CHALMERS
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Hydrogeological Modelling for Optimised Countermeasures of Leaking Landfills

Case Study of Välen Dredge Landfill

Master's thesis in groundwater modelling

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Cover: The dredge landfill and Välen bay.

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ABSTRACT

Leaking landfills are a worldwide spanning issue. Optimal countermeasures are therefore essential to prevent leakage of leachate. Hydrogeological conceptual modelling can be a tool to better understand a system and required actions. The aim of this study was to estimate flow patterns at a case study area and use that to evaluate where countermeasures and further investigations should be implemented. The landfill, studied in this project, has problems with leaking leachate and previous countermeasures have been insufficient.

Sustainable countermeasures that treat the source of contamination are recommended by the Swedish Environmental Protection Agency. In this project, countermeasures that prevent water from infiltrating contaminated masses were considered the most optimal. Vertical screening and covering was therefore suggested as suitable countermeasures.

A method of creating a conceptual model, which was converted into a numerical model in Visual MODFLOW was used in this project. The model was calibrated towards observed groundwater heads, but acceptable levels could not be reached. Therefore, suggested countermeasures were only based on the conceptual model created to describe the landfill. The conclusion was that an improved cover and a vertical barrier to prevent inflow are possible countermeasures in the area. However, further investigations are needed to ensure geotechnical stability and to dimension the suggested countermeasures.

Key words: Hydrogeology, Hydrogeological Modelling, Visual MODFLOW, Välen Dredge Landfill, Landfill Leakage, Countermeasures

Hydrogeologisk modellering för optimerade åtgärder vid läckande deponier
En studie av Välens mudderdeponi

Examensarbete inom mastersprogrammet Infrastruktur och miljöteknik

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SAMMANFATTNING

Läckande deponier är ett världsomfattande problem. Optimala åtgärder är därför väsentligt för att hindra läckage av lakvatten. Hydrogeologisk konceptuell modellering vara ett verktyg för att förstå ett system och föreslå lämpliga åtgärder. Syftet med detta projekt var att uppskatta flöden vid en deponi och använda det för att föreslå var åtgärder och fortsatta utredningar bör genomföras. Deponin som studerades i projektet har problematik med läckage av lakvatten och tidigare åtgärder har varit otillräckliga.

Hållbara åtgärder som behandlar källan till föroreningar är rekommenderat av Naturvårdsverket. I det här projektet är därför åtgärder som hindrar vatten att infiltrera förorenade massor att föredra. Vertikal avskärmning och täckning är därför föreslagna som lämpliga åtgärder.

En konceptuell modell skapades och användes för att skapa en numerisk modell i programvaran Visual MODFLOW. Modellen kalibrerades mot observerade grundvattennivåer, men accepterade nivåer kunde inte nås i modellen. Därför användes endast informationen från den konceptuella modellen för att beskriva systemet. Slutsatsen var att en ny täckning och en vertikal avskärmning där inflöde till deponin sker är mögliga åtgärder för området. Emellertid behövs ytterligare utredningar för att fastställa att föreslagna åtgärder inte påverkar den geotekniska stabiliteten samt för att dimensionera åtgärderna.

Nyckelord: Hydrogeologi, Hydrogeologisk modellering, Visual MODFLOW, Välen deponin, Läckage, Åtgärder

Contents

Preface

This report comprises the master thesis of Erika Lindqvist at the master programme Infrastructure and Environmental Engineering at the department of Architecture and Civil Engineering, Chalmers University of Technology. The thesis has been conducted in cooperation with Water Resources at Ramboll Sverige and was founded by Kretslopp och vatten. Supervisors for this project has been Lars Rosen, Environmental Geology – Land and Water Resources, Chalmers University of Technology, and Per Sander, Water Resources, Ramböll Sverige, with support from colleges.

I would like to thank the persons that have supported me at Chalmers, Ramböll and Kretslopp och vatten for all the help and assistance they have provided. I would also like to thank the people at Ramböll for including me in the organisation, which have given me a supportable working environment during this semester. Last but not least, I thank my family and friends for their support and understanding during this period of time.

Göteborg, 29 May, 2018

1. Introduction

Leaking landfills is a world spanning issue (Modin 2012). Optimal countermeasures are therefore essential to prevent leakage of leachate (Swedish Environmental Protection Agency 2009). Nowadays numerical groundwater software programs can be effective tools to support the decision-making process of countermeasures for leaking landfills (Von Brömssen et. al. 2006).

1.1 Background

Sweden has during the last decades reduced the use of landfills, as disposal of waste and landfills should now only be used when no other treatment method is possible (Avfall Sverige, 2017). However, old landfills are still causing problems with for example polluted leachate. In other parts of the world, the use of landfills for disposal of waste is still the main treatment method and leaking leachate is therefore an issue across the world (Chen, Wang, Nai and Dong 2012; Modin 2012).

Landfills are generally constructed with a sealed base to prevent leakage. Common cover materials are sludge, ashes or soils to prevent rainwater to infiltrate and produce contaminated leachate (Avfall Svergie 2017). This construction provides a possibility to collect and treat leachate from the landfill. In Sweden, less than half of the landfills treat the leachate in wastewater treatment plants. The alternative is to treat the leachate locally before it reaches a recipient or prevent water to become contaminated.

Landfills can be complex, and it can be difficult to estimate suitable countermeasures and where to implement them. Therefore, hydrogeological conceptual modelling can be a tool to better understand a system (Von Brömssen et. al. 2006). Analytical or numerical hydrogeological modelling can be useful to evaluate the flow patterns, amount of leakage and mass transport of pollutions of a landfill that can be used for answering which countermeasures should be implemented at what locations.

A nature reserve called Välen, is located in the southern parts of Gothenburg, Sweden, as shown in figure 1 (Stadsbyggnadskontoret 2013). The nature preservation area is of regional importance regarding the rich bird life and the area is widely used for recreation. A decommissioned landfill, called the Välen dredge landfill, is located within the nature reserve area. In 1976 and 1977 the Välen bay was dredged to improve the environment in the bay (Göteborgs vatten och avloppsverk 1977). The bay was severely affected by contamination from an old wastewater treatment plant called *Näsetverket* (Ramböll 2017*).* The bay was dredged to improve the environmental condition of the bay and to accelerate the recovery of the fauna living in the bottom sediments, and also to prevent the contaminations from spreading out into the sea (Magnusson et.al. 2014).

