocode is a European wide regulation and consists of 10 standards that cover topics related to structural design and civil engineering (Svensk Standard, 2010). The first part, only called Eurocode (SS-EN 1990), sets the basics for structural design and defines terms used in all parts. Geotechnical design is more in-depth examined in Eurocode 7 (part 1 and 2). In addition to Eurocode, The Swedish Transport Administration (Trafikverket) have their governing documents that are mandatory in every project purchased by them (Trafikverket, 2016a). For geotechnical constructions, the governing document is TK Geo (Trafikverkets tekniska krav för geokonstruktioner). In the first chapter of TK Geo, the Swedish Transport Administration state that dimensioning of geotechnical structures should be done according to Eurocode 7, but their document adds some complementary rules to follow for Swedish conditions. Together with TK Geo, the Swedish Transport Administration has issued TR Geo (Trafikverkets tekniska råd för geokonstruktioner) that adds advice to the requirements stated in TK Geo (Trafikverket, 2016b).

Eurocode requires that a structure should be designed and performed in such a way that it resists all likely actions (loads) during its intended lifetime with satisfying reliability and that it remains fit for its intended use (Svensk Standard, 2010). The design of structures according to Eurocode is based on the limit state principle, and Eurocode defines two different limit states. Firstly, the Ultimate Limit State (ULS), that is defined as a limit state that concerns the safety of people and the structure. Secondly, Serviceability Limit State (SLS), which is a limit state that concerns the functionality of the structure, comfort of people, and appearance of the construction work. Eurocode requires that the design is verified so that any relevant limit state not is exceeded during the lifetime of the structure and in any specified design situation.

Eurocode defines design situations as conditions in which the structure can be during different moments of its lifetime (Bond & Harris, 2008). In Eurocode, four different design situations are described (Svensk Standard, 2010). The four design situations are; persistent design situations (where the structure is during normal use), transient design situations (temporary conditions), accidental design situations, and seismic design situations. All design situations are connected to different actions (load situations) and every design situation that is relevant to the circumstances under which the structure must fulfil its function should be included in the verification.

In Eurocode, actions are defined as all forces that act on the structure, in other words, all loads the structure needs to resist (Svensk Standard, 2010). Further, a geotechnical action in Eurocode is defined as an action to the structure caused by soil, fill, or groundwater. How to evaluate a geotechnical load is determined by Eurocode 7.

In Eurocode 7, several examples of what to include as actions are given and one of them is groundwater pressure (Svensk Standard, 2009a). However, later in the same chapter it is stated that groundwater levels are treated as geometrical data. So, it is a differentiation in the standards between the handling of groundwater pressure as a force (load) to the structure and groundwater levels used as a nominal input parameter. However, the two parameters are dependent on each other since the magnitude of the groundwater pressure to a structure is determined by the location of the groundwater level. Groundwater pressure is also treated as a load in TK Geo (Trafikverket, 2016a).

2.5.1 Evaluation of characteristic and dimensioning values

Suitable values of geotechnical parameters are needed for design of geo-constructions (Bond & Harris, 2008). The process of converting test results to design values is called ground characterization and is used for geotechnical parameters in Eurocode. The process is graphically shown in Figure 5.

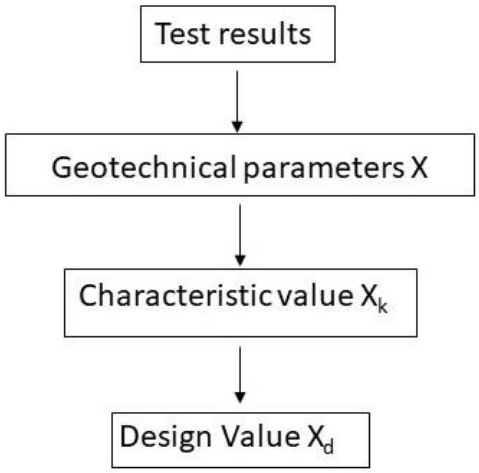

Figure 5: Ground Characterization Process.

Firstly, test results obtained from field tests or laboratory tests are used to derive different geotechnical parameters (Bond & Harris, 2008). The derivation can be done either through correlations, theories, or empirical rules. The second step in the process is to evaluate a characteristic value for the specific parameter. A characteristic value of an action is in Eurocode defined as *"principal representative value of an action"* (Svensk Standard, 2010). The evaluation of a characteristic value should be done with statistical methods as either the 5^{th} and 95^{th} fractile value depending on if a high or low value is most unfavourable. This approach works well for man-made materials such as concrete and steel that is well controlled and statistically known, but falls

short for geomaterials due to their huge variability in the properties (Bond & Harris, 2008). Therefore, an additional definition of characteristic values for geomaterials are given in Eurocode 7 as *"The characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state."* (Svensk Standard, 2009a). This principle does not say how to evaluate any specific geotechnical parameter but Bond & Harris (2008) give their interpretation of what a cautious estimate is in their book. Bond & Harris states that a cautious estimate is an *"approximate calculation/judgment that is careful to avoid problems or dangers".* Further, Bond & Harris explains the impact of Eurocodes quotation "*affecting … the limit state*" which means that the characteristic value of a geotechnical parameter is depending on the limit state, and thus exists not any value that are valid for all situations. The characteristic value of a geotechnical parameter varies depending on which limit state that is evaluated.

Eurocode also defines characteristic values for geometrical data, such as groundwater levels. Eurocode states that characteristic values of geometrical data should be measured, nominal, or estimated upper or lower levels (Svensk Standard, 2009a).

The last step in the ground characterization process is to obtain the design value. The design value is obtained by factorization of the characteristic value. Factorization is done by applying a partial factor to the characteristic value to decrease the risks in the design (Bond & Harris, 2008).

Eurocode give special considerations for design values of groundwater pressure. Eurocode states that design values for ultimate limit states shall represent the most unfavourable condition that could occur during the intended lifetime of the structure (Svensk Standard, 2009a). Furthermore, the design values for serviceability limit states should represent the most unfavourable condition that could occur during normal circumstances. Eurocode give two alternative ways to derive design values for groundwater pressure, either by apply partial factors to characteristic water pressure or adding a safety margin to the characteristic groundwater levels.

The approach with applying partial factors to groundwater pressures is debated by engineers (Bond & Harris, 2008). An argument not to apply partial factors to water pressures (or water levels) is that the quantity is relatively well known, and it is illogical to apply a safety factor to a known parameter, especially if the highest possible water level is used and it is placed at the ground surface. On the other hand, it is illogical to treat groundwater differently to other loads and it may cause problems in numerical analysis if earth pressures are factored but not groundwater. Eurocode does not give any regulations or recommendations regarding which approach to use when deriving design values for groundwater pressure. Accordingly, it is a question all engineers need to face for every single case. The choice of approach for evaluation of design values may also be dependent on how the selection of characteristic water levels are done.

2.5.2 Comments to Eurocodes approach

The partial factor approach is a method that is used for estimation of design values for all types of geotechnical parameters in Eurocode since it simply adds a safety margin (in general partial factors scale up the loads and scale down the resistance/strength

and if the resistance/strength still is larger than the loads should the construction be safe). This works well for most geo-parameters evaluated with field or laboratory test such as strength of soil or rock and for loads such as traffic loads. However, when it comes to groundwater it starts to be somewhat confusing and unclear how the evaluation should be performed. That depends on several aspects. Firstly, Eurocode write both about managing of groundwater pressures and groundwater levels and states that groundwater pressures are an example of a geotechnical load to a construction while groundwater levels are a nominal geometrical input data. This is true, but the two quantities are also depending on each other. The magnitude of the groundwater pressure to a construction is decided by the groundwater level in the surroundings. Accordingly, to enable calculation of characteristic values of groundwater pressures (that later can be factorized to design values) the groundwater level must be known.

Groundwater levels, as describe more in detail in section 2.3, are a result of natural variation and does not take one single value at all time. Groundwater levels varies according to climate (precipitation etc.), with seasons and between years. Consequently, the groundwater pressures to constructions also varies. However, when designing constructions, a decided value for these quantities are needed to enable verification if the construction resists the loads or not. To be able to find the characteristic groundwater pressure, the characteristic groundwater level has to be evaluated first.

Characteristic groundwater levels are evaluated from measurement series (more about that in the following section), since one single measurement in an observation well simply tells the status that single day and says nothing about if the level is high or low. From such groundwater measurement series, levels that corresponds to both ULS and SLS has to be evaluated (since structures, in general, must be verified for failure according to both limit states). The evaluated levels can then be used to calculate corresponding water pressures that are needed for estimation of design values (that can be done with either partial factors or by adding a safety margin).

Eurocodes procedure with first evaluate characteristic value and then recalculate it to a design value are the most common way to evaluate design values for geotechnical parameter, but dimensioning groundwater levels (i.e. design values for groundwater levels) can also be evaluated directly by using statistical methods (without first asses a characteristic value). In such cases, statistical methods that includes the concept of return times are used, and that are described more in section 2.6 and corresponding sub-sections.

The connections between groundwater levels, groundwater pressures and evaluation of corresponding characteristic and design values are not completely understandable when reading in Eurocode. The confusion depends partly on the fact that the information are given in different standards and chapters, but also on the fact that Eurocode not explicitly explain the natural connection between groundwater pressures and groundwater levels and that makes it harder to understand the standards and how it should be used. Figure 6 shows an overview of governing regulations, applicable methods for calculation of dimensioning groundwater levels and the reference/sources to the different methods. Extreme value analysis and a reference well method are described in section 2.6 and corresponding sub-sections.

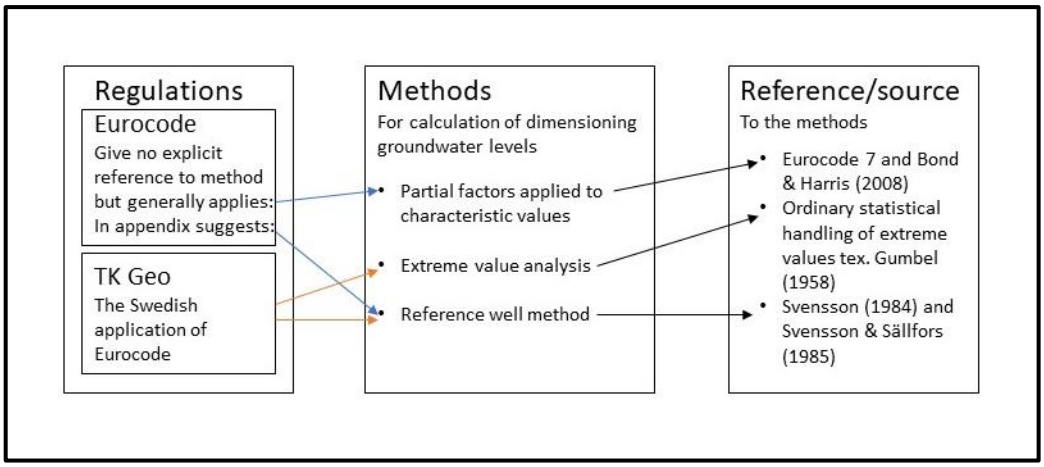

Figure 6: Overview of governing regulations, methods and references/sources.

2.6 Methods for evaluation of groundwater measurements

In the following sub-sections different approaches for evaluating groundwater measurements are described. The methods are used to estimate dimensioning values of groundwater levels needed as input to later calculations in the design process.

2.6.1 Eurocode

Eurocode states that evaluation of groundwater level measurements must consider geological and geotechnical conditions at the site, the accuracy in the measurements, changes due to time, the length of the measurement period, the season when the measurements are done and other climate factors during and before the measurement period (Svensk Standard, 2009b). Further on, the evaluated results should include the highest and lowest levels measured during the measurement period and, if possible, should both upper and lower limits for both normal and extreme conditions be derived from the measurement series (correlates to ULS and SLS as described in the comments above). Such evaluation is usually difficult to do since it requires long measurement series which is uncommon to have for infrastructure projects.

Eurocode therefore suggests in an informative appendix (compare to normative paragraphs or appendices) that a statistical method can be used to evaluate groundwater measurements instead. A statistical method can be used when only a short measurement series for the construction site is available, but a reference well with a long measurement series in the region exists (Svensk Standard, 2009b). If a short measurement series at the actual site (at least 3 months with at least 7 recorded levels) are available and a 15 years long measurement series (at least) in a reference well that is situated in a similar aquifer exists it is possible to evaluate the dimensioning water levels at the site with statistical methods. Statistical evaluation should be compared with hydrogeological information about the site and the reference site. Eurocode does not explicitly explain the methodology for such statistical methods but refers, in the informative appendix mentioned above, further to Chester Svensson's publication from 1984 regarding the analysis of groundwater observations (Svensson, 1984).

2.6.2 TK Geo

The Swedish Transport Administration states in TK Geo that dimensioning water pressure (a dimensioning value in the Swedish governing documents is the same as a design value in Eurocode) should be evaluated from the most unfavourable water level with at least 50 years return time, but if the consequences are considerable should longer return times be used (Trafikverket, 2016a). Further on the Swedish Transport Administration state that extreme value analysis on the measurement series from the construction site should be used primarily, but if the amount of measurements are limited, they suggest that a method including a reference well could be used instead (the same method as Svensson & Sällfors published already 1985, see further in chapter 2.6.3) or that the value of the dimensioning water levels can be evaluated based on the topography and hydrogeology of the area. TR Geo does not give any requirements on how long the measurement series for the well at the construction site (observation well) or the reference well needs to be if reference well method is used for evaluation of dimensioning groundwater levels. However, they state that the reference well should be located within 50 km from the construction site and in the same climate zone (Trafikverket, 2016b). If these requirements are fulfilled, Equation 2 can be used to calculate the dimensioning level with 50 years return time at the construction site, $Y_{O,max,50}$.

$$Y_{O,max,50} = Y_{O,max} + S_R^{50} * \frac{r_0}{r_R} \quad (2)$$

Where
$Y_{O,max}$ = maximum level in the observation well during the observation time
S_R^{50} = the difference between $Y_{R,max,50}$ (calculated maximum value with 50 years return time for the reference well, see chapter 2.6.5 for calculation procedure) and $Y_{R,max}$ (measured maximum level in the reference well) during the observation time
r_0 = range (maximum-minimum value) in the observation well during the observation time
r_R = range (maximum-minimum value) in the reference well during the observation time

The same equation can be used to calculate dimensioning water levels with longer return times if a lower risk for exceedance is required, by changing the value of $Y_{R,max}$ to another theoretical calculated return time for the reference well. The minimum levels can also be calculated with the same equation if the minimum level with required return time is inserted instead. This, however, is not described explicitly in TK Geo.

If Equation 2 is used the dimensioning groundwater levels (design values) are evaluated directly from the measurement series without having to first evaluate characteristic values. The safety is instead counted for when selecting return time used in the calculations.

2.6.3 Svensson & Sällfors

The equation for estimation of dimensioning groundwater levels presented in TK Geo (Equation 2) is the same as Svensson & Sällfors published 1985 in a report regarding calculations of dimensioning groundwater levels for construction sites in the Gothenburg area. The equation is similar to an equation Svensson presents in his

doctoral thesis in 1984. The difference is that Svensson only has done calculations for the existing length of measurement series from reference wells (i.e. he has not estimated levels with longer return time than the existing measurement series length, such as levels with 50 or 100 years return time), which by this time was around 13 years.

Svensson & Sällfors developed the method to enable estimation of dimensioning groundwater levels for construction sites in a simple way when only a short measurement series is available for the construction site. In the publications (Svensson, 1984; Svensson & Sällfors, 1985) more explanations are given to the factors in the equation and assumptions and theoretical background to the whole method compared to in TK Geo and TR Geo (Trafikverket, 2016a, 2016b). Svensson & Sällfors also gives a stepwise calculation procedure and show how to use the equation with an example.

The method includes some assumptions that have been verified by Svensson (1984) in his doctoral thesis. The first assumption is that the groundwater levels in aquifers, located close to each other, covary (i.e. aquifers in the same region with similar climate such as precipitation etc.). Even if the magnitude (how much the level increase or decrease due to a specific weather event) of the fluctuations varies between different aquifers, the variation tends to be analogous in time (increase and decrease simultaneously). The second assumption is that variations in groundwater levels during a short period are proportional against the total variation width for a specific aquifer. These two assumptions have been verified by Svensson (1984) by systematic test the method with several wells from three different areas in western Sweden and some longer measurement series from other places in Sweden and abroad. The result from the verification of the method shows that it can be used with desirable accuracy (±0.5 m should be reasonable accuracy for geo-constructions (Svensson, 1984)) for calculation of dimensioning groundwater levels for construction projects. The verification also shows that the method predicts dimensioning maximum levels better than minimum levels. That is probably due to the short duration of dry periods and thus a higher risk that these are not registered.

Svensson & Sällfors (1985) recommends that the groundwater level in the observation well is measured two times per month for at least three months (seven observations). The selected reference well should be located in the same climate zone as the observation well and for the Gothenburg area is that approximately within a distance of 50 km. The accuracy in the prediction will increase if the reference well and observation well have similar locations within the aquifers, such as high or low position (recharge/discharge area) (Svensson & Sällfors, 1985).

This method, where Equation 2 is used to predict the dimensioning groundwater levels, that are developed by Svensson & Sällfors, and implemented in the governing documents by the Swedish Transport Administration, and used and tested in this thesis project is further on in this report noted the *TK Geo method,* for simplicity.

Figure 7 shows an overview of key aspects and terms included in the TK Geo method and how the different wells are related to each other.

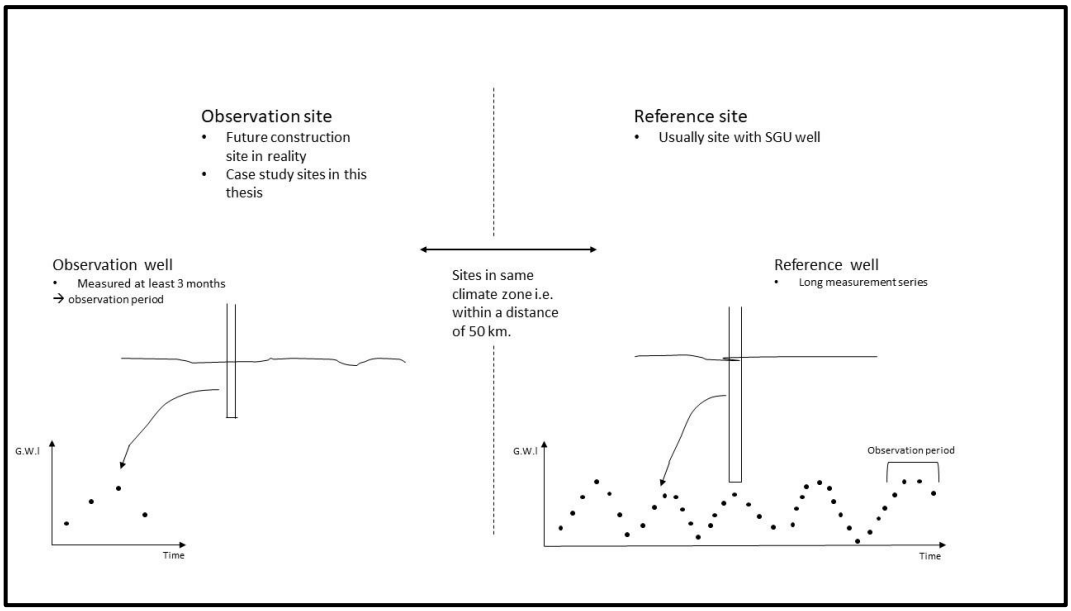

Figure 7: Overview of key aspects of the TK Geo method.

To use the equation for dimensioning groundwater levels (Equation 2) data from the selected reference well must be evaluated statistically to find the level with a certain return time. This is further explained in the coming sections.

2.6.4 Extreme value analysis

Extreme value analysis is from the beginning used to analyse extreme values and the probability of their occurrence (Gumbel, 1958). The probability of occurrence of events with severe consequences for society is important knowledge in many fields and has been for a long time. Especially for businesses that are dependent on constant (or periodical) water supply, such as agriculture, hydroelectric power production, and all types of industries that need large volumes of water for production or cooling. Water supply from surface water bodies is depending on the levels/flow in the natural body and that varies with dry and wet periods. A long dry period may decrease the flow in a river or water level in a lake significantly and thus also the amount of water that can be pumped for societal use. For a business owner it may be important to know how often the water level or flow is too low to allow pumping of water to be able to plan for reserve water or set up emergency plans. For society it is important to know the frequency of high flow or levels to plan for flooding, but also the frequency of low levels or flow in raw water bodies for drinking water production.

Extreme value analysis has been used in hydrology for a long time to estimate the probability that a specific event occurs (Gumbel, 1958). The method is commonly used to calculate flows or levels (high and low) in streams and rivers with certain return times but can also be used for precipitation to calculate the intensity e.g. a 100 years rain. Return time is a concept that describes how common a specific event is and it is used to describe how often extremes occur in nature (such as floods or droughts) (SMHI, n.d.-b). The return period is the average time between similar events (Wilson, 1990) e.g. the return time of a certain high level in a lake is 10 years. It means that this specific level will be equalled or exceeded on average once every 10 years. The probability that the same level will be equalled or exceeded this year is 10

% and the probability that the level is equalled or exceeds during a specific 10-years period is 65 % since the risk accumulates. Return time and the probability of exceedance is linked by a simple mathematic connection, see Equation 3.

$$T_r = \frac{1}{P(X \geq x)} \quad (3)$$

Where
T_r= Return time
$P(X \geq x)$= Probability of exceedance

Extreme value analysis can be done in two different ways, with series of annual maximum (or minimum) values or with exceedance series (Svensson, 1984). For annual maximum series, the maximum value each year (or hydrogeologic year) is selected. These values form a maximum series that can be adjusted to common statistical distributions and levels with longer return time than the length of the series can be calculated. In exceedance series, all values above a selected threshold value is included. This usually gives series with more data to adjust to a statistical distribution. However, groundwater levels are not independent which is one of the fundamental requirements in statistical analysis, therefore, the use of exceedance series for groundwater data is less appropriate. One way to come around this problem is to use some declustering method to ensure the independence of the values included in the series (Haaf, 2015).

The next question then becomes which distribution the extreme value series should be adjusted to? Svensson (1984) tested to adjust the extreme value series of groundwater levels to five common distributions and found that normal distribution cannot be rejected for groundwater levels. The normal distribution is also used in the calculation method for dimensioning groundwater levels by Sällfors & Svensson (1985) to find the level with a specified return time for the reference well. Haaf (2015) has tested the adjustment of groundwater level series to more distributions and found that it depends on the measurement series (i.e. the form of the maximum/minimum values distribution, such as tails etc.) which distribution that fits best. Haaf further finds that normal distribution usually cannot be rejected for most of the series (same as Svensson found), but also that generalized extreme value distribution and log Pearson type III distribution have a good fit for many series.

2.6.5 Calculation method for evaluation of return times

In the publication by Svensson & Sällfors (1985), a stepwise procedure to statistically treat the data from the reference well is described. The procedure is used to find the level with a certain return time needed in the term S_R in Equation 2.

To enable prognosis of high and low levels with long return times (usually much longer than the length of available measurement series) for the reference well is the normal distribution used (Svensson & Sällfors, 1985). Firstly, the maximum and minimum values of each year are selected, and these values form the series of annual maximum and minimum values. The method uses hydrologic years as base. The hydrologic year in southern Sweden is from 1 October to 30 September. The values in the annual maximum and minimum series are then ranked from most extreme to less extreme (highest to lowest for maximum values and reverse for minimum values) by giving the values a rank number starting from 1. The rank number is denoted *m*. For

each extreme value, the probability of exceedance is calculated with Weibull's formula, see Equation 4.

$$P = \frac{N+1-m}{N+1} \quad (4)$$

Where
N=total number of values in the extreme value series
m=rank of the value

The probability is then plotted against the maximum (or minimum) value on a normal probability paper, see Figure 8 for an example of how it looks in theory. From this graph, the levels corresponding to longer return times could be extracted (since a specific return time corresponds to a specific probability of exceedance).

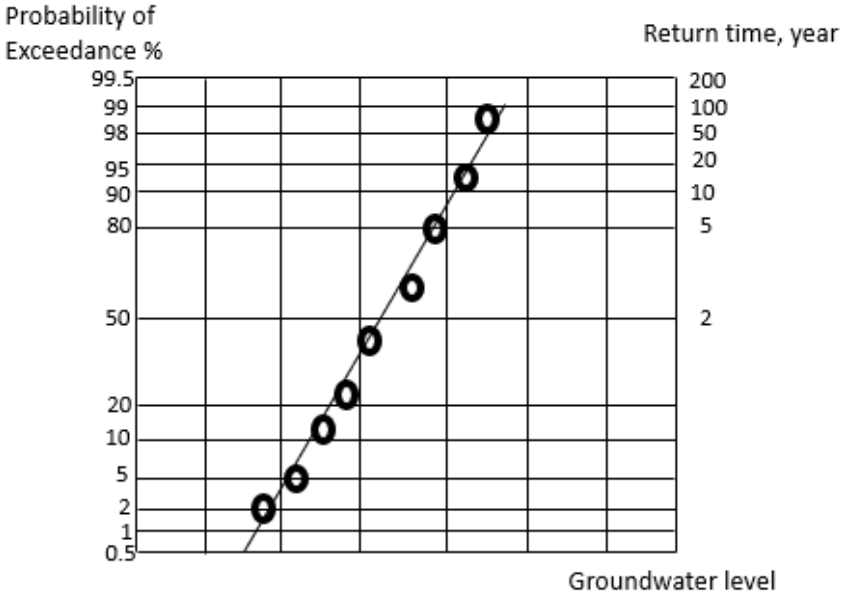

Figure 8: Theoretical plot of groundwater levels on probability paper.

The level with a certain return time can also be calculated based on the annual extreme value series with Equation 5 (Svensson & Sällfors, 1985).

$$y^{T}_{max/min} = \bar{y}_{max/min} \pm t_T s_{max/min} \quad (5)$$

Where
$y^{T}_{max/min}$ = The value of a level with the certain return time, either max or min
$\bar{y}_{max/min}$ = average of the values in the annual extreme value series
t_T = frequency factor (see Appendix I)
$s_{max/min}$ = standard deviation of the values in the annual extreme value series

The calculated level with a certain return time is then used in factor S_R to calculate the dimensioning groundwater level.

3 Method

The method is developed to answer the research questions stated for this thesis project and to fulfil the aim. The aim is to test the accuracy of the calculation method for dimensioning groundwater levels presented in TK Geo by performing a case study and investigate if there are any hydrogeological risks connected to the calculation method. Within the case study was the method tested on two different locations, one in an urban environment and one in a rural environment. The locations for the case study were mainly chosen by the ability to find sites where long measurement series of groundwater levels are available.

The method includes three different parts (see Figure 9); conceptualization of the sites, calculation of dimensioning groundwater levels according to TK Geo, and calculation of dimensioning groundwater levels with the statistical method extreme value analysis. The TK Geo method calculations were performed with three different observation period lengths to analyse if the length affects the accuracy of the results. The different parts are described more in detail in the sections below.

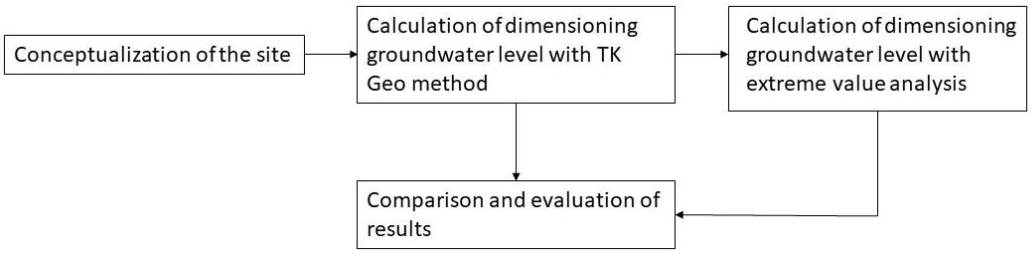

Figure 9: Overview of the method.

The results from the two calculations parts were then compared to evaluate how precise the TK Geo method estimates the dimensioning groundwater levels.

3.1 Conceptualization

The first step was to conceptualize the selected site to understand the hydrogeologic conditions at the site and the position of the well that the measurements come from. The conceptualization was done by gather available information about the site from different sources, see Figure 10 for sources used in different parts. How detailed the conceptualization can be done depends on the information available for the specific site and that varies for the sites used in the case study. In section 2.4 in the literature study, hydrogeological characterization is described in general and factors that are important to include in Swedish settings according to Stejmar Eklund (2002) are listed. Information about all properties in the hydrogeological and parameter systems may not be possible to find for all sites included in the case study. The focus in the conceptualization of the sites were on general information about geology, hydrogeology, hydrology, and land use.

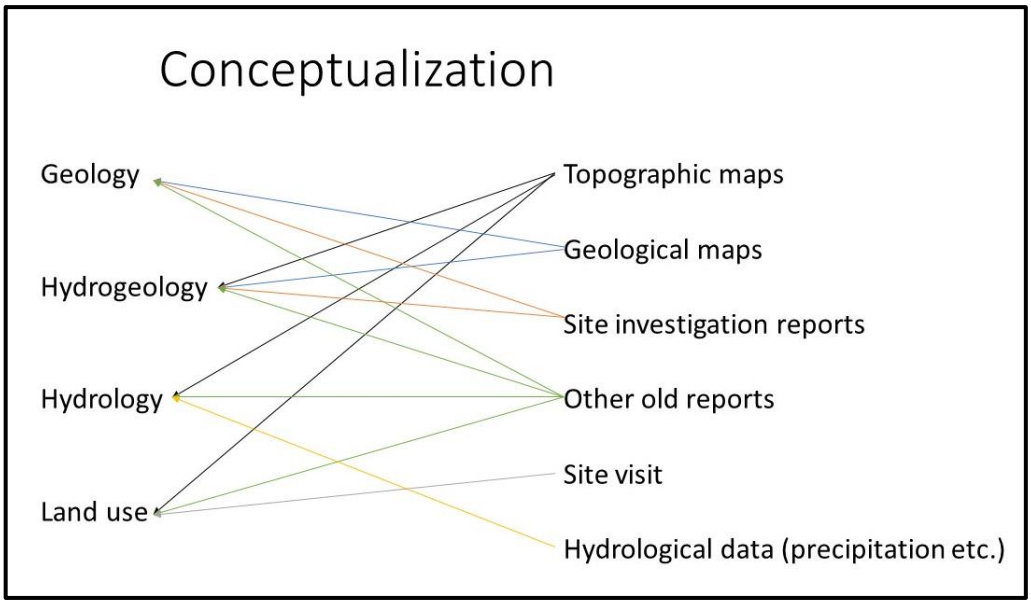

Figure 10: Information sources used for the conceptualization of sites.

The conceptualization was performed as a desk study where information about geology, hydrogeology, hydrology, and land use was gathered. The first step was to look at maps, both topographic and geological maps. Topographic maps were used to get an understanding of the location of the site compared to the surroundings and get knowledge about land use. Geological maps were used to get information about soil and water in the ground. The different types of geological maps used for characterization of the geology at the sites were quaternary deposits, soil depth, and rock type. Maps that show the spreading and extraction possibilities of groundwater in aquifers were used to characterize the hydrogeology of the site. Used maps come from The Swedish National Survey (Lantmäteriet) for the topographic map and the Swedish Geological Survey (Sveriges Geologiska Undersökning, SGU) for geological maps.

The well archive (Brunnsarkivet) was used to search for drilled wells in the surroundings. The well archive provided by SGU is an archive for all drilled wells in Sweden, both wells drilled for drinking water supply and wells for energy production (SGU, n.d.-a). Information from drillings in the surroundings to the case study site was used in the characterization of the geology of the sites.