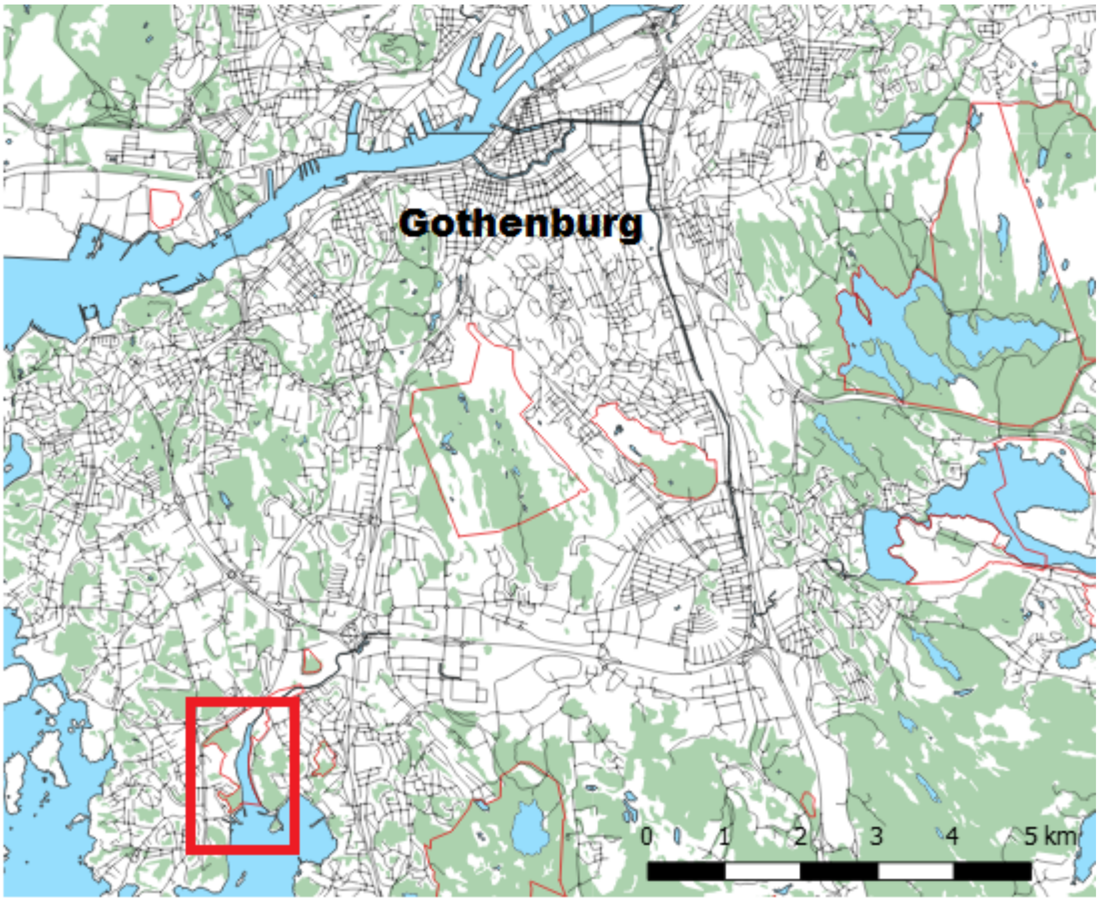


Figure 1. Location of dredge landfill at Välen. (© Lantmäteriet)

The dredge masses have been covered with lime sludge from the wastewater treatment plant *Ryaverket* (Ramböll 2017). The landfill consists of contaminated dredge and sludge material and potentially affects the sensitive nature surroundings, which have both rich ecosystems and are of importance for recreation (Magnusson et al 2014). Some of the contaminants that have been detected in high or moderate concentrations in the leachate are mercury, nickel, chrome, phosphorus and nitrogen (Ramböll 2017), all of which can cause negative environmental effects.

Investigations show that polluted leachate is leaking out into the nearby bay, which potentially can cause negative health effects and affect the sensitive environment in the nature reserve (Magnusson et. al. 2014). Countermeasures have been taken to stop leachate migration from the landfill by setting up an impermeable corrugated plastic barrier and a drainage well in the southern embankment where most of the leakage were assumed to discharge from the landfill (Ramböll 2017). However, these measures have proven to be insufficient. Investigations show that additional measures have to be implemented to prevent contamination of the surroundings.

1.2 Aim

The overall aim of this study is to perform conceptual and quantitative modelling to estimate flow patterns in the Välen dredge landfill and evaluate where countermeasures and further investigations can be implemented. The aim is also to conduct sensitivity analysis of modelling issues, including the choice of conceptual model and assumptions on how parameters affect the results. Investigations and earlier measures have shown to be insufficient and therefore, this thesis will evaluate new potential countermeasures.

To reach the aims of the study, the following objectives were defined:

- To create a conceptual and quantitative groundwater model of the site Välen and use that to evaluate flow patterns in the landfill.
- To perform a sensitivity analysis regarding the influence of the conceptual model.
- To recommend countermeasures for the site in the case study and evaluate the uncertainties of possible measures.
- To present, on a general level, social, ethical, environmental and technical aspects of the considered countermeasures.

1.3 Limitations

This thesis is focusing on the objectives mentioned above, and it will not consider:

- Aspects regarding the quality of the water other than very generally in relation to reasonable countermeasures.
- Countermeasures concerning on-site facility for treatment of leachate water since this was investigated in 2012.
- The effect that the sea level in the bay has on the groundwater levels inside the landfill in the modelling process.
- Biochemical processes of the waste material in the landfill.

1.4 Outline of thesis

The report structure includes an introduction of the site used in this project in chapter 2. The main methods used during the project are presented in chapter 3. However, more specific parts of the method are described in chapters 5 and 6 that combine method and result. Chapter 4 presents regulations and commonly used countermeasures to prevent spreading of contamination from landfills. The chapters 5 and 6 present the results and more detailed methods to create a conceptual model for Välen and a numerical groundwater model in Visual MODFLOW. Chapter 7 discusses results from the numerical modelling combined with information presented in chapter 4. The report ends with a more general discussion, conclusion and recommendations. Several appendixes are enclosed with the report presenting maps, drawings, relevant pictures and other information.

2. Site description

The Välen site is located in the south part of Gothenburg and comprises of the inner part of a sea bay (Standsbyggnadskontoret 2013). This area both on land and in water is an important environmental and recreational area. However, the area has been suffering from pollution created in earlier decades and the problems are still of social and environmental concern.