Lastly, a map that shows surface water basins were used. The map is provided by The Swedish Meteorological and Hydrological Institute (Sveriges meterologiska och hyderologiska institut, SMHI). From such a map it is possible to find surface water dividers and see the size of the water basin that the case study site is located in. Surface water dividers follow the topography in the landscape and also groundwater levels in fine soils tend to follow the topography while groundwater levels in coarser material (material with higher hydraulic conductivity) tend to follow the bedrock topography instead (Bovin, 2011).

The second part of the conceptualization was to look at reported results and findings from historical site investigation and other types of old reports regarding the site. This was done to increase the level of details in the conceptualization and get more site-

specific information. Sources used for this part varies due to performed investigation at the site and availability of reports. Examples of site investigation that can give valuable information are drillings (e.g. for wells) and geotechnical soundings (e.g. CPT sounding). Protocols from this type of investigation can give information about soil types in different layers, the thickness of layers, depth to bedrock, and hydraulic properties of the layers. Important hydrogeological parameters are hydraulic conductivity and storativity. These were determined by using data from historical site investigations or if no such data was available were numbers from the literature for the soil types present at the site used instead.

3.2 TK Geo method

The second part of the case study was to estimate the dimensioning groundwater level with the TK Geo method. The calculations were done with the equation presented in TK Geo (Equation 2, see literature study section 2.6.2). The processing of data was done according to the description of the method by Svensson & Sällfors, (1985), see literature study section 2.6.3., 2.6.4, and 2.6.5.

Three different lengths of observation periods were used in the calculations to fulfil the aim of this thesis and test the ability of the method presented in TK Geo to predict the dimensioning groundwater levels. The tested observation periods were 3, 6, and 12 months. In real construction projects, the observation period is the time when the observation well has been measured, but in this thesis project can the period seen as the observation period be chosen by other criteria. The frequency of the performed measurements in the wells located at the sites used in the case study has varied a lot during the years. Some years it is only 2-3 recorded levels and some years have automatic pressure loggers been installed that register the level several times per day (depending on the installation of the logger).

For the reference and observation well, the observation period is used to find the range of the groundwater levels (maximum-minimum value during observation period). For the reference well, the observation period also is used to find how the levels during this short period relate to the level with a certain return time (Svensson & Sällfors, 1985). To enable that these estimations become as good as possible, the measurements from both wells should in the very best case be performed on the same day. This is not always obtainable in reality and a difference of a few days may be ok and will not affect the results significantly. If the number of days between the measurement occasion is longer can linear interpolation between available measurement points be used to estimate the level a certain day. This thesis project, where the whole measurement series are available from the beginning, has the advantage to choose which period to use as observation period and has thus select periods with enough resolution of data. If some single level measurement was missed during a used period was linear interpolation used.

The method requires the use of a reference well located in the same climate zone. Svensson & Sällfors (1985) states that in the Gothenburg area should that correspond to a distance no longer than 50 km between the observation well and the reference well. Svensson & Sällfors states further that the reliability of the prognosis increases if the wells have similar locations within their aquifers. Important features to know about the well location are if the well is situated in a confined or unconfined aquifer

and if the well is placed in a recharge or discharge area of the aquifer. The placing of the observation well was interpreted by looking at maps; both topographic and geological to find where the bedrock outcrops, where the soil is permeable and where not, and how the landscape look (heights and valleys).

Wells from SGU was used as reference wells and SGU usually provide some information about the well, such as type of aquifer (confined/unconfined), recharge or discharge area, and the depth of the well. Such information is useful in the selection of a representative reference well.

3.2.1 Selection of reference well

SGU has three different areas with recorded groundwater wells around Gothenburg, see Figure 11. The wells in these areas have been measured since the early seventies (SGU, n.d.-f). The used reference wells were selected from the wells in these three areas.

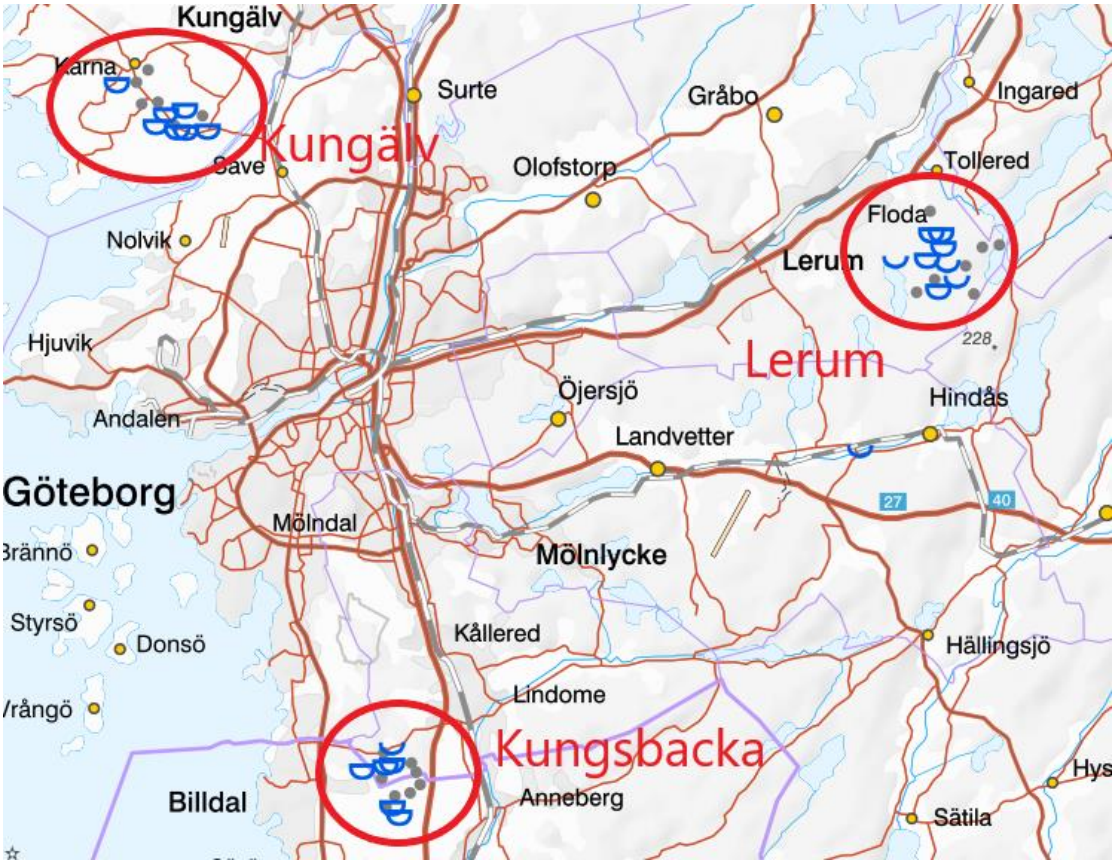

Figure 11: SGU:s Groundwater wells in the Gothenburg area (SGU, n.d.-f). © *Sveriges Geologiska Undersökning.*

The area north of Gothenburg located south-west of Kungälv has area number 53 (SGU, n.d.-f). The area constitutes only of wells in confined aquifers. The area east of Gothenburg located east of Lerum has area number 54. The area includes three well in unconfined aquifers and five in confined aquifers. The area south of Gothenburg located north of Kungsbacka in Sandsjöbacka nature reserve has area number 52. The

area includes one well in an unconfined aquifer and the rest are placed in confined aquafers. All three areas are rural. SGU measures in general manually two times per month in all these wells, but in some wells are automatically pressure loggers installed that measure several times per day. The measurement interval may have varied in different wells during the years.

To find a reference well that is unaffected by unforeseen events and to the greatest possible extent only varies naturally was all the measurements series from all SGU wells in Kungälv, Lerum and Kungsbacka plotted and inspected visually to search for inaccuracy. The visual inspection was done primarily to find out if the wells were affected by human activities in the surroundings. If some well shows clear signs of being affected or any other strange behaviour was that well deselected for the case study. The next step was to find a well that is representative for the specific case study sites. This was done by comparing the characteristics of the SGU wells to the observation wells and a similar was chosen. The comparison was carried out by listing the main characteristics in a table and then was a representative one selected. The well characteristics included in the comparison are listed in Table 1.

Table 1: Well characteristics included in the selection of reference well.

Well characteristics
Aquifer type (confined or unconfined)
Well placing in the aquifer (recharge/discharge)
Soil type at the surface (Geological map showing Quaternary deposits)
Soil type at the filter

To further analyse the representativeness of the selected reference well was the measured levels during the observation period from both the reference and observation wells plotted and the trends were analysed. If both wells covary (increase or decrease in level roughly at the same time etc) was the chosen reference well considered representative for the observation site. If not, another well was selected instead. This imply that optimal (or as optimal as possible) conditions for the case study. In real cases it may be more difficult to find a suitable reference well, and less covariance must be accepted to enable any calculations at all.

The analysis in this thesis project was done based on calendar years and not the hydrological year. The effects of that are examined further in the discussion sections in this report.

3.3 Extreme value analysis

Extreme value analysis was carried out and the results were compared to the results obtained with the TK Geo method. The whole measurement series from the observation well was used for the extreme value analysis. The calculations were done in the same way as the statistical treatment of the reference well. See the literature study section 2.6.5. The extreme value analysis based on long measurement series is considered to give dimensioning levels as close to the “true values” as possible. If the TK Geo method give dimensioning levels close to the results obtained with the extreme value analysis it is considered as a good result/fit.

4 Results

In this chapter, the results from the case study are presented and discussed briefly, a more detailed discussion about risks and further development of the method follows in the next chapter.

The results for each case study area are presented in a separate sub-chapter (4.1-4.2). Firstly, the site is described conceptually and then the results of the calculations of dimensioning groundwater level with the TK Geo method and extreme value analysis are presented.

4.1 Lorensberg

The first case study site is Lorensberg. In the following sections, the conceptualization of the site (section 4.1.1 to 4.1.4) and the results of the calculations (section 4.1.5 to 4.1.6) are presented.

4.1.1 Land use

The case study site Lorensberg is located in the central parts of Gothenburg. The well used as observation well is placed in a park area called Himlabacken, west of Götaplatsen, see Figure 12. The park is surrounded by streets, parking lots, and buildings, thus a lot of impermeable surfaces.

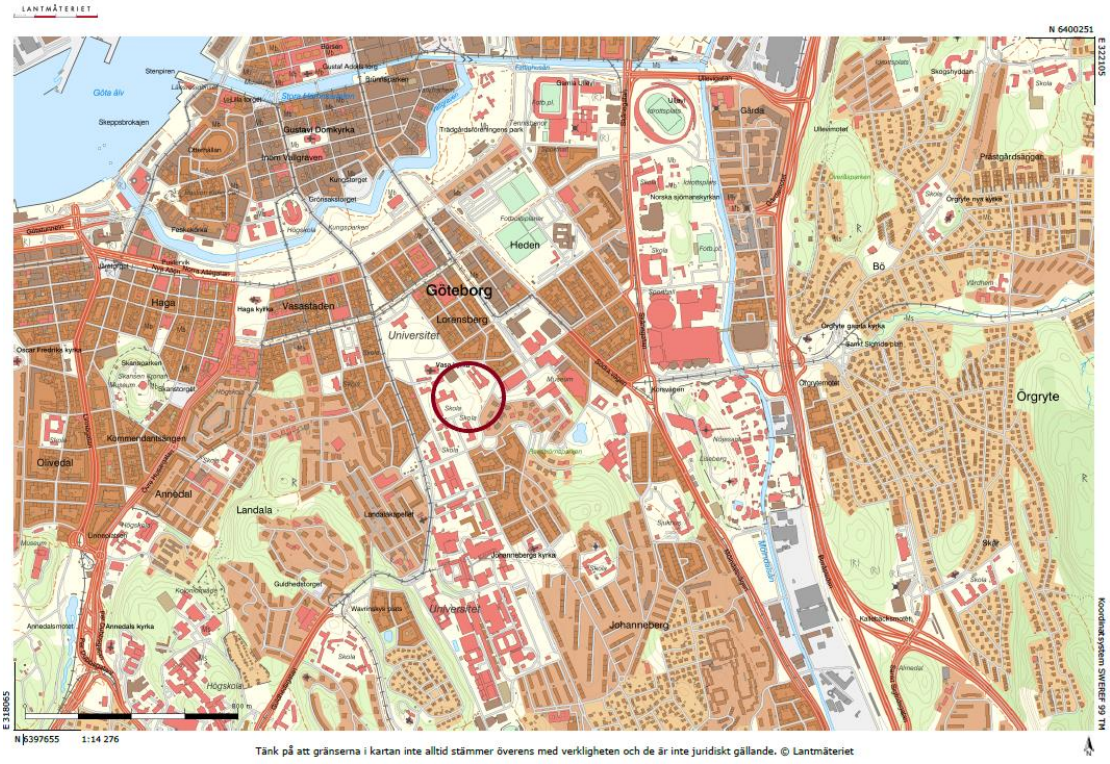

Figure 12: Topographic map of the central parts of Gothenburg with the case study location marked with a red circle. © Lantmäteriet.

The well used as observation well for this site is a wells from the city's groundwater control program. The well is notated GW485 and has been measured since June 1974. The measurement interval has varied during this period.

4.1.2 Geology

The soil close to the ground surface around the observation well is postglacial silt (SGU, n.d.-g), see the clip from the geological map showing quaternary deposits in Figure 13.

Figure 13: Map of Quaternary deposits with the location of observation well (star) and area for site investigations (ellipse) marked (SGU, n.d.-g). *© Sveriges Geologiska Undersökning.*

West of the well, the bedrock outcrops and forms a local height. Viktor Rydbergsgatan (south of the well) follows a depress filled with postglacial sand, and east of the depression, the bedrock outcrops and forms another height. North-east of the case study area, the postglacial silt changes to postglacial clay that the whole inner city is built on (SGU, n.d.-g). South from the site (outside the small clip of the map in Figure 13), at higher terrain level, consists the ground of glacial clay. The case study site is placed at the boundary between the glacial and postglacial clay areas.

The whole Gothenburg area has been below the highest shoreline (Andréasson, 2015), which affects the expected soil stratigraphy. The wave-washed gravel is sorted by waves at the edge of a sea or a lake before the land raised above the sea level. The postglacial silt and clay are sediments settled after the drawback of the ice. Both silt and clay consist of very small particles that deposit in calm water. Postglacial sediments are usually underlaid by glacial sediments, such as glacial clay. In general, the glacial sediment is underlaid by layers of glaciofluvial sediments or till. These layers vary in spreading and in thickness from only some single meter to tens of meters. A layer of glaciofluvial sediments or till forms in this situation a confined aquifer that is recharged where the material reaches the surface, often next to bedrock

outcrops, or if the layer is in contact with another water-bearing layer such as postglacial sorted sand or gravel.

A site investigation has been done for other reasons approximately 50 meters south-east of well location (see Figure 13), in the grass-covered area next to Viktor Rydbergsgatan. The historical site investigation includes both geotechnical sounding with CPT (cone penetration test) and hydrogeological testing performed in installed wells (Sweco Civil AB, 2019; Sweco Environment AB, 2018). The hydrogeological testing includes slug-test and sieve-analysis on disturbed soil samples. The interpretation of the CPT-sounding shows varied soil stratigraphy with several layers of sand, silt, and clay. The layers closer to the ground seems to be more permeable (consists of more sand and silt) while the deeper layers seem to be less permeable (consists of more silt and clay). The depth to bedrock in this part is between 4 and 7 meters and the bedrock is overlaid by a till layer with a thickness of 0.5-1 meter. A well was installed within the investigation area with the filter in the till layer, and the hydraulic conductivity of this layer was evaluated with slug-test in the well. The evaluation of the slug-test gave a transmissivity of the till layer in the magnitude $1*10^{-6}$ and a storativity of 0.025. Sieve- and sedimentation analysis was performed on soil samples from around 2.5 meters depth. The hydraulic conductivity was evaluated to be in the magnitude of 10^{-9} to 10^{-8} m/s, which corresponds to fine silt and clay (Carlsson & Gustafsson, 1997). The conclusion from the findings by the site investigation are that the stratigraphy at the site is complex and not follow the expected stratigraphy due to location below the highest shoreline.