2.1 The landfill history

One of the main sources of pollution into the sea bay came from a river called *Storaån*, which was the receiving water of a waste water treatment plant operating between 1953 and 1974 (Ramböll 2017). After the closure of the waste water treatment plant, the pollution of the river and bay was still an issue since it affected the fauna severely (Magnusson et. al. 2014). Parts of the bay were therefore dredged to increase the speed of the recovery of the fauna living in the bottom sediments.

Figure 2. Välen landfill inside a nature reserve area marked with a red line. The landfill is located between Välen bay and Åkared sport centre, with football fields and indoor sport halls, and south of the landfill is a residential area located. (© Lantmäteriet)

The Välen dredge deposit was created from autumn 1976 to spring 1977 (Göteborgs vatten och avloppsverk 1977). At first, a test dredge lagoon was built in 1976 to evaluate if the procedure would be successful and the year after, the main dredging was implemented. The cover with lime sludge, from *Ryaverket*, was finished in 1980 (Elisabet Porse personal communication 2018). However, this procedure resulted in many complaints from the public living or working in the area (VA-verket Göteborg 1975 - 1979). The creation of the landfill is presented in figure 3 and 4 below, which shows changes in the area from 1963.

Due to the high ecological values in the area, a national reserve status was created in 2013, which includes the landfill, see figure 2 (Stadsbyggnadskontoret 2013). Several studies have been carried out to evaluate the status of the landfill and its effect on the surroundings, including the present state of Välen bay.

1963 1976

Figure 3. Aerial photography showing the land use of the area close to Välen bay. To the left, when the area in 1963 was used for agriculture. To the right, preparation for the dredge landfill and filling below the sports center in 1976 (© Lantmäteriet).

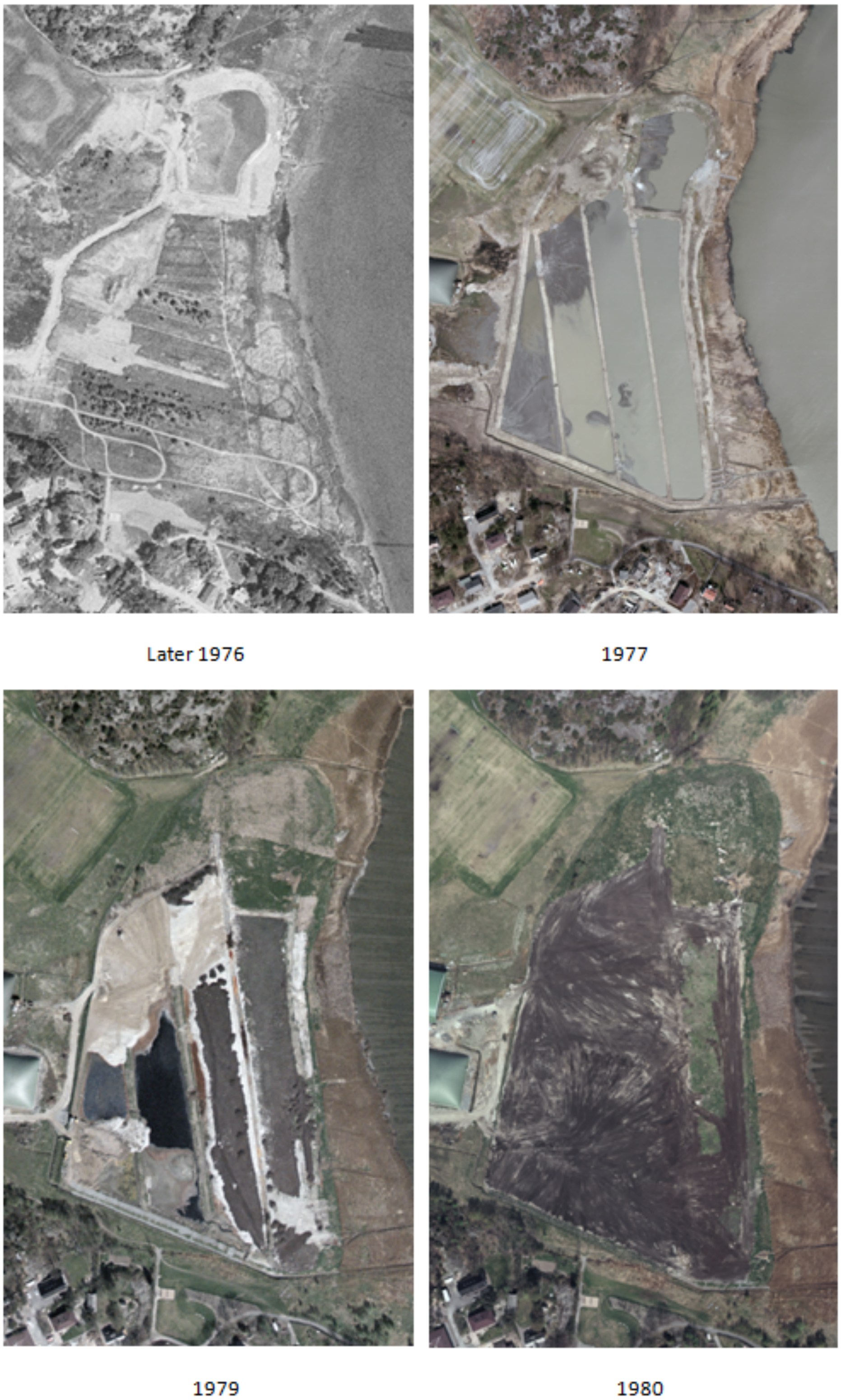


Figure 4. Upper left, test dredge with a smaller lagoon created 1976. Upper right, the embankments have been created and the dredging occurs in 1977. Lower left, during 1979 the dredge is covered with limed sludge. Lover right, in 1980 the entire dredge landfill is covered with limed sludge (© Lantmäteriet).

2.2 Previous actions and investigations

Several academic reports with different objectives have been carried out investigating the landfill at Välen (Jamali and Skantz 2012; Karlsson 2014; Dinger et.al. 2016). Most of the available literature describing Välen focused on the water quality in the landfill or its effect on the surroundings. However, the groundwater flow in the landfill has not been properly evaluated, which according to COWI (2012 a.) is necessary before suggesting measures to prevent leakage of leachate.