The soil depth in the area around the well is about 4.5 meters according to the soil depth map from SGU (SGU, n.d.-h). The map shows an increase in soil depth east from the case study site (in areas with clay cover), and no soil at all in the area where the bedrock outcrops.

The geological maps showing bedrock implies that the bedrock in the area consists of metamorphic Granitoid from the Sveconorwegian orogen (1.6-1.5 Ga) (SGU, n.d.-c, n.d.-d). The maps do not show any deformation zones (fractures in a deformation zone may be connected to the soil aquifer and can affect the groundwater levels) in the close surroundings to the case study area.

4.1.3 Hydrogeology

According to the map with groundwater aquifers from SGU, it is a confined aquifer under the clay in the central parts of Gothenburg (SGU, n.d.-e). The edge of this aquifer is relatively close located to the case study site. The aquifer has an extraction potential of 1-5 l/s, see Figure 14. The water in the aquifers flows from the edges towards the middle parts. The case study area is likely a recharge area to this big confined aquifer under the clay. The extend of the local aquifer around the well is more difficult to evaluate from maps like these.

The surface water runoff from the area is towards Göta Älv (SMHI, n.d.-e), and the groundwater usually flows in the same direction as surface water, so the groundwater discharge is probably towards the Göta Älv.

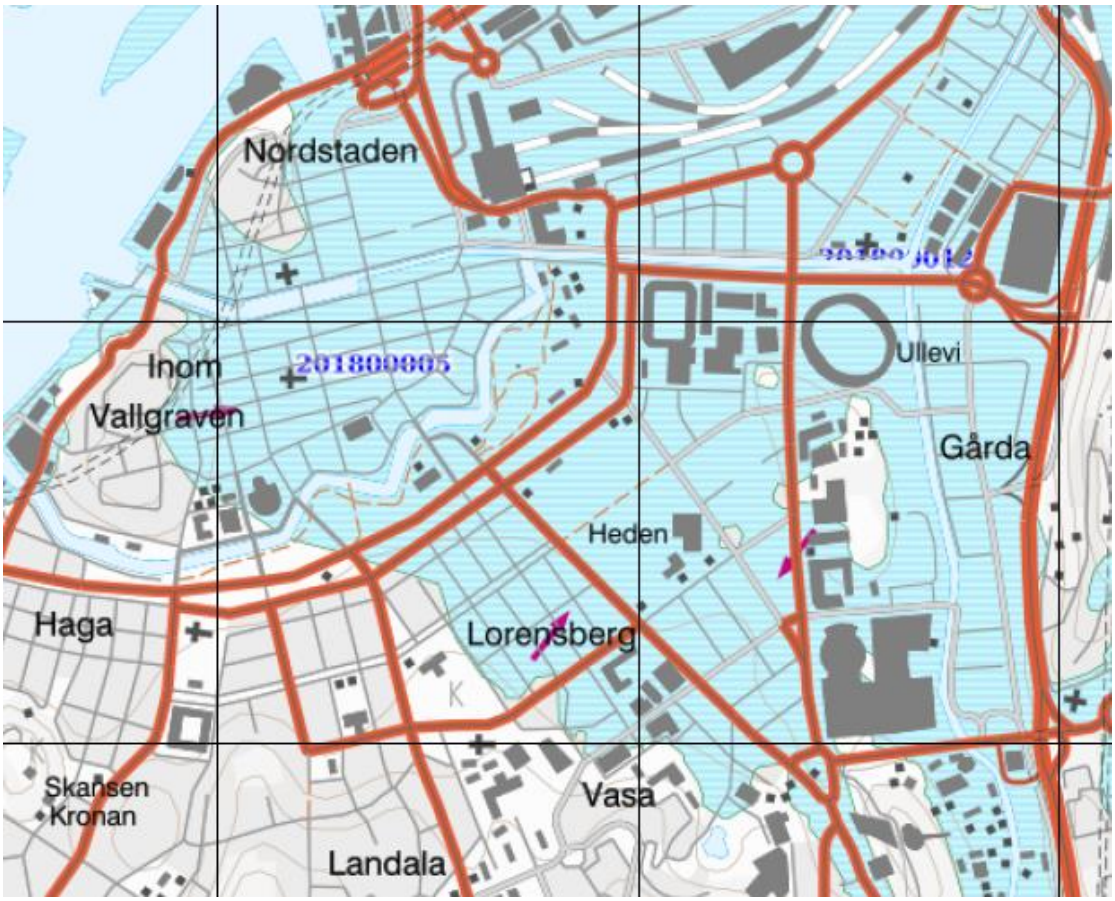

Figure 14: Soil aquifers in central Gothenburg (SGU, n.d.-e). *© Sveriges Geologiska Undersökning.*

4.1.4 Hydrology

The case study site in Lorensberg is in an urban environment and that affects the water movements in the area e.g. by more surface runoff and less groundwater recharge. The actual well is placed in a small park area called Himlabacken. The park's surface is covered with grass and some trees and shrubs. The near surroundings to the well may allow infiltration of water to the ground, but the park is surrounded by streets, buildings, and impermeable surfaces (e.g. parking lots paved with asphalt). The hardened covers create surface runoff that may be received by the stormwater system, runoff to surface water bodies, or infiltrate to the ground if it reaches areas where it is possible. The ground surface falls from higher elevation south-west of the park area (Kapellplatsen/Läraregatan) towards lower elevation north-east of the park area (Götaplatsen/Avenyn). It implies that surface runoff from the higher elevation south-east of the park area may end up within the park.

The total amount of precipitation during a year in Gothenburg is around 800 mm (SMHI, n.d.-c) and the evapotranspiration is about half (400 mm) (SMHI, n.d.-a).

4.1.5 Observation well and reference well characteristics

Dimensioning groundwater levels are calculated with the equation from TK Geo as described in the method chapter earlier in the report, see section 3.2. To enable the calculations, a representative reference well for the case study site is needed.
As observation well for the case study site Lorensberg, a well from the city's groundwater program is used (Göteborgs Stad, n.d.). The well is notated GW485. Well GW485 is located in a recharge area to the large confined aquifer under the clay in the central parts of Gothenburg, but the location of the well within the local aquifer is more difficult to define. The complex stratigraphy in the area makes it hard to interpret how water infiltrates and flows in the ground. The well filter is placed in the lower aquifer (Göteborgs Stad, n.d.). The well is 4.64 meters deep and that depth corresponds to the soil depth at the site given at the soil map by SGU. This means that it is reasonable to assume that the filter is placed in the till layer according to the site investigation performed in the area. If the aquifer in the till is confined or unconfined is more difficult to evaluate. The area has a very complex soil stratigraphy and the till is overlaid by both permeable and less permeable layers. If the water can infiltrate directly to the till depends mainly on the horizontal spreading of the impermeable layers and thus if the water can find a way down. In this case, may the local aquifer be something between a confined and unconfined aquifer.

As reference well, wells from SGU's groundwater program are used. The data within SGU's groundwater program is openly available at their website (SGU, n.d.-f) (and also at other websites that collect geodata from several authorities) and is free to use under the creative commence license CC-BY 4.0. For this site, well SGU 52_2, which is placed in Sandssjöbacka nature reserve south of Gothenburg, is used (SGU, n.d.-f). The well is selected since its characteristics are similar to the observation well (see Table 2) and it fulfils the requirements in TK Geo (within 50 km).

Table 2: Characteristics of observation and reference well.

Characteristics	**Observation well, GW485**	**Reference well, SGU 52-2**
Aquifer type	Confined/Unconfined	Unconfined
Well placing in the aquifer	Recharge	Recharge
Soil type at the surface	Postglacial sand	Glacial clay
Soil type at the filter	Till	Till

The observation well, as described earlier, is placed in an aquifer that is hard to classify as either confined or unconfined. The surface material (postglacial sand) allows water to infiltrate (thus unconfined) but the many different soil types with lower permeability in the stratigraphy above the till layer may affect the amount of water that reaches the aquifer in the till. The reference well (SGU 52_2) is classified as unconfined by SGU (SGU, n.d.-f), but classified as confined by Svensson & Sällfors, (1985). The soil type at the surface is glacial clay according to the geological map showing quaternary deposits (SGU, n.d.-g) and that indicated thus confined conditions. Therefore, may also this well be placed in something between confined and unconfined conditions.

To further confirm that the selected reference well is suitable for the case study site is the groundwater levels during the six months long observation period plotted for both wells to see that the levels covary, see Figure 15 and Figure 16.

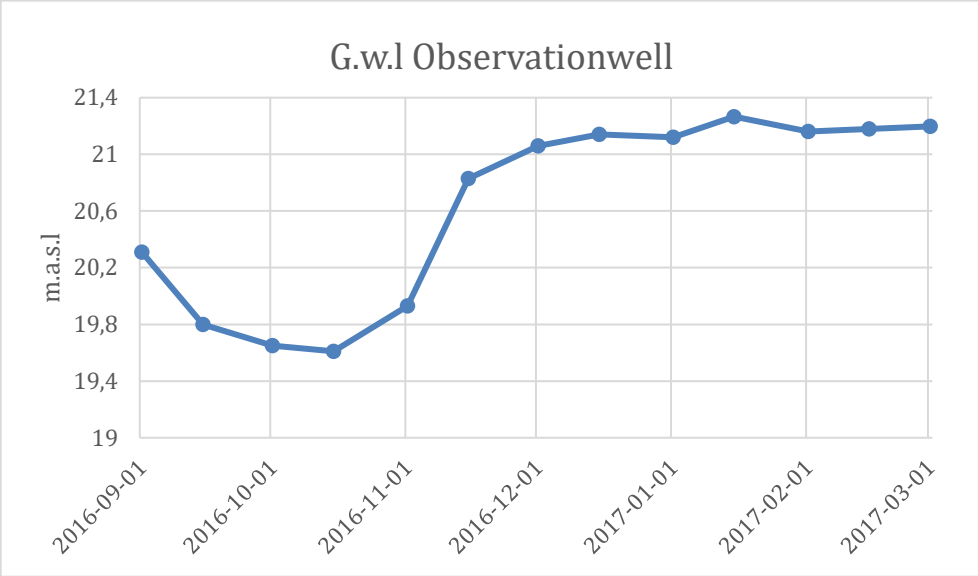

Figure 15: Groundwater levels in the observation well for six months observation period.

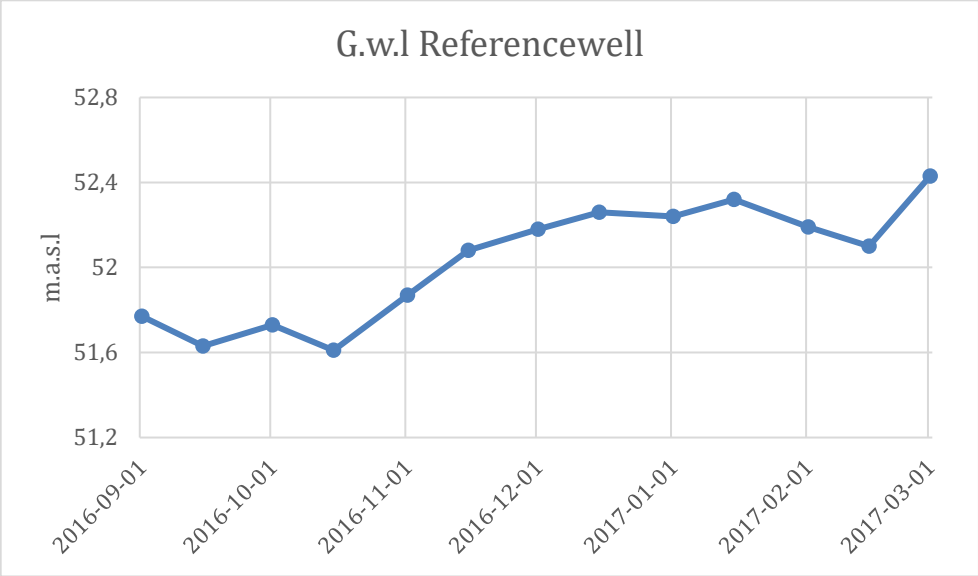

Figure 16: Groundwater levels in the reference well for six months observation period.

As can be seen in Figure 15 and Figure 16 covaries the levels in the two wells to a high degree. Only some small differences could be seen by visual inspection, so this reference well seem to be representative of the case study site.

4.1.6 Dimensioning groundwater levels

The results from the calculations of dimensioning groundwater levels (both maximum and minimum levels) according to the TK Geo method and with extreme value analysis are presented in Table 3 and Table 4. For this case study site, only dimensioning levels with 3- and 6-months observation period is calculated since the period with high-resolution data is too short to allow calculation with 12 months observation period. For the 3 months observation period, data from September 1, 2016, to December 1, 2016, are used and for 6 months observation period, data from September 1, 2016, to March 1, 2017, are used. This period is simply selected as the observation period since high-resolution data are available for the observation well. The high-resolution data are measured with automatic pressure loggers. For the calculation of dimensioning groundwater levels, measurements twice a month are needed (in total 7 recorded levels for three months' observation period) and that is selected from the logged data by sort out the first value of the day for the 1st and 15th of every month. Even for the reference well, the first measured value from the 1st and 15th of every month are selected to be included in the observation period series. For calculation of dimensioning levels with long return times, required in the term S_r in Equation 2, the whole available measurement series is used.

Table 3: Dimensioning groundwater levels, maximum levels, according to the TK Geo method (with 3- and 6-months observation period) and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	3 months observation period	Diff [m]	6 months observation period	Diff [m]	Extreme value analysis
50 years	22.46 m.a.s.l	+ 0.57	21.87 m.a.s.l	- 0.02	21.89 m.a.s.l
100 years	22.54 m.a.s.l	+ 0.56	21.94 m.a.s.l	- 0.04	21.98 m.a.s.l
200 years	22.62 m.a.s.l	+ 0.55	22.00 m.a.s.l	- 0.07	22.07 m.a.s.l

Table 4: Dimensioning groundwater levels, minimum levels, according to the TK Geo method (with 3- and 6-months observation period) and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	3 months observation period	Diff [m]	6 months observation period	Diff [m]	Extreme value analysis
50 years	18.27 m.a.s.l	- 0.69	18.55 m.a.s.l	- 0.41	18.96 m.a.s.l
100 years	18.12 m.a.s.l	- 0.68	18.43 m.a.s.l	- 0.37	18.80 m.a.s.l
200 years	17.98 m.a.s.l	- 0.68	18.31 m.a.s.l	- 0.35	18.66 m.a.s.l

As can be seen in Table 3 gives 6 months observation period lower dimensioning maximum levels (less extreme levels) for all return periods, compared to 3 months observation period. The differences between the calculated dimensioning levels with 3 months observation period and extreme value analysis are between 0.5-0.6 meter. Different return times but same length of observation period does not give any notable changes in difference when comparing to extreme value analysis. The difference

between TK Geo method with 6 months observation period and extreme value analysis are much less, only a few centimetres. The results from the extreme value analysis show somewhat higher values than 6 months observation period, but much lower than 3 months observation period.

Table 4 gives the dimensioning minimum groundwater levels for the same calculation options. Even here seems a shorter observation period to give more extreme (in this case lower levels) dimensioning levels. The difference between 3 months observation period and extreme value analysis are somewhat bigger compared to maximum levels. The difference is nearly 0.7 meter for all three tested return times. With 6 months observation periods decreases the difference to around 0.4 meter. The difference compared to maximum levels is that the levels from 6 months observation period and extreme value analysis do not end up that close.

The whole measurement series from the reference well (SGU 52_2) and observation well (GW485) are also plotted against probability (as described in the literature study section 2.6.5) to see how well the levels adjust to a normal distribution. The results show that both minimum and maximum levels for the reference well adjusts well to the normal distribution (see Appendix II for figures) and thus should the calculated levels with different return times used in the term S_r in Equation 2 be representative since the calculation procedure is based on the assumption that the data is normally distributed. Even the minimum and maximum levels for the observation well shows a relatively good adjustment to normal distribution. That implies that the levels calculated with extreme value analysis should be representative, at least regarding the factor adjustment to statistical distribution.

4.2 Brudaremossen

The second case study site is Brudaremossen. In the following sections, the conceptualization of the site (section 4.2.1 to 4.2.4) and the results of the calculations (section 4.2.5 to 4.2.6) are presented.

4.2.1 Land use

The case study area Brudaremossen is located east of central Gothenburg at the edge of Delsjöarnas nature reserve, see Figure 17. The environment is rural. The area is used for recreational activities like strolling and biking etc. There are two lakes in the close surrounding. The lake Härlanda Tjärn is a popular place for swimming in the summer and the lake Svarttjärn is an important habitat for birds.

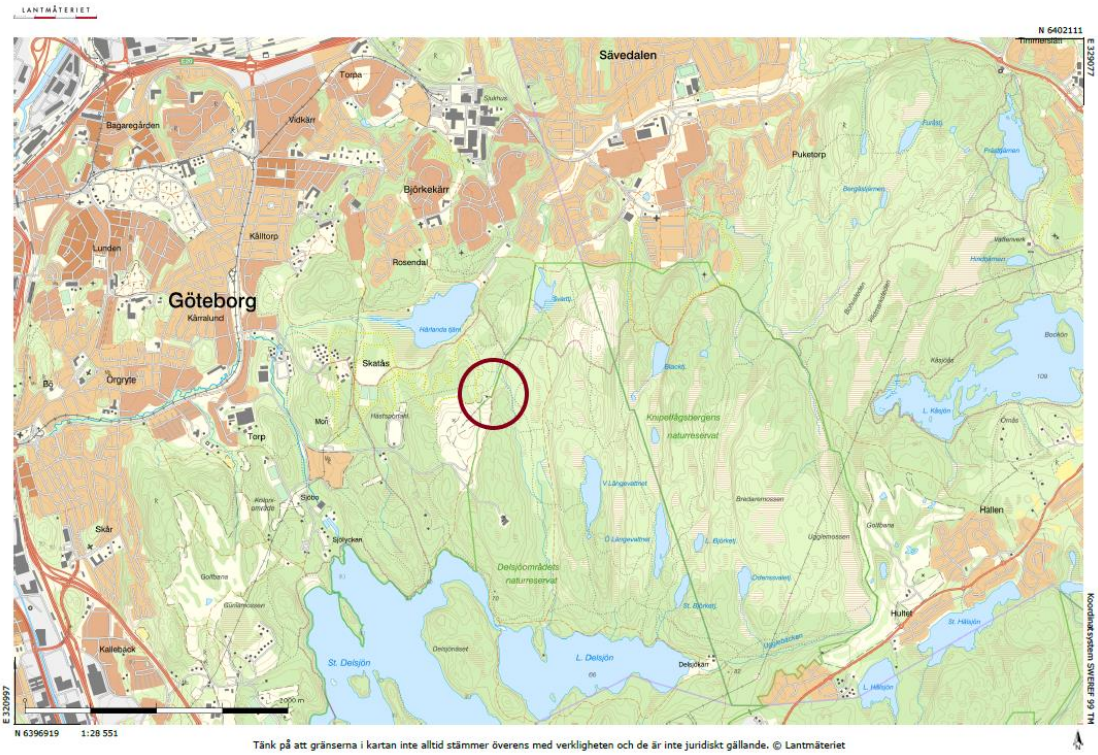

Figure 17: Case study location Brudaremossen marked with a circle. © Lantmäteriet.

Brudaremossen is an old landfill placed on peat and bedrock outcrops. The landfill was used from 1938 to 1978 (Nielsen, 2007). For this case study site, two different wells are used as observation well, see more explanation in section 4.2.5. One of the wells (noted G13) used was installed as a part of Nielsen's thesis project year 2007 and was later included in the environmental control program regarding the effects of the landfill to the surroundings. The second well used in the case study is an older well (noted G5) installed in the late 1980s. Both wells used in the case study are situated in the valley north of the landfill. The used wells are situated outside the actual landfill area and are assumed to have natural groundwater variation.

4.2.2 Geology

The wells are placed in a depression north of the landfill area between two local heights. The material around the wells is postglacial sand according to the geological map of quaternary deposits from SGU (SGU, n.d.-g), see the clip in Figure 18.

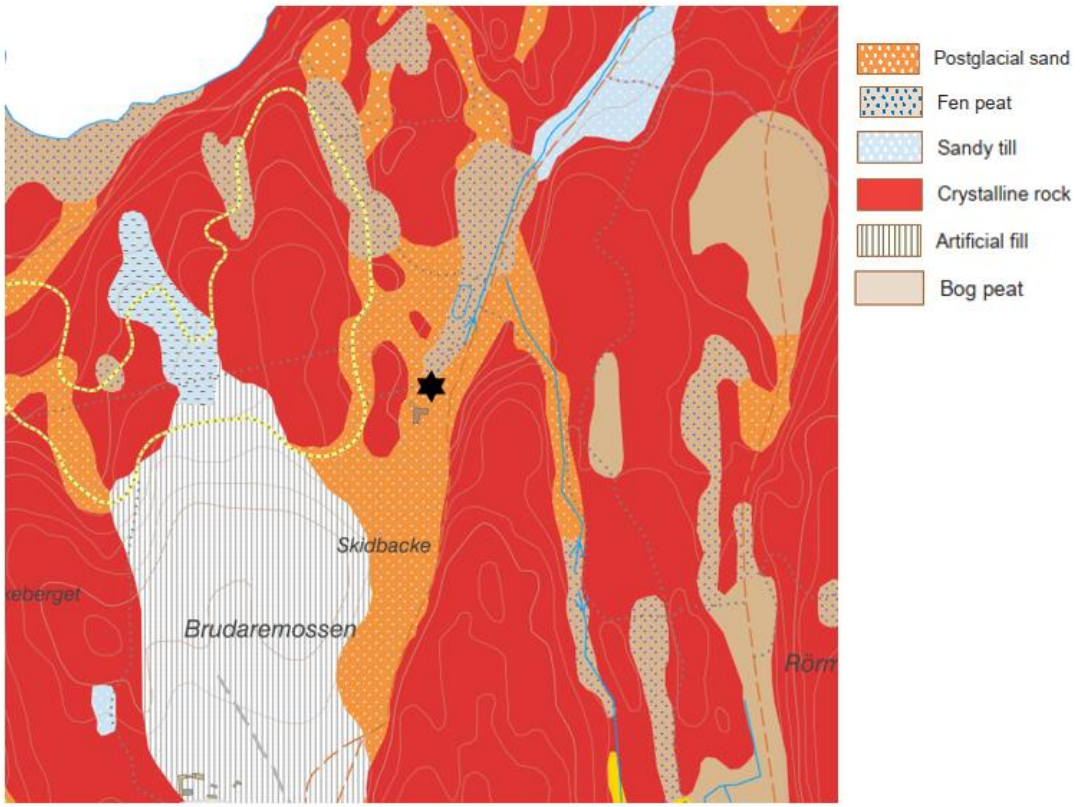

Figure 18: Geological map of Quaternary deposits north of Brudaremossen. The approximate well location marked with a star (SGU, n.d.-g). © *Sveriges Geologiska Undersökning.*

The highest shoreline in the area is about 20 to 35 meters above today's ground surface in the depression north of the landfill (Nielsen, 2007). The soil stratigraphy profile from the drilling of well G13 shows that the depth to bedrock is about 10.5 meters which coincides with the soil depth from the geological map (SGU, n.d.-h). The soil stratigraphy from the drilling tells that the layers are first 5 meters clay, then 2.5 meters sand, then 2 meters gravel, and lastly 1 meter bottom moraine (Nielsen, 2007). This corresponds not to the information about soil type at the ground given by the geological map of quaternary deposits for the site. Anyhow, the map in the area is on scale 1:25 000, so the precision of the spreading of soil layers may be relatively low when looking at a such small area as the case study site. Therefore, the geological investigation and interpretation done by Nielsen (2007) in his thesis project is more reliable for this small area.

The bedrock in the area consists mainly of gneiss with granitic to tonalitic composition (Nielsen, 2007). There are three main fracture sets in the area with the orientations NNE-SSW, WNW-ESE, and N-S respectively. The most common of these fracture sets are the one with orientation NNE-SSW, which coincides with the direction of the valley from the north end of Brudaremossen to Svarttjärn. The fracture set with orientation N-S coincides with the direction of the heights in the area and the fracture set with orientation WNW-ESE coincides with the direction of the bigger valleys in the Gothenburg area. The fractures with this orientation are filled with clay-rich minerals and have thus low permeability.

4.2.3 Hydrogeology

The geological map showing aquifers does not indicate that any aquifer with water extraction possibilities exists in the area (SGU, n.d.-e). According to Ramböll (cited in (Granberg et al., 2015)), there are two main aquifers in the area, one in the soil layers and one in the underlying bedrock. The soil aquifer stretches below the landfill and continues in the depressions north and south of the landfill. The aquifer is connected to Delsjöarna in the south and Härlanda Tjärn and Svarttjärn in the north. The hydraulic head is highest in the middle of the aquifer (below the landfill) which implies groundwater flow in two directions, towards south and north (Granberg et al., 2015). The measured hydraulic heads in the bedrock and soil wells show clear distinction and it indicates that the two aquifers not are connected. The pressure level in the bedrock wells are controlled by groundwater in deep fractures while the pressure levels in soil wells are controlled by shallower aquifers. The upper part of the bedrock may still contain fractures that are connected to the soil aquifer and affect its pressure levels. This, however, cannot be seen from the levels in the bedrock wells since these are much deeper.

The surface soil around the wells are clay and that is a very low-permeable material that not allows water to infiltrate to the ground and thus implies that the aquifer around the wells is confined. According to Granberg et al., (2015) are the groundwater levels in the wells outside the landfill impacted both by flow from the central parts of the aquifer (under the landfill) and local recharge. The local groundwater recharge occurs outside the clay lens (that most likely only covers the middle parts of the valley) where the bedrock outcrops.

4.2.4 Hydrology

The total amount of precipitation during a year in Gothenburg is around 800 mm (SMHI, n.d.-c) and the evapotranspiration is about half (400 mm) (SMHI, n.d.-a). Local measurements give that the annual precipitation during the years 2004-2014 has been between 603 and 1250 mm with an average of 991 mm per year (Granberg et al., 2015).

4.2.5 Observation well and reference well characteristics

Due to the difficulties with finding usable data for this case study site two different, close located wells are used as observation well. Both wells are situated north of the old landfill in the depression between two local heights, see Figure 17 and Figure 18. Data with high resolution for a shorter time from well G13 is used for the observation period in the TK Geo method. Data from well G5 is used for the extreme value analysis since that well is recorded within the control program since 1989, though with low data resolution. The data with high resolution (well G13) used in this project is provided by the research group for hydrogeology at the Institution of Earth Science (Institutionen för Geovetenskaper, GVC) at Gothenburg University. The data for well G5 comes from the environmental control program regarding the old landfill at Brudaremossen. It is the municipality of Gothenburg (Kretslopp och Vatten) that is responsible for the control program, but for this thesis project, the data is provided by Sweco.

The well G13 is drilled to bedrock, which is at 10.5 meter, but the filter is placed in the sand layer, at 5.5 to 6.5 meters depth (Nielsen, 2007). The well G5 is shallower, around 6 meters, and the filter is most likely placed at the bottom in the sand layer. The wells are situated very close to each other in the same aquifer and they seem to be representative to use as observation wells in the case study.

As reference well, wells from SGU's groundwater program are used (free available under creative commence license CC-BY 4.0). For this site, well SGU 54_10, which is placed in the Lerum municipality east of Gothenburg, is used (SGU, n.d.-f). The well is selected since its characteristics are similar to the observation well (see Table 5Table 2) and it fulfils the requirements in TK Geo (within 50 km).

Table 5: Characteristics of observation and reference well.

Characteristics	**Observation well, G13/G5**	**Reference well, SGU 54-10**
Aquifer type	Confined/Unconfined	Unconfined
Well placing in the aquifer	Recharge/Intermediate	Recharge
Soil type at the surface	Clay	Peat
Soil type at the filter	Sand	Till

The soil type at the surface around the observation well is clay and that implies confined aquifer conditions at the site. The clay lens in the valley is probably relatively small, due to the limited width of the valley, and the well is likely placed close to the edge of the clay lens. This means that the behaviour of the groundwater level in the well probably not is exactly like in an ordinary confined aquifer. The location close to the clay lens edge allows water infiltrated in the surroundings to also affect the level in the well. Therefore, should the conditions around this well be classified as something in between confined and unconfined.

The levels in the well are, as mentioned earlier in the conceptualization, dependent both on local infiltration and flow from the central parts of the aquifer (below the landfill). Therefore, can the well placing be interpreted as either recharge zone or intermediate zone of the aquifer.

The well SGU 54_10 is selected as reference well. The aquifer characteristics in Table 5 do not look similar, but both wells are placed in somewhat confining layers (the reference well is placed in peat that is somewhat confining) and close to the edge of these layers. The surrounding consists of permeable materials (sand for the observation well and till for the reference well) that allows infiltration that probably affects the levels in the wells. The two wells show also similar variation during the observation period (see Figure 19 and Figure 20) and are therefore seen to be representative.

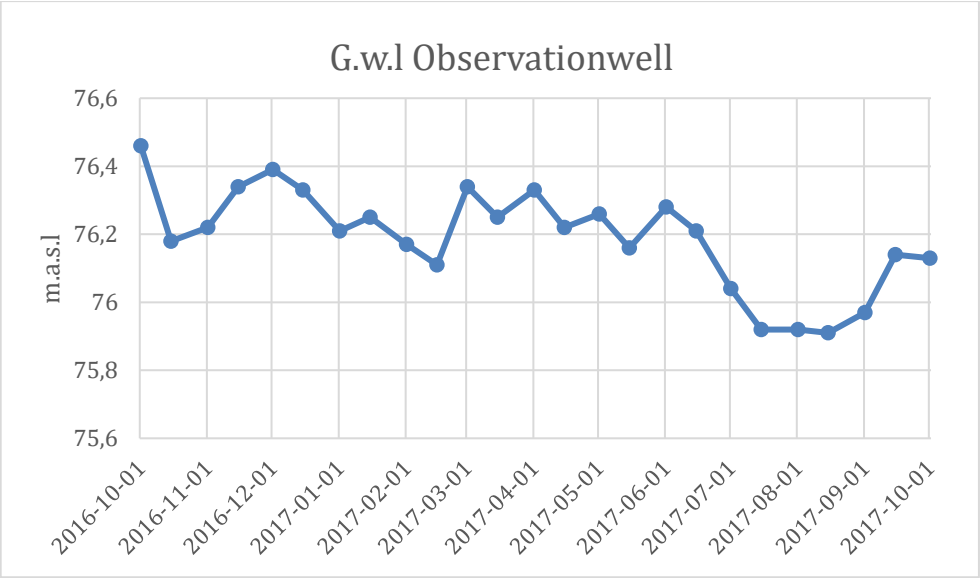

Figure 19: Groundwater levels in the observation well for 12 months observation period.