A control program was implemented 2004 (Elisabet Porse personal communication 2018), after recommendations from Golder (2004). These recommendations highlighted that the state of the landfill at Välen needed to be evaluated and that countermeasures where needed. A report from the control program is prepared yearly and information from these reports has been used in this master thesis. A drainage well and an impermeable barrier was constructed at the south embankment during 2005 (Elisabet Porse personal communication 2018). The drainage well was constructed to filtrate leachate and to use for monitoring. However, these measures were proven insufficient due to that the flow in the drainage well has been too low. Hence, leakage at other locations likely occurs.

In 2012, COWI made an environmental and geotechnical investigation of the area and concluded that the situation was unsustainable and that countermeasures were needed. However, COWI also suggested further investigations to be carried out before decision of which countermeasures to implement should be taken. From a geotechnical perspective, it was concluded that the area currently was stable, but that complementary calculations should be carried out if masses are to be redistributed or added. Jamali and Skantz preformed a study in 2012 where potential leachate treatment methods were investigated. The study mainly focused of leachate discharging from the landfill's southwestern edge since most of the leachate was assumed to leave the landfill there. They tried adsorption with activated carbon columns as a pilot plant project and concluded that activated carbon would be the preferred method to use if an on-site treatment plant would be used at Välen.

In 2013, locations of leakage were investigated by Sweco (2013). Leakage was located through a visible drainage pipe in the south part of the embankment and some leakage was assumed to occur at different locations lime deposits were found. Leachate was assumed to be the cause of areas with visual lime deposits, due to the lime content in the sludge material in the landfill.

Karlsson (2014) investigated the effects of the landfill on the sea bay, as did Magnusson et.al. (2014). The conclusions were that the area is severely contaminated and that some fish species should not be consumed due to contamination. However, the dredge landfill was not the only source of pollution and to only focus on countermeasures there would not solve the whole problem with the sea bay (Karlsson 2014). Dinger et.al. (2016) made a conceptual model from existing and gathered information about the landfill. It included soil classification from surface sampling, electrical conductivity, slug tests and a geographic information system (GIS) analysis. However, there were still uncertainties in how the system correlates with the surroundings. Therefore, this study was very useful in the further evaluation of the hydrogeological characteristics at the Välen landfill.

3. Methods

The methods that were used in this master thesis were to

1. Review literature and other information
2. Collect data of groundwater levels in the case study area
3. Develop a conceptual hydrogeological model of the area
4. Develop a numerical groundwater model.

A literature study was carried out to use the information to create a conceptual model and find possible measures for the case study site. Site specific literature was an important tool to create a conceptual model. Especially the thesis written by Dinger et.al. (2016), with the goal of creating a conceptual model for the dredge landfill at Välen, was useful in the process. Documents from the creation of the landfill and information from earlier investigations were gathered from the Region Archive in Gothenburg and from *Kretslopp och vatten,* which is the municipal department responsible for the landfill.

The flow pattern in the landfill was evaluated by creating conceptual and numerical groundwater models. The numerical model in Visual MODFLOW was used to evaluate how sensitive the method was with respect to the choice of conceptual model and parameter values used. Data used for the numerical model was collected partly from earlier measurements, partly from new measurements of groundwater levels in the landfill and other information gathered from the site. The available data was used to set up a model, but additional data were needed to calibrate the model. Data from Lantmäteriet and the Geological Survey of Sweden (SGU) were used for estimation of inflow into the landfill area and also to estimate location of the embankments in the landfill. Precipitation and evapotranspiration estimations were made from information provided by the Swedish Metrological and Hydrological Institute, SMHI. All information was used for developing conceptual models. Observed groundwater levels was used to interpolate groundwater table maps and estimate flow patterns when the numerical groundwater model failed.

Countermeasures were implemented in the model after construction and calibration to ensure that the model represented reality properly. For Välen, the most interesting measures to investigate were vertical closure and horizontal covering described further in chapter 4. These countermeasures were implemented by placing an impermeable barrier along the inflow line to the landfill. To place an impermeable layer over the sludge, to prevent infiltration to occur, was also considered. Due to the geotechnical instability in the area and costs, it was investigated which parts of the landfill that should be prioritized to cover.

4. Conceptual description of countermeasures

Contaminated leachate can be handled in several different ways and for each specific site, a suitable solution needs to be evaluated (Swedish Environmental Protection Agency 2009; Swedish Environmental Protection Agency 2004). Many landfills that were closed during the 1960s and 1970s now need improvement of cover due to aging (Länsstyrelsen Västra Götaland 2013). The Swedish Environmental Protection Agency (2009) stated that there are different approaches of countermeasures to limit the effect of contaminated areas on human health and the environment. The preferred countermeasures should be the ones that reduce the contamination at the source, whereas protective measures should be used when reduction is not possible, and concentrations exceed acceptable requirements. The Swedish Environmental Protection Agency consider other so-called administrative measures, including restrictions regarding land use and groundwater use, to only be implemented during short periods or to be combined with other countermeasures.

In the following sections, requirements regarding landfills sites according to Swedish legislation and selected countermeasure alternatives commonly used for landfill sites are presented.

4.1 Legal requirements of countermeasures at closed landfills

Legal requirements are set to landfill sites to ensure that the spreading of contamination is restricted (Swedish Environmental Protection Agency 2004). In Sweden, the ordinance (2001:512) on the Landfill of Waste describes the legal requirements. The main characteristics of this ordinance are to ensure that sufficient geological or constructed barriers exist. Depending on the classification of the content in the landfill, the requirements on the barrier differs in accordance with paragraph 20. The paragraph states that the permeability of the barrier should be lower than or equal to 10^{-9} m/s and a constructed barrier should be thicker than 1 meter for non-hazardous material and thicker than 5 meters for hazardous material.

If any risk of flooding or leakage exists, additional measures are needed in accordance with paragraph 21 (Sveriges Riksdag 2018). These measures should be placed in the flow direction to ensure that the requirements in earlier paragraphs are met. Generally, these protection measures should have a long lifespan and be designed with regard to the characteristics of the leachate and the sensitivity of the surroundings (Swedish Environmental Protection Agency 2004). Furthermore, the ordinance declares in paragraph 23 that landfills should be protected from intrusion of surface runoff or groundwater (Sveriges Riksdag 2018). According to the Swedish Environmental Protection Agency (2004) countermeasures should be based on hydrogeological characteristics and water balance calculations. Materials with equal and long lifespans should be used in countermeasures solutions to ensure the function during several decades. Countermeasures should also be passive to reduce the need of maintenance. Measures should not induce leachate to mix with non-contaminated surface or groundwater.

For old deposits, the owner is responsible for a cover, constructed to allow leachate to pass through the cover not to exceed 5 $l/m^2/year$ for hazardous material and 50 $l/m^2/year$ for non-hazardous material (Sveriges Riksdag 2018). The closed cover should have a slope of minimum 1:3 and maximum slope 1:2 (Swedish Environmental Protection Agency 2004) and have a depth to handle influence of erosion or frost in the ground. However, the thickness should not be less than 1.5 m due to risk of root penetration.

4.2 Typical countermeasures of closed landfills in Sweden

There are many different countermeasures that could be used to prevent spreading of leachate from landfills (Swedish Environmental Protection Agency 2008). However, it is more problematic to install measures for old landfills than for new constructed modern sites. Landfills are described as closed after the operational phase (Swedish Environmental Protection Agency 2004). This chapter describes the main characteristics of some chosen methods to prevent leachate from polluting the surroundings of landfills. A detailed description of treatment in wastewater treatment plants or on-site treatment plants was not included in this report. Jamili and Skantz described, in their master thesis 2012, possible countermeasures for treatment of leachate in an on-site facility at the Välen landfill. Therefore, those measures were not investigated further in this project. The focus has instead mainly been on passive solutions that could reduce diffuse leachate to migrate untreated to the surroundings.

4.2.1 Infiltration prevention

Countermeasures for closed landfill often include limitation of leachate production (Swedish Environmental Protection Agency 2009). As mentioned in chapter 4.1 it is required to prevent production of leachate (Sveriges Riksdag 2018), which could be achieved by preventing infiltration of precipitation or to install a barrier around the polluted area to reduce inflow of groundwater or surface run-off (Swedish Environmental Protection Agency 2008). Prevention of infiltration reduces non-contaminated water from becoming leachate. This follows the recommendations from the Swedish Environmental Protection Agency (2009) to prevent the sources of leachate production.

The infiltration can be reduced by cover with an impermeable material, which can be natural or constructed. Cover can be defined as simple cover that reduces spreading of gas, particles and direct exposure or closed cover, which reduces the potential of precipitation to infiltrate and create leachate (Golder 2004). By closed cover, the infiltration can be reduced to approximately 200 mm/year with natural materials or theoretically impermeable with impermeable materials. A closed cover can be constructed by using clay of 0.5 meters thickness covered by a protective layer of 0.5 – 1 meter till.

4.2.2 Vertical barriers - drainage ditches and impermeable barrier

Old landfills are often drained with ditches that collect the leachate (Swedish Environmental Protection Agency 2008). The ditches need to be deep to secure that leachate, which has reached the groundwater, discharges to a constructed ditch. Since groundwater inflow is common at old landfills, it is also necessary that the ditches are deep to prohibit inflow (Swedish Environmental Protection Agency 2008). Double ditches or a cut-off wall around landfills can be used to avoid contamination of unaffected groundwater or surface run-off that enters ditches around a landfill. Vertical closure, as well as infiltration, follows the recommendations by the Swedish Environmental Protection Agency (2009) to prevent the leachate to form as first option.

Cover or enclosing should be followed by monitoring to ensure the function of the measure to be sufficient to reduce the health and environmental risks to an acceptable level (Swedish Environmental Protection Agency 2009).

4.2.3 Removal or replacement of waste

This measure relocates landfill masses with the purpose to reduce the area of possible infiltration (Golder 2004). It can potentially also mean to move the waste to another location, but that is rarely an option. Golder (2004) stated replacement as an option for Välen since the masses could be compacted to cover a smaller area, which would lead to that less infiltration of rainwater can occur.

4.2.4 Wastewater treatment plants

In Sweden, it is common to use wastewater treatment plants for treatment of leachate (Swedish Environmental Protection Agency 2008). However, this method can lead to problems in the treatment process depending on leachate composition. Treatment of leachate in wastewater treatment plants can be considered a simple solution since the infrastructure usually is already in place (Flodin 2015). However, the leachate can restrict respiration or nitrification in the treatment plant and also affect the sludge created in the plant. Leachate is also often corrosive, which can affect the collection network. Due to that the wastewater treatment plant in Gothenburg already have troubles to meet the needs of the city (Mattson 2015) and that leachate can affect the collection network and treatment plant efficiency, this solution is not optimal for the dredge landfill at Välen.

4.2.5 Leachate treatment pond

Treatment ponds are used for various kinds of treatment of water (Swedish Environmental Protection Agency 2008). Regarding leachate in Sweden, this method is usually used as a pre-treatment option. Leachate is collected in a pond with impermeable bottom and sides. Several ponds in a row or barrier walls can be used to increase retention time in the pond. For treatment ponds to be effective, aeration can be necessary. This method reduces the Biological Oxygen Demand, BOD, and partly metals, while the treatment of Chemical Oxygen Demand, COD, is uncertain. This method has some advantages as the use of technical solutions is low as well as the costs and labour. However, the method needs effective aeration and is dependent on temperature, which can be a problem in cold climates (Swedish Environmental Protection Agency 2008). Furthermore, moderately large areas are needed, and this method usually requires complementary measures. This could mean that the required space for a leachate treatment pond could be 0.5 – 1 ha.

At Välen, methods with large spatial requirements were not possible to implement due to that the landfill is located inside a sensitive nature reserve area and that additional treatment methods probably are needed for sufficient treatment. At present, no collection of leachate makes it possible to control it to enter a pond.

4.2.6 Constructed wetlands

Wetlands are good at treating ammonium (Swedish Environmental Protection Agency 2008) but can also treat other pollutants (Flodin 2015). The wetlands should be oxygen rich, which can be achieved by wetland vegetation and low water depths of 0.5 – 1 meter (Swedish

Environmental Protection Agency 2008). Wetlands offer moderate treatment of BOD, COD, organic pollutants, ammonium and metals (Flodin 2015). The use of technical installations is limited in this method, alongside with low use of chemicals and labour. However, like the treatment ponds, this method requires supplementary treatment methods and large available land for construction of a wetland close to the landfill site. As described for treatment ponds, measures requiring large spatial areas are not a realistic option for the dredge landfill at Välen.