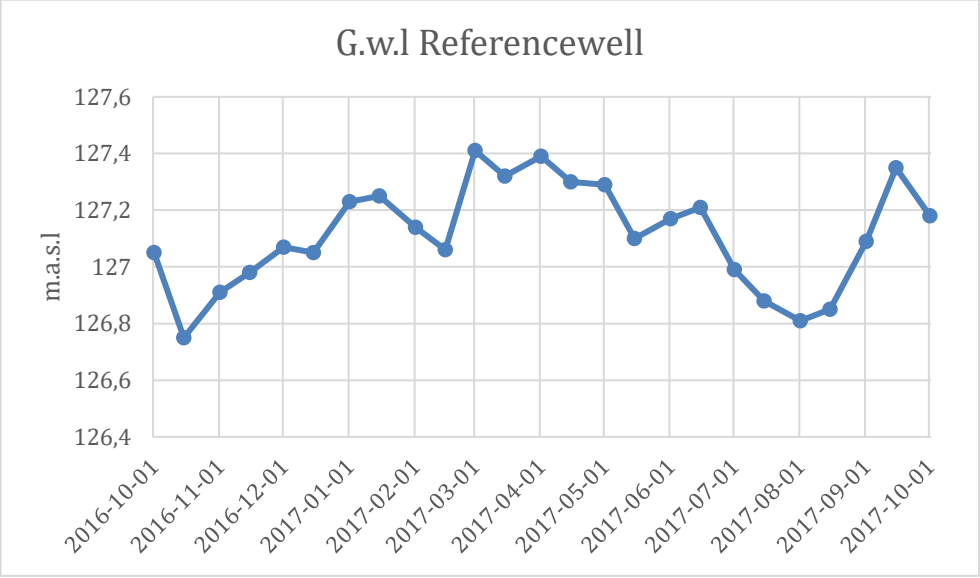

Figure 20: Groundwater levels in the reference well for 12 months observation period.

The groundwater levels in the two wells (observation and reference) tend to have similar variations during the year, but there is a difference during December to January. During that period, the levels in the reference well continues to increase while the levels in the observation well decrease. This difference may affect the calculated dimensioning groundwater levels. Anyhow, the well SGU 54_10 is seemed to be representative of the case study site at Brudaremossen and is used in the calculations.

4.2.6 Dimensioning groundwater levels

The results from the calculations of dimensioning groundwater levels (both maximum and minimum levels) according to the TK Geo method and with extreme value analysis are presented in Table 6 and Table 7. The observation period is set to be October 1 to January 1 for the three months observation period and October 1 to April 1 for the six months observation period (autumn-winter time).

Table 6: Dimensioning groundwater levels, maximum levels, according to the TK Geo method (with 3-, 6-, and 12-months observation period) and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	3 months observation period	Diff [m]	6 months observation period	Diff [m]	12 months observation period	Diff [m]	Extreme value analysis
50 years	76.74 m.a.s.l	- 0.11	76.62 m.a.s.l	- 0.23	76.71 m.a.s.l	- 0.14	76.85 m.a.s.l
100 years	76.76 m.a.s.l	- 0.16	76.63 m.a.s.l	- 0.29	76.73 m.a.s.l	- 0.19	76.92 m.a.s.l
200 years	76.77 m.a.s.l	- 0.21	76.65 m.a.s.l	- 0.33	76.76 m.a.s.l	- 0.22	76.98 m.a.s.l

Table 7: Dimensioning groundwater levels, minimum levels, according to the TK Geo method (with 3-, 6-, and 12-months observation period) and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	3 months observation period	Diff [m]	6 months observation period	Diff [m]	12 months observation period	Diff [m]	Extreme value analysis
50 years	75.85 m.a.s.l	+ 0.57	75.81 m.a.s.l	+ 0.53	75.45 m.a.s.l	+ 0.17	75.28 m.a.s.l
100 years	75.82 m.a.s.l	+ 0.63	75.78 m.a.s.l	+ 0.59	75.39 m.a.s.l	+ 0.20	75.19 m.a.s.l
200 years	75.78 m.a.s.l	+ 0.66	75.75 m.a.s.l	+ 0.63	75.34 m.a.s.l	+ 0.22	75.12 m.a.s.l

For the dimensioning maximum groundwater levels, the extreme value analysis gives higher levels (more extreme levels) than all three tested lengths of observation periods, see Table 6. It can also be seen that the 6 months observation period gives lower levels than the 3- and 12-months observation period (i.e. larger difference when comparing with extreme value analysis). That may depend on the differences in behaviour between the observation and reference well 3 to 4 months after the beginning of the observation period. The differences between the calculated levels with the TK Geo method and extreme value analysis, for all three tested observation period lengths and all three return times, are within 0.35 meter (i.e. better predicted than corresponding calculations for Lorensberg).

The difference between dimensioning minimum levels calculated with TK Geo method and extreme value analysis are larger than for corresponding maximum levels. Interesting to note is also that 3 and 6 months observation period give differences between 0.5-0.65 meter, while 12 months observation period give only around 0.2 meter in difference. Accordingly, for this case study site, 12 months observation period give much more precise results than shorter observation periods. However, for both Lorensberg and Brudaremossen, the difference between the dimensioning levels calculated with the TK Geo method and extreme value analysis is bigger for the minimum levels than for the maximum levels. This result coincides with Svenson's (1984) findings that the method estimates dimensioning maximum levels more precisely than dimensioning minimum levels, see further in the literature study section 2.6.3.

The results from Brudaremossen, both the dimensioning minimum and maximum groundwater levels, follow a trend with less extreme levels for 3 months observation and most extreme levels for the extreme value analysis. This is not in line with the results obtained from the case study site Lorensberg. For Lorensberg, the trend is opposite, and the extreme value analysis gives less extreme levels and the 3 months observation period most extreme levels. The contradictions in these results do not give any clear indication if the TK Geo method, in general, gives higher or lower levels (i.e. more or less conservative estimation) than extreme value analysis of long measurement series.

In an attempt to clarify the trends and test the TK Geo method once more, the dimensioning levels for Brudaremossen with 3- and 6-months observation period are calculated again, but this time the observation period is moved to spring-summer time instead. The 3 months periods start April 1 and ends July 1 and the 6 months observation period start April 1 and ends October 1. The results are presented in Table 8 and Table 9.

Table 8: Dimensioning groundwater levels, maximum levels, according to the TK Geo method (with 3- and 6-months observation period) for spring-summer time and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	**3 months observation period**	**Diff [m]**	**6 months observation period**	**Diff [m]**	**Extreme value analysis**
50 years	76.56 m.a.s.l	- 0.29	76.56 m.a.s.l	- 0.29	76.85 m.a.s.l
100 years	76.58 m.a.s.l	- 0.34	76.58 m.a.s.l	- 0.34	76.92 m.a.s.l
200 years	76.60 m.a.s.l	- 0.38	76.60 m.a.s.l	- 0.38	76.98 m.a.s.l

Table 9: Dimensioning groundwater levels, minimum levels, according to the TK Geo method (with 3- and 6-months observation period) for spring-summer time and with extreme value analysis. The Diff. columns gives the difference between the calculated level with the TK Geo method and Extreme value analysis.

Return period	**3 months observation period**	**Diff [m]**	**6 months observation period**	**Diff [m]**	**Extreme value analysis**
50 years	75.46 m.a.s.l	+ 0.18	75.46 m.a.s.l	+ 0.18	75.28 m.a.s.l
100 years	75.41 m.a.s.l	+ 0.22	75.42 m.a.s.l	+ 0.23	75.19 m.a.s.l
200 years	75.37 m.a.s.l	+ 0.25	75.37 m.a.s.l	+ 0.25	75.12 m.a.s.l

The results in Table 8 and Table 9 show similar levels for both 3 and 6 months observation periods, and that depends probably on the fact that the minimum and maximum level in the observation and reference wells is nearly identical for both observation period lengths (i.e. the maximum and minimum level appears during the first three months of the observation period and are thus the same in both calculations). The minimum and maximum levels are used in the calculations in term r_o and r_R, see Equation 2 in section 2.6.2 in the literature study.

The maximum levels (Table 8) calculated with the TK Geo method and spring-summer observation period give levels further away from the extreme value analysis levels compared to the corresponding autumn-winter observation period. The difference is about 0.30-0.40 meter. The spring-summer period gives, in general, lower dimensioning maximum levels than the autumn-winter observation period. It may depend on the fact that the levels measured during the observation period are lower and thus predicts also the TK Geo method the maximum levels lower, since the method does not consider the season when the measurements are performed.

The minimum levels for the spring-summer observation period (Table 9) are closer to the extreme value analysis levels compared autumn-winter observation period. The difference is about 0.20-0.25 meter compared to as high as 0.50-0.60 meter for autumn-winter observation period. That depends probably on the opposite fact that the observation period includes the lower levels of the year and thus predicts the TK Geo method the minimum levels more accurate.

The trend, however, is still the same when comparing the TK Geo results with extreme value analysis. The extreme value analysis gives more extreme levels for the for spring-summer observation period. Consequently, the same trend as for maximum and minimum levels with autumn-winter observation period, but opposite to the results obtained from the Lorensberg case study site. The results show that the TK Geo method, for the site at Brudaremossen, not predicts safe levels.

The annual extreme value series, both minimum and maximum levels, are also plotted against probability to analyse the adjustment of the series to the normal distribution, see Appendix II for figures. The graphs (Figure 24) shows that both the maximum and minimum series for the reference well (SGU 54_10) adjusts well to the normal distribution, and thus should also the calculated return times used in the term S_r in TK Geo method be representative (at least regarding this factor). The adjustment of the

maximum series of the observation well (G5) indicates that the series includes one measure that probably is an outlier, but except that single value shows the series good adjustment to the normal distribution (see Figure 25 and Figure 26). The probable outlier value is not excluded from the extreme value analysis for the observation well. Consequently, it is included in the calculated average and standard deviation of all values in the annual extreme value series, see Equation 5 section 2.6.5 in the literature study. The average and standard deviation is further used to calculate the level with a certain return time for the observation well. The outlier, therefore, affect the results for the extreme value analysis for the observation well (the levels that the results from the TK Geo method are compared to) and it can be seen in the standard deviation for the adjustment to the normal distribution (see Appendix II). The standard deviation including the probable outlier is 0.25 while the standard deviation without the probable outlier is 0.10. So, if the probable outlier had been excluded from the calculations, it probably would increase the accuracy of the results even more.

The minimum series for the observation well (G5) does not show any good adjustment to the normal distribution (see Figure 26). The reason for that is difficult to know but one possible explanation is the low data resolution in the measurement series. The data for well G5 comes from the environmental control program and measurement has been done since the late 1980s, but only a few times per year (around 4 times per year). Such few measurement points increase the risk for missing the actual minimum (or maximum) level in the well and increase thus the uncertainty in the annual minimum series. That affects also the adjustment of the series to statistical distributions, such as normal distribution in this case.

Another possible explanation for the bad adjustment of the minimum series to the normal distribution may be found in the hydrogeological system. One possible option is a threshold in nature, such as a bedrock outcrop, that controls the minimum level in the aquifer and not allows it to fall below a certain level. If there are any threshold in nature that controls the minimum levels (or maximum levels in other cases) it will also affect the adjustment of an extreme value series to a statistical distribution, such as normal distribution.

5 Discussion

In this section, the results from the case study are discussed together with uncertainties and connected issues. The discussion is done in the view of the findings within this thesis project. Of course, there are a lot of other ways to test and evaluate a calculation method like this, but for a thesis project must some limitations be done, and the results are thus discussed within this limited framework.

5.1 Case study findings

The results from the calculations done within the case study does not show any clear trends regarding how well the TK Geo method predicts the dimensioning groundwater levels compared to extreme value analysis. The dimensioning levels calculated with the TK Geo method deviate in various orders and directions depending on case study site. The results vary also depending on the measurement season for the used data. An extreme value analysis of a long measurement series from the observation well (future construction site) should, in theory, be the most accurate way to estimate dimensioning groundwater levels. That because the calculations are done for the actual site and if the data resolution of the measurement series is high enough and the series is reasonable long should the calculated levels with certain return times be as close to reality as possible. However, construction sites are rarely equipped with observation wells such long time in advance that is needed to enable extreme value analysis. The TK Geo method, on the other hand, is a simplified method to use when the measurement series at the observation site is too short to allow extreme value analysis. In theory, should the TK Geo method be somewhat more uncertain than extreme value analysis, even if the aim with the TK Geo method is that the method should be good enough to estimate dimensioning levels when extreme value analysis not is possible.

The results from the case study site Lorensberg give more extreme levels (higher for maximum levels and lower for minimum levels) with the TK Geo method compared to extreme value analysis. It means that the TK Geo method, in this case, predicts levels that are on the safe side if they are used for dimensioning of e.g. a geo-construction. The difference between calculated maximum levels with TK Geo method and extreme value analysis for 3 months observation period is over half a meter, while the difference is only some centimetres for 6 months observation period. For dimensioning minimum levels, the corresponding differences are nearly 0.70 meter for 3 months observation period and around 0.4 meter for 6 months observation period. Accordingly, the maximum levels for 6 months observation period are closer to comparative extreme value analysis levels than minimum levels for 6 months observation period. One possible reason for such difference is that the observation period, in this case, are placed during autumn-winter and thus the lowest values of the year are not included in the observation period and that may affect the results. In general, the TK Geo method is less precise in predicting minimum dimensioning levels than maximum dimensioning levels (Svensson, 1984) since the dry period during summer often is short and may be missed when recording levels only twice a month or less. However, in infrastructure projects the maximum levels usually are the ones that are needed to achieve safe and resilient constructions. Minimum levels may be used for following up groundwater lowering caused by the construction work in the surroundings.

The results from the second case study site, Brudaremossen, gives the most extreme levels (highest for maximum levels and lowest for minimum levels) with extreme value analysis and less extreme values for the different observation periods lengths calculated with TK Geo method. For this case, the TK Geo method does not predict dimensioning levels that are on the safe side, given that the extreme value analysis results are reliable and close to reality. The trend in the results is the same for both autumn-winter and spring-summer observation periods even if the calculated maximum levels are closer to extreme value analysis levels with autumn-winter observation period and the opposite for minimum levels.

The trends in the results from the case study site Lorensberg and Brudaremossen are the opposite. For Lorensberg, the TK Geo method (with 3 months observation period) gives the most extreme levels while for Brudaremossen the extreme value analysis gives the most extreme levels. Given the results from these two case study sites it is not possible to draw any general conclusion regarding if the TK Geo method predicts levels that are on the conservative (safe) side or not. Anyhow, if the TK Geo method is accurate enough depends on how exactly the predicted levels need to be. It is enough that the predicted levels are within half a meter from the correct level, or is higher precision needed, or can even lower precision be accepted? Svensson (1984) states in his doctoral thesis that up to 0.5 meters difference is acceptable for geo-construction. However, the results from this case study give differences up to around 0.7 meter between the TK Geo method with 3 months observation period and extreme value analysis. If that is an approved difference or not depends on the case where the predicted levels are used.

Dimensioning levels that are conservative (safe) can also be achieved by changing the governing return time. In this thesis project levels with 50, 100 and 200 years return time are calculated, but in construction projects where safety is important may much longer return times for dimensioning levels be needed (e.g. return times of 1000 or 2000 years). This, however, is outside the scope for the thesis project, but it is important to remember the impact of selected return time in the calculations.

The method developed by Svensson and Sällfors, that also is stated in the TK Geo documents, is primarily created for estimation of groundwater levels as input to dimensioning of constructions but might be used also for other type of prognoses that needs assessment of groundwater levels (e.g. environmental judgments). If levels predicted with this type of reference well method (as the TK Geo method) are used in environmental judgments as strict levels that groundwater not can fall below, and the estimated level is 0.5-1 meter away from its “real” value it may cause consequences. Take as an example a construction project where the environmental court declares that the groundwater levels in the surroundings cannot fall below the level with 50 years return time to not cause irreversible damage. The environmental court tells also in the judgement which level 50 years return time corresponds to in an explicit number (say in meters above sea level or some other local coordinate system). If the level in the judgment is up to 1 meter away from the “real” level with 50 years return time it may cause consequences. If the set level in the judgment is higher than the real level it may be a level that is impossible to not fall below during construction and unreasonable large and extremely costly measures needs to be taken. It can also cause production stop, and that is very costly for big infrastructure projects. If the levels set in the

environmental judgment are lower than the "real" levels may a groundwater lowering cause damage to surrounding nature even if the requirements in the judgment are fulfilled. So, groundwater changes may cause consequences that can be both costly and devastating for the environment depending on how the levels in the environmental judgment are predicted.