4.2.7 Overland flow of leachate

Overland flow, or warping, means that water is spread and allowed to flow over a sloping soil surface (Swedish Environmental Protection Agency 2008). Infiltration should be avoided not to create contaminated land or affect groundwater. This method makes the water rich of oxygen that helps nitrification of ammonium to occur. Metals and organic materials can be sorbed to the ground materials and be separated from the leachate. Overland flow can be combined with wetlands. Since nitrification then occurs before the water enters the wetlands, the treatment becomes more effective. For overland flow to be used as a treatment method, it is required that the water is collected for control before it reaches recipient waters.

This solution, as many others, is optimal when combined with other methods (Swedish Environmental Protection Agency 2008). For Välen a simple solution was needed, and no large areas are available. Therefore, this solution might not be the optimal solution for the dredge landfill.

4.2.8 Irrigation of soil-plant systems

The process of using leachate for irrigation has similarities with overland flow and likewise the water need to be controlled, for this method to be counted as a treatment method (Swedish Environmental Protection Agency 2008). However, irrigation focuses more on the sorption of contamination by plants. Depending on the characteristics of the leachate, the soil can possibly get contaminated. Irrigation of leachate for so called energy forest mainly reduces the volume of leachate, but also reduces the pollutant concentrations by sorption to soil particles. The method is regulated by seasons due to that irrigation needs varies over the year. Therefore, large storage capacity is needed to store leachate during periods when less irrigation is performed. This method was not regarded suitable at Välen mainly due to that large areas needed.

4.2.9 Recycling leachate back to the landfill

An alternative measure method is to collect leachate and pump it back into the landfill site (Abbas et.al. 2009). This method is widespread mainly due to that it often is the least expensive solution available. However, the efficiency has been questioned and it can cause instability in the landmasses. The landfill area at Välen is presently stable (COWI 2012 a.) but landslides have occurred in the area (Elisabet Porse personal communication 2018) and a solution that potentially affects the stability cannot be considered without further investigations.

4.2.10 Infiltration through barrier

Infiltration through a barrier is a common method to reduce contamination (Swedish Environmental Protection Agency 2004). The barrier can be either natural or constructed. A constructed barrier should be built up by specially processed clay mix with sand or stone dust, and it is important to ensure that the barrier fulfil legal requirements by monitoring water quality. To ensure that the flow time through the barrier is adequate, it needs to be constructed with sufficient hydraulic and sorption capacities. Otherwise, there is a risk of flooding or leakage from the landfill. In landfill areas with geological barriers, no construction work is allowed, which have the potential to affect the flow or flow time through the geological barrier.

Many filter materials are good at removing organic components but are insufficient for metals (Swedish Environmental Protection Agency 2004). Peat is a material that can treat both metals and organic contaminations. The material is relatively cheap but has a short lifespan and does not work effectively at a high pH of incoming water. The leachate from the dredge landfill has a high content of metals. However, peat as a material is not suitable to combine with the leachate at Välen due to the high pH of over 12 (Ramböll 2017) and that any considered solution must have a long lifespan (Swedish Environmental Protection Agency 2004). The hydraulic conductivity of a barrier material should not exceed $5 \cdot 10^{-10}$ m/s according to Helldén et. al. (2006).

4.2.11 Countermeasures to further consider in this project

Generally, passive methods with low cost and with low maintenance requirements are suitable for landfills like Välen. Impermeable barriers, like improved cover and cut-off walls, were the methods evaluated in the hydrogeological model. These were regarded as the two most interesting countermeasures for Välen due to the space limitation, long time spans and with regards to the recommendations from The Swedish Environmental Protection Agency (2009) to treat the source of leachate formation. Table 1 describe the suitability of the different considered countermeasures.

Table 1. Suitability of countermeasures

Countermeasure	Suitability	Comment
Infiltration prevention	Suitable	Need geotechnical investigation
Vertical barrier	Suitable	Need geotechnical investigation
Removal or replacement	Not suitable	Could cause geotechnical instability
Wastewater treatment plant	Not suitable	Can cause problems in the treatment plant and collection network
Wastewater treatment pond	Not suitable	Require large land areas and require additional treatment
Constructed wet lands	Not suitable	Require large land areas and require additional treatment
Overland flow of leachate	Not suitable	Require large land areas and require additional treatment
Irrigation of soil-plant system	Not suitable	Require large land areas and require additional treatment
Recycling leachate back to the landfill	Not suitable	Could cause geotechnical instability
Infiltration through barrier	Possibly suitable	Require further investigations

5. Conceptual model

A conceptual model with focus on groundwater flow conditions was developed to highlight important characteristics of the landfill and it was the basis for the numerical model. The information was collected from literature describing earlier investigations, maps, construction plans and field investigations.

5.1 Geology and landfill construction

The bedrock in the area can be characterised as gneiss with some deformation patterns (SGU 2018). The soil cover is presented in a map from SGU showed in figure 5. The bedrock is covered with marine clay, and potentially with a glacial till layer in between, for the main part of the area, and closer to the shoreline, the clay contains organic material (gyttja). The clay underneath the landfill was estimated to have an approximate mean thickness of 12 meters. The natural clay layer was assumed to be impermeable and the bedrock and potential till layer was therefore not further investigated in this project. North, west and south of the landfill are outcrops of rock and some areas with sand and glacial till. Filling material covers a larger area than the boundary of the landfill as can be seen in figure 5.