In general, for both case study sites longer observation period give predicted levels closer to the levels according to the extreme value analysis. So, a longer observation period than 3 months (with recorded level every second week) is according to these results preferable since it predicts the dimensioning levels more precise. However, this conclusion raises the question if 3 months observation period but with higher data resolution (e.g. data automatically logged several times per day) could be a solution instead of a longer observation period? The advantages with higher data resolution are that the probability of measure the highest and lowest levels increases and the accuracy in the data series becomes higher. But still, if measurements are done only for 3 months there are a big risk that this single period may be far away from "normal behaviour" for the specific season. So, higher measurement frequency gives probably better accuracy in the data series during the specific time (and interpolation of missed datapoints are not needed), but it is hard to say if that can replace longer measurement series. On the other hand, if the Swedish Transport Administration would change the recommendation to 6 months observation period would still a recommendation of data resolution be needed, because otherwise could the performer or purchaser set the data resolution to as low as once every second month (so only three measurements even if the total observation period is 6 months) to save time and money. That again increases the risk of not cover the highest and lowest levels in the measurement series and probably decreases the accuracy of the results, even if it not is tested explicitly in this master thesis.

Important to remember together with the question of measurement series length and data resolution is the season when the levels are measured. The results from this thesis project shows differences between dimensioning levels calculated on spring-summer data series and autumn-winter data series. The results from the case study gives dimensioning maximum levels closer to extreme value analysis with autumn-winter observation period and dimensioning minimum levels closer to extreme value analysis with spring-summer observation period. The TK Geo method itself does not mind about the season the levels are recorded, but it may affect and is worth to remember when doing these types of calculations.

5.2 Uncertainties connected to case study calculations

One major uncertainty or source to error in the results is the low data resolution in the measurement series used for extreme value analysis for the observation well. Few recorded levels during a year (only 4-6 recorded levels) increase the risk that the actual highest or lowest levels (that is included in the annual extreme value series in the analysis) are missed and thus become the annual extreme value series more uncertain. However, this is somewhat compensated for with the length of the measurement series (over 40 years), but it is still a source to error in the calculations. If the actual highest or lowest level is missed several years during measuring it is a risk for bias in the annual extreme value series, and that may give a systematic error in the calculations. If there are any bias in the used measurement series in the case

study is impossible to know, but the uncertainty regarding low data resolution is a factor especially for Brudaremossen (low data resolution in the measurement series from well G5) but also partly for Lorensberg since there are some years during the measurement series for well GW485 with few recorded levels (but other years with more recorded levels, in total around 45 years).

Another possible source for error in the results is the simplification regarding calendar year done in the project method. Svensson & Sällfors (1985) state that the calculations should be done based on annual extreme values that are selected for hydrogeological years (October 1 to September 30). In TK Geo, the Swedish Transport Administration does not explicitly write anything about how the annual extreme values should be selected (Trafikverket, 2016a, 2016b), but since the method is based on Svensson & Sällfors (1985) would hydrogeological years probably be more correct. Anyhow, this simplification is done and the calculation in this thesis project is performed based on calendar years. It is probably common that calculations like this are done based on calendar years within the industry. However, it may give some error in the annual extreme value series.

5.3 The required length of the measurement series

The results from the calculations performed within the case study show that longer observation periods (the observation period is in reality the whole measurement series available for the site) predicts dimensioning levels closer to the levels calculated with extreme value analysis. The results also show tendencies of being dependent on the representativeness (e.g. better covariation between observation and reference well will probably give more accurate results) of the reference well, so it is not given that a longer observation period always will predict more precise levels. For example, Brudaremossen with 6 months observation period gives levels with larger difference to the extreme value analysis levels than both 3- and 12-months observation period. That may depend on less covariation between observation and reference well during the three added months for 6 months observation period compared to the 3 months observation period (see Figure 19 and Figure 20).

Svensson & Sällfors (1985) states in the description of the method that at least 3 months measuring with 7 recorded levels are needed in the observation well to be able to use the method with satisfying results. In the TK Geo documents from the Swedish Transport Administration, it is not stated explicitly how long the measurement series that is needed and with what data resolution (Trafikverket, 2016a, 2016b).

The length of the measurement series in the reference well is also a factor in the TK Geo method. In this thesis project, wells from SGU's groundwater program are used as reference wells and the whole available measurement series are included in the statistical treatment. The used wells have around 45 years of recorded levels. In general, it holds that the longer the series are the better when a statistical evaluation is done to find levels with long return time (e.g. 50, 100, 200 years or even longer). In the report about the method, Svensson & Sällfors (1985) uses reference wells with 10-20 years recorded levels (that's what was available from SGU at that time) and it works out satisfactory. So, the lower limit for the reference well is therefore probably between 10-20 years measurement series, even if longer always is better. However, as mentioned above, it is important to remember that not only the length of the

measurement series affects the results, the covariation between the observation and reference well is at least as important when selecting reference well.

5.4 Need for hydrogeological conceptualization and selection of suitable reference well

Neither TK Geo or Eurocode explicitly give any requirements on hydrogeological characterization for the actual sites (Svensk Standard, 2009b; Trafikverket, 2016a, 2016b). Svensson & Sällfors (1985) on the other hand states that the results from the calculation method (TK Geo method) become more accurate if the two wells have similar characteristics. To know if the two wells are situated in such locations so the characteristics become similar (type of aquifer, recharge/discharge area etc) knowledge about the sites (such knowledge and information that usually are gathered within a hydrogeological conceptualization) is important.

In this thesis project, reference wells are selected with an as good fit as possible to the observation well. Both the characteristics of the aquifers where the wells are placed and the level variation in the wells during the observation period are considered. A reference well is not seen representative if the groundwater levels not covary (increase and decrease simultaneously) during the observation period. There may be other ways to find a suitable reference well too but within this thesis project seemed this to be the most appropriate way to select reference well to use. This method implies that the thesis does not test how the results are affected if the selected reference well not suits the observation well characteristics and groundwater level variation. It is not unbelievable to think that the results most likely will get less appropriate if the reference well not is representative of the observation site. It also raises the question if it is enough to have two wells that covary during the observation period, but not have similar characteristics? This question cannot be answered from the results within this thesis project, but the characteristics most likely affects how the groundwater fluctuates over a longer period, and covariation during a short period may not imply long time covariation. So, short time covariation may give appropriate results, but it is not sure.

Even if the thesis not test the need for hydrogeological characterization explicitly it is believable that it improves the accuracy of the results significant since it ensures similar characteristics of the observation and reference well. The most important characteristics to know to be able to select a representative reference well are; type of aquifer (confined or unconfined) and location within the aquifer (recharge or discharge area). These two characteristics are important for the natural groundwater variation both regarding short time (e.g. fast or slow level increase) and long-time (e.g. occurrence of high and low levels during a year) (see literature study e.g. section 2.3). If these two characteristics are similar for the observation and reference well the accuracy in the result may increase significantly, or it at least eliminates one of the major error sources in the calculations, that the wells do not fit hydrogeological.

5.5 Risks connected to TK Geo method

There are several risks and uncertainties connected to the use of the TK Geo method for prediction of dimensioning groundwater levels for e.g. geo-construction projects. For example, there are commonly uncertainties regarding the accuracy of data depending on how it is measured (level reading when measuring manually, misprinting when reporting data, etc.). Another major risk that probably can affect the results significantly is the representativeness of the reference well to the observation well. If the characteristics of the reference well differ clearly from the observation well it may affect the accuracy of the results, as discussed above. However, there is a high risk of selecting a reference well with less suitability if the performer is not aware of the conditions at the sites and selects according to that. To avoid this risk basic knowledge in hydrogeology and geology is preferable so the performer of the calculations understands and can select a suitable reference well.

Another risk or important topic to consider when using the TK Geo method is the principles about the probability of an event to happen and the statistical concept of return time. The concept of return time means that an event has a specific probability to occur, as described in section 2.6.4 in the literature study. For example, if 50 years return time is used as dimensioning groundwater level for a geo-construction it is a 2 % probability that the specific level is equalled or exceeded a single year and it is a 63 % probability that the specific level will be equalled or exceeded during a 50 years period. In addition, the expected lifetime of the construction must be considered. If the expected lifetime for a construction is 50 years and the dimensioning level is the level with a return time of 50 years it is a higher probability that this level will be equalled or exceeded during the construction's lifetime than not exceeded. The follow-up question becomes then, is that ok? That question is impossible to answer to because it depends on the type of project and requirements connected to that specific project. However, the consequences of selecting return time for a construction with a specified expected lifetime could be more described and explained in TK Geo to avoid that too short return times are used for estimation of dimensioning groundwater levels.

Many constructions for infrastructure projects (e.g. tunnels for roads and railways etc) are expected to have a lifetime of maybe 50 or 100 years. It is then appropriate to design such constructions to only resist a level with 50 or 100 years return time, that during the expected lifetime may have a probability of 63 % or even higher to occur? This, of course, is a question for the owner of the construction (who is responsible for maintenance and the basic conditions for the planning) to think about, but it is important to know that a 50 years level probably not is a safe dimensioning level for constructions that have an expected lifetime up to 100 years or more. For example, the probability of exceedance for a level with 50 years return time during a constructions 100 years lifetime is as high as 87 %. Further, if the issue is move around and the problem is formulated; you have a construction with an expected lifetime of 100 years and the risk assessment says that only 5% probability of occurrence is acceptable then you need to dimension the construction to resist a level with return time of around 2000 years.

In conjunction with the question of selecting the accurate return time it also raises the question of who should select governing return time for a construction? Consequently,

who decides what risk level that is tolerable for this specific construction? Should it be the owner of construction, a specialist, such as hydrogeologist, or should it be worked out together? This is outside the scope of this thesis project, but it is an important issue and an actual questing in the industry.

Regardless of how the dimensioning groundwater levels are predicted, if the concept of return times is used to asses which level the construction should resist it is very important to be aware of what risk such level corresponds to during the construction's whole lifetime. Return time of 50 or 100 years may sound safe but for constructions with similarly expected lifetime the probability that the level is exceeded may be as high as 63 % and is that considered to be safe? When selecting which return time a specific construction should be dimensioned for it is important to be aware of what risk that corresponds to during the expected lifetime.

Another always important issue these days are the climate changes and how that may impact the subject. The dimensioning groundwater levels are calculated using measurement series from the past (that in an unexploited area should represent natural groundwater variation). If the climate changes affect the natural groundwater levels (rise or sink) or the variation pattern that can affect the dimensioning levels and either make them total irrelevant or impossible to fulfil. Exact how future climate change may affect dimensioning levels and the use of them are difficult to predict, and it depends on how the groundwater levels will be affected (rise or sink? probably different in different regions). If the groundwater levels change dramatically in an area the use of past measurement series may be irrelevant for calculation of reference levels. That can cause complications, since lack of representative data cannot be exchanged in only a few years (it takes time).

One possibility in a climate with more extreme weather is that also the groundwater fluctuations becomes more extreme and rapid changes with greater magnitudes become more common. That may affect the possibility to use statistical methods but more important it may cause damage to constructions and cause changes in nature that are irreversible. Anyhow, this is somewhat outside the scope of this master thesis, but it is an important topic that need further studies and attention.

Lastly, if terms for drawdown of groundwater in connection to construction sites (in decisions from environmental court) are based on methods that use past measurement series that not are relevant anymore there are a risk that the levels are hard/impossible to fulfil, and the contractor are forced to pay high penalties. Accordingly, there are economical risks connected to the use of dimensioning levels in court decisions, and if the set level not is representative it may cause unnecessary problems. There may also be a risk that the groundwater levels naturally sink (or rise) below (or above) a set level in a court decision, due to extreme weather (like the summer 2018, when the precipitation was very limited). Such variation may be hard to prove for a constructor in a negotiation but is also impossible to avoid.

5.6 Further development of TK Geo method

The TK Geo method is used in the industry to assess dimensioning groundwater levels for construction projects. If the performer of this analysis only has access to the description in the governing documents from the Swedish Transport Administration

and not have the whole background to the development of the method from Svensson & Sällfors it is a risk that the hydrogeological assessment regarding observation and reference well is missed out. That may lead to an impropriate selection of reference well and thus results that is not as accurate as it could be. So, adding some advice of how selection of reference well should be done would improve the TK Geo method description and avoid this potential mistake. The state that the reference well should be located within same climate zone is quite diffuse and do not give clear guidance on how to select appropriate if you not have much former experience or are aware of the hydrogeological aspects of how a well works and how groundwater levels are affected of different weather events.

Another possible improvement to the description of the method in TK Geo regards the selection of return time for the calculations. The current formulation says that the dimensioning groundwater level should be decided according to the most adverse level with at least 50 years return time, and if the consequences are severe should longer return time be used (Trafikverket, 2016a, 2016b). The risk for exceedance, as mentioned earlier, for 50 years return time is high for common lifetimes for constructions (e.g. 100 years), so longer return times are probably preferable in many cases. Anyhow, the current formulation make it easy to believe that calculating with 50 years return time is acceptable, even if it not, so some adding's about how to select an appropriate return time would increase the user-friendliness of the description an decrease the risk that to short return times are used.

Lastly, the TK Geo method description would also be improved if any recommendations regarding the length of the observation period and data resolution of measurement were added. The current formulation gives no recommendations at all regarding this, and that leads to uncertainties for the performer of the calculations.

Figure 21 shows an updated version of Figure 7 (in literature study). The red text indicates the updates and it shows possible additions/clarifications to the description text in TK Geo that would improve the user-friendliness of the method and decrease the risk that mistakes are done.

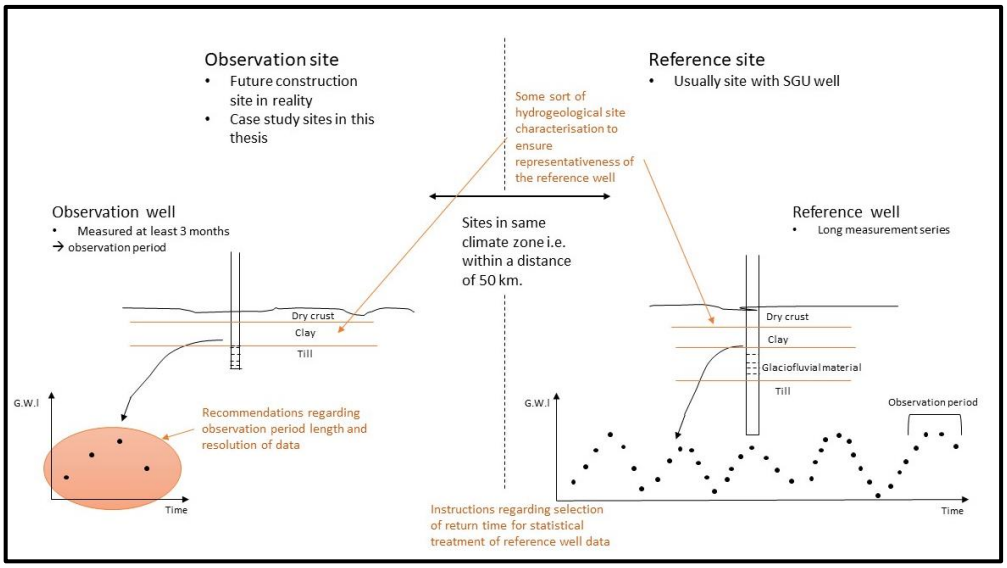

Figure 21: The picture shows possible updates to the TK Geo method description.

6 Conclusions and further studies

This chapter summarises and concludes the findings for the case study part of the thesis project. The research questions for the literature study are answered in chapter 2 and works as a fundament for the case study part and therefore are not answered here again.

The case study does not give any clear picture of how accurate the TK Geo method predicts dimensioning groundwater levels since the results differ so much for the two case study sites. However, the results show that the TK Geo method gives both over- and underestimations of the dimensioning levels compared to the results from the extreme value analysis and the levels differ up to 70 cm for the tested cases, which may have significant effects.

Within the thesis project, different lengths of observation periods are tested, and the results indicate that the longer the better, even if the study may be too small to allow general conclusions. The same holds for the need of hydrogeological conceptualization, it seems to increase the accuracy in the results, but the case study does not test it explicit, so any general conclusion is impossible to draw. However, the results from this thesis project strengthen that longer measurement series and better conceptualization seems to give more accurate results. Anyhow, recommendations and instructions about this are not included in the description of the method in TK Geo.