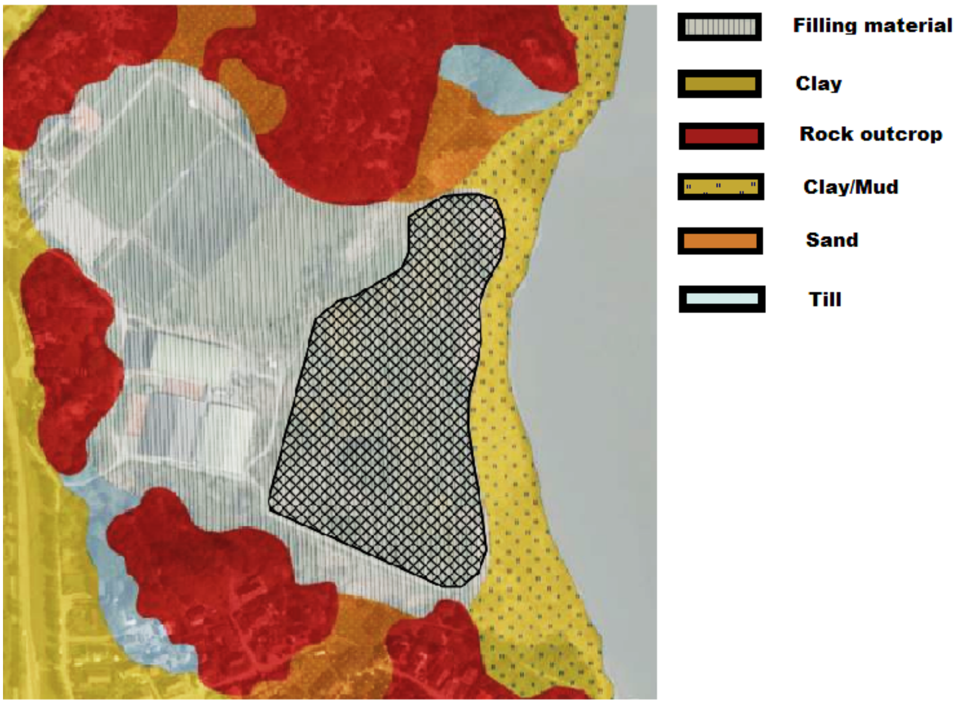


Figure 5. Quaternary map provided by SGU (2018).

The area is relatively flat and available terrain data did not allow any description of the landfill surface in the detail preferred in this project. Lantmäteriet provided laser scanned data, but the area was scanned with relatively sparse intervals and small differences in elevation were therefore hard to distinguish.

The landfill system could be described as complex due to that the layers were not naturally created and therefore geological history only gives answers about the natural underlying layers. Site investigations are important in the process of finding the characteristics of each layer. However, site investigations only cover a minimal part of the considered site and therefore historical documents could give more information of the geological features of the man-made landfill.

Documents created by VA-verket Göteborg from the 1970s revealed that the filling materials below the football fields contain everything from excavation material to construction material. A letter, archived at the Region Archive in Gothenburg, describes that for example stoves and other electronic devices were included in the filling material. The composition of the fillings underneath the sports area will therefore likely be highly variable (SGU 2018; VA-verket Göteborg 1975).

Profiles representing the landfill at Välen are presented in figure 6 below. These were based mainly on data collected by Dinger et.al. (2016) but also on old photographs from the construction of the landfill, maps from SGU (2018), field observations, communication with Elisabet Porse from Kretslopp och vatten, and earlier reports describing the landfill. Technical descriptions and plans, describes the construction of the embankments and the features like drainage pipes. The average thickness of the sludge was 1.76 m while the average thickness of the dredge layer was 0.4 m (COWI 2012 b; Melica 2009). The embankments were built to a height of 2 m except of the embankment closest to the sea bay with a height of 3 m. However, the embankments were flattened during the end of the construction phase when the dredge material was covered with sludge. Therefore, the exact present height of the embankments is unknown.

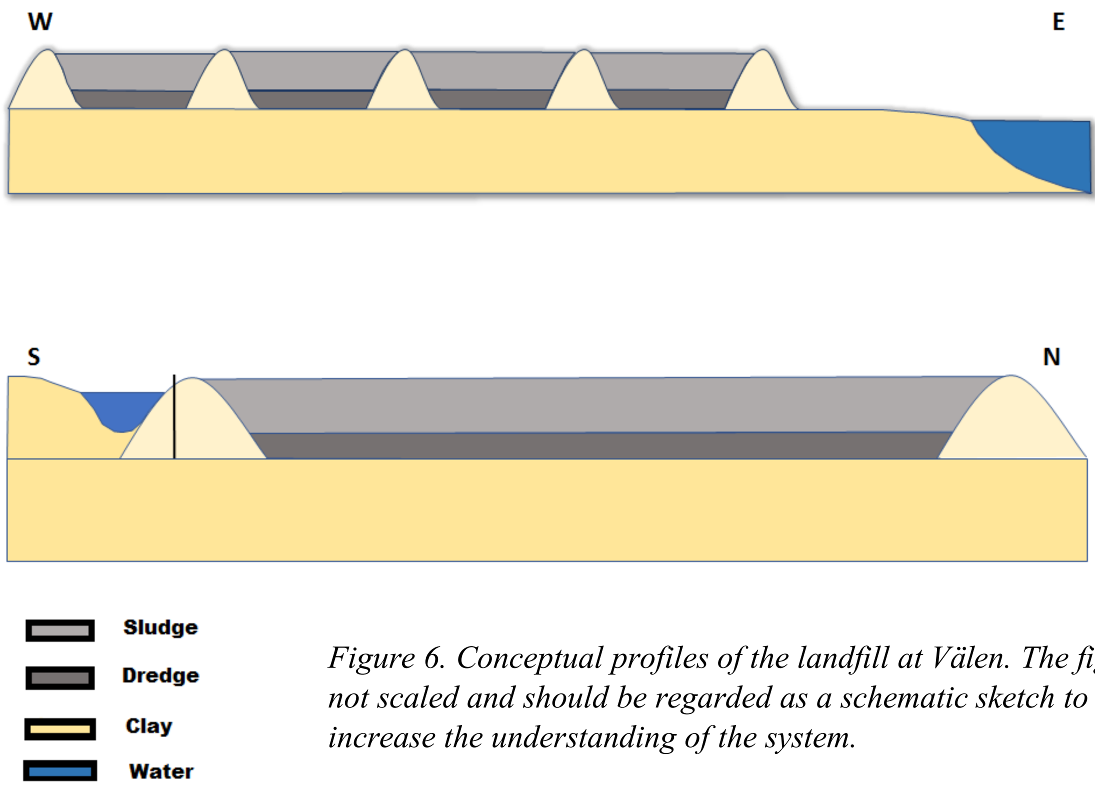


Figure 6. Conceptual profiles of the landfill at Välen. The figure is not scaled and should be regarded as a schematic sketch to increase the understanding of the system.

The landfill was created in two parts, first a test dredging was tested for a smaller area in the north part of the landfill. Photographs from the construction of the landfill are presented in appendix A. This was made to test the planned properties of the embankments used for the landfill. However, the first embankment consisted of a 20 meters long stone filter that was concluded to be too permeable (VA-verket Göteborg 1976), due to that too many suspended particles returned to the sea bay. The embankment was complemented with a sand filter and a filter made of nylon, which turned out to be too impermeable. Therefore, a drainage pipe was constructed in the test dredge embankment. This drainage pipe has been located at field visits and is marked at the plan for the landfill construction, in appendix B (VA-verket Göteborg 1976). Flow out from the landfill through this drainage pipe is likely based on field observations. However, the flow could not be evaluated and was therefore not included in the numerical model. Old construction plans show that the drainage pipes in the south parts of the landfill were placed on level with the sludge layer, see appendix B. The ground water levels in the monitoring well GV2 indicate that the drainage pipes in the south part of the landfill potentially could affect the level inside the landfill. A visible pipe end was found and a flow from the pipe has been observed after days with rain and snow melting. However, the pipe does not have a flow out from the pipe end at most observations occasions during the spring 2018. Smaller separate parts of concrete pipes were found during field visits and it was assumed that the pipes were crushed after the dredging was finished and no longer have a draining function.