There are several risks connected to the TK Geo method, but one major is the selection of return time that is governing for the dimensioning levels for a project. Another risk is the description of the method in TK Geo by the Swedish Transport Administration. The description is quite short and does not give any details about the required lengths of measurement series for observation or reference wells neither about data resolution for the measurement series. Therefore, one conclusion from this thesis project is that the TK Geo method description would improve if recommendations about the required length of measurement series and data resolution were added. The description would also improve if the requirements on the selection of reference well were clearer and more specific.

To further test the TK Geo method's ability to predict dimensioning groundwater levels would a larger case study with more sites contributes to the possibility to draw more general conclusions. A further case study would also give the possibility to test different lengths of measurement series for both observation and reference well and the requirement of representativeness of the reference well by test wells with various characteristics.

Another related question is for which return time should a specific construction be dimensioned? How high risk is a tolerable risk regarding groundwater levels for different infrastructure projects? These questions are not answered within the frame for this thesis project, but it is interesting for further studies. Lastly, and maybe most important, how will climate change impact calculations like these?

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8 Appendices

8.1 Appendix I

Table 10: Frequency factor, t_T, for normal distribution at different return times (Pearson & Hartley, 1972) *cited in* (Svensson & Sällfors, 1985).

T [years]	Frequency factor t_T
10	1.2816
20	1.6449
50	2.0538
100	2.3264
200	2.5758
500	2.8782

8.2 Appendix II

This appendix contains the plots of the adjustment of the measurement series to normal distribution.

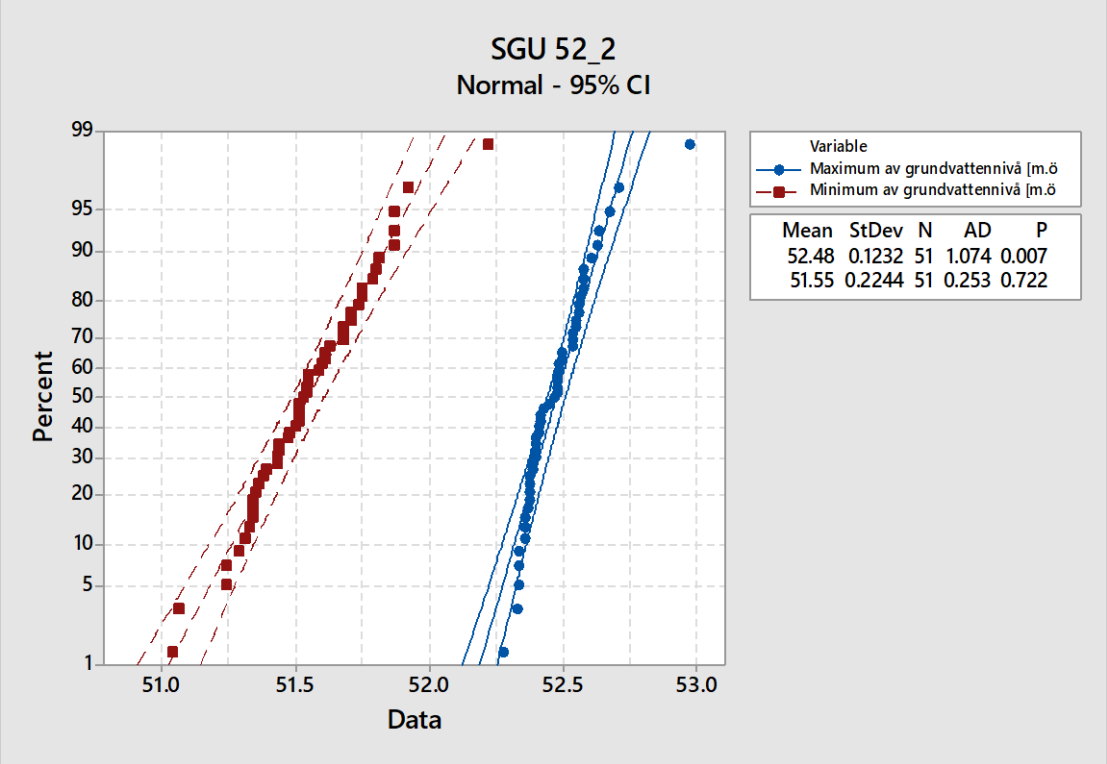

Figure 22: Adjustment of annual extreme value series (both maximum, blue, and minimum, red) to a normal distribution for reference well (SGU 52_2) to case study site Lorensberg.

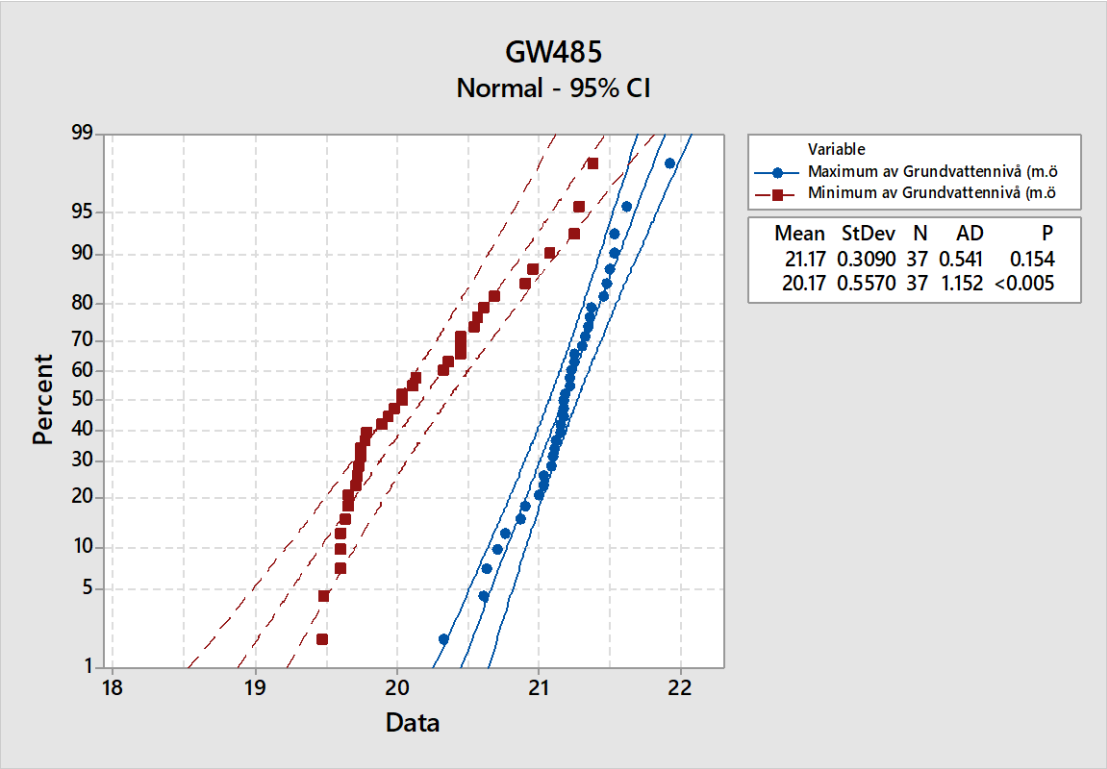

Figure 23: Adjustment of annual extreme value series (both maximum, blue, and minimum, red) to a normal distribution for observation well (GW485) for case study site Lorensberg.

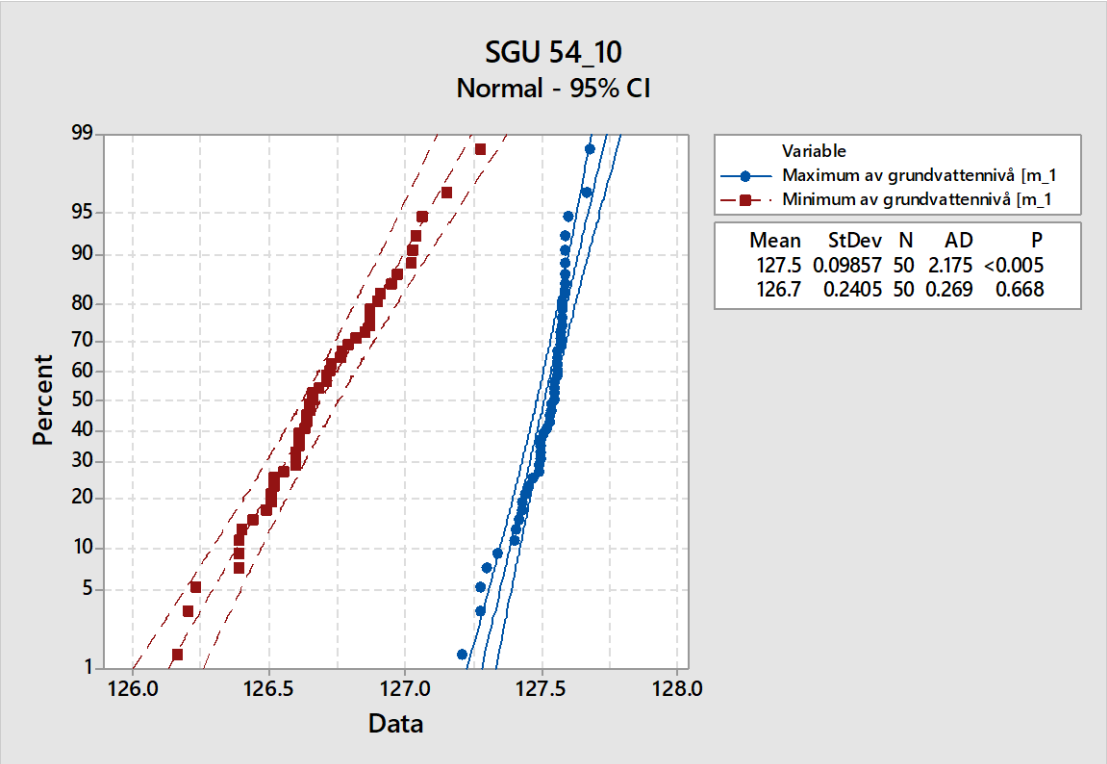

Figure 24: Adjustment of annual extreme value series (both maximum, blue, and minimum, red) to a normal distribution for reference well (SGU 54_10) to case study site Brudaremossen.

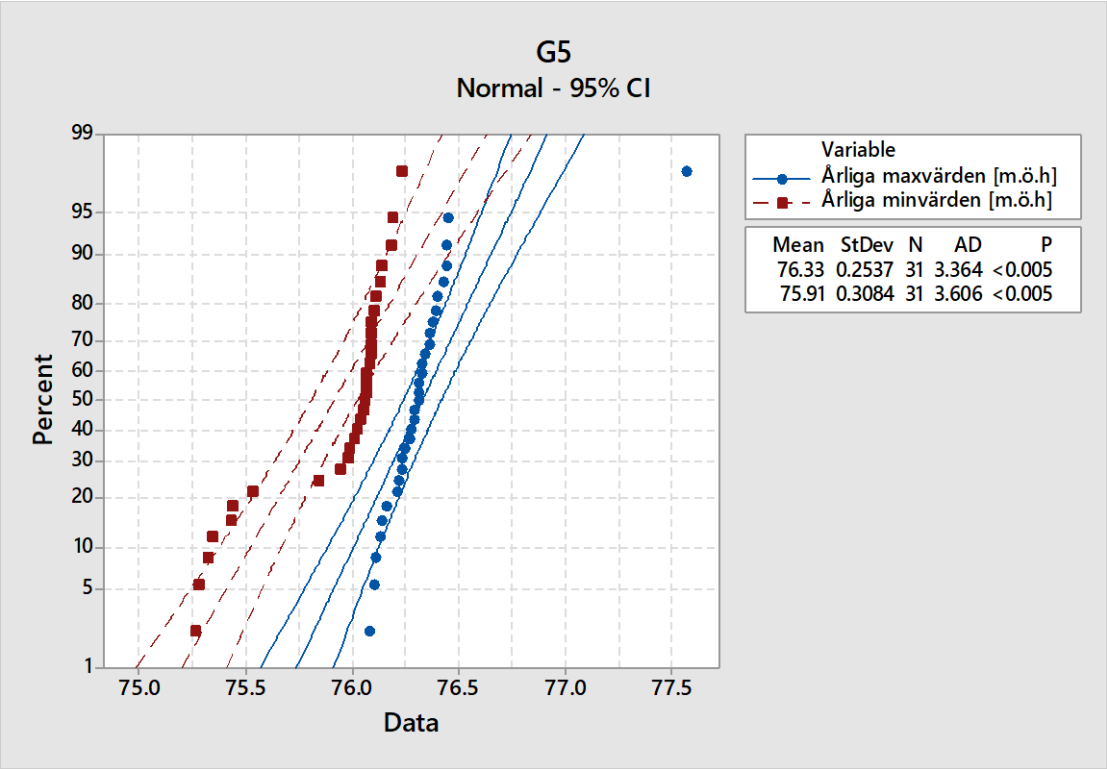

Figure 25: Adjustment of annual extreme value series (both maximum, blue, and minimum, red) to a normal distribution for observation well (G5) for case study site Brudaremossen. With likely outlier.

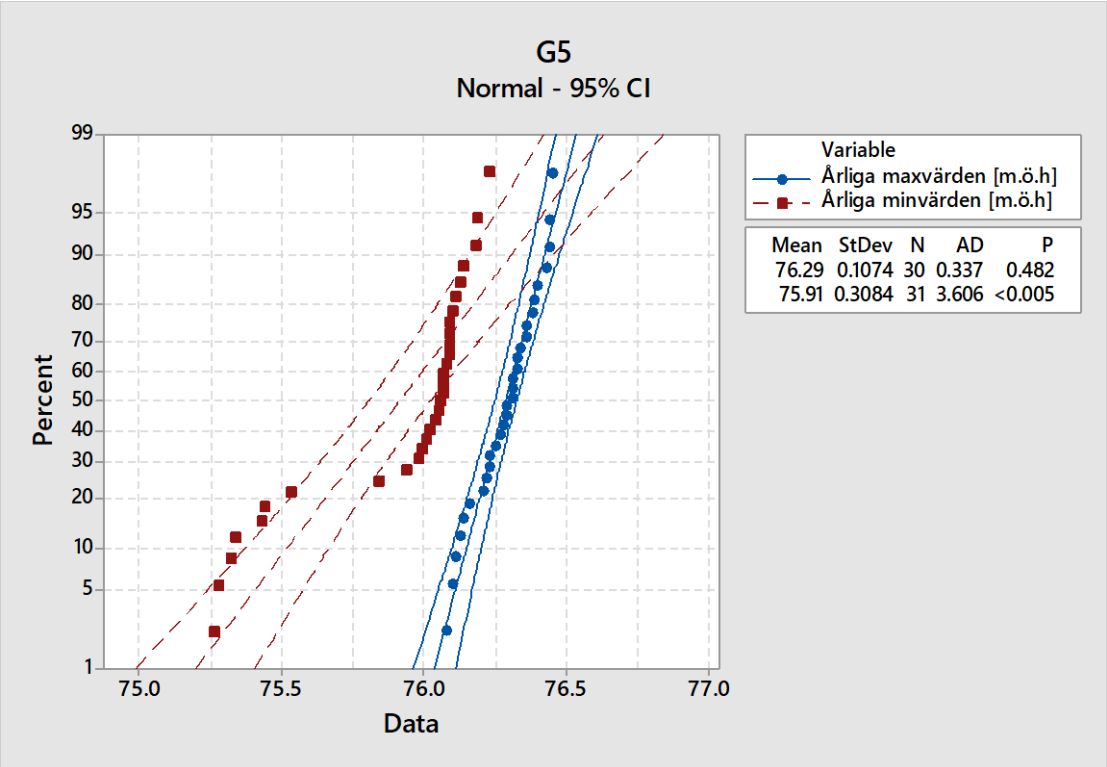

Figure 26: Adjustment of annual extreme value series (both maximum, blue, and minimum, red) to a normal distribution for observation well (G5) for case study site Brudaremossen. Without likely outliers.