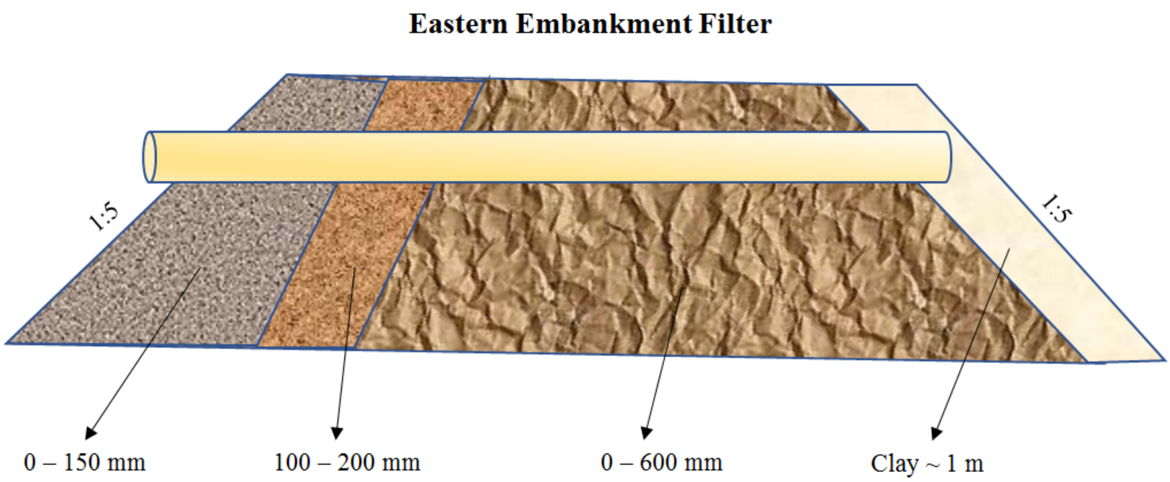


Figure 7. Embankment construction with grain sizes for the embankment facing the sea bay (based on drawings from VA-verket 1975).

The construction plans showed that the eastern embankment was created as showed in figure 7 with material of small grain size closest to the dredge and sludge material with a gradual increase in grain size to the outer part of the embankment. The outer slope of the embankment is covered with a clay layer. The landfill was constructed with four inner embankments to give a longer delay time when the dredge material was drained at site (VA-verket Göteborg 1976). These embankments were constructed with filling material, which resulted in a spatial variation of properties of these embankments, verified when new measurement wells were installed. The inner embankments were constructed with spillways for the draining of the dredge material during construction. The present function of these spillways is unknown. Early construction plans show drainage pipes at the bottom of the eastern embankment. However, it is assumed that these were never installed due to that it is not showed in later construction plan drawings (VA-verket Göteborg 1975; VA-verket Göteborg 1976).

The surface material at the landfill is variable according to investigations made by Dinger et.al. (2016). Sludge, till, sand and clay have been found at the surface. The clay was assumed to have been added when a small road was constructed at the southern edge of the landfill. The till found at the surface was likely the uppermost part of one of the embankments, which was no longer covered with sludge. Sand was found at the surface but very locally and with no clear purpose. When the landfill was covered, it seems like the embankments were covered with limed sludge. However, erosion could possibly reveal the eastern embankment inside the landfill. Settlements have likely occurred and could affect the flow direction in parts of the landfill. During 2018 new monitoring wells were installed at the landfill and it was concluded that the cover of sludge thickness had a large variation and that some parts of the embankments were covered with sludge while some parts were not.

An impermeable barrier was constructed in the south embankment in 2005 as a countermeasure to drain leachate to a drainage well (Elisabet Porse personal communication 2018). However, this has been showed to be inefficient due to that the drainage does not lead water to the drainage well installed in the south-east corner as planned. Appendix C shows the location and a photograph of the barrier in the south embankment.

5.2 Groundwater characteristics

At Välen, the groundwater conditions are characterised by low flows and polluted groundwater due to the flow through contaminated masses (Jamali and Skantz 2012). Most of the landfill was assumed to be saturated and the groundwater level is close to the surface in some monitoring pipes in parts of the landfill and standing water was observed at the landfill surface.

The hydraulic gradient of the groundwater table within and around the dredge landfill was estimated from groundwater monitoring wells, showed in figure 8. The wells were installed in different stages with the first two, GV1 and GV2, in 2008. In 2012, three additional wells where installed and since then, all wells have been measured twice a year as a part of the control programme (Ramböll 2017). New monitoring wells were installed 6 April 2018 to evaluate the hydraulic gradient in the landfill. The locations of the groundwater monitoring wells are shown in figure 8 below. The new monitoring wells were placed to investigate how the embankment affects the groundwater. Earlier, the general understanding has been that the hydraulic gradient slopes towards the sea. However, that assumption was based on a coarse approximation of surface elevation and did not consider the construction of the landfill or the ditches present around it. An alternative for the general flow in the landfill is described in chapter 5.4.

Figure 8. Groundwater monitoring wells at the landfill. Wells installed 2008 is marked with green, 2012 with blue and 2018 with red. The wells are presented with a contemporary background to the left and a background from 1977 revealing the location of embankments (© Lantmäteriet).

5.3 Hydraulic boundaries

The complex landfill system has been divided into five different parts separated by embankments which were filled with dredge during construction (Dinger et. al., 2016), see figure 8. A diffuse leakage was assumed due to findings by Jamali and Skantz (2012) and observed lime deposits along the embankments and at the ground surface (Dinger et.al. 2016). A diffuse leakage has been assumed to occur around almost the entire landfill, due to the hydraulic gradients observed in the landfill and an assumption that the inner embankments are more permeable than other materials in the landfill.

No clear compartmentalization with no-flow boundaries can therefore be assumed, but fluxes can occur around the entire landfill. The catchment area was therefore assumed to be the boundary for the maximal inflow into the landfill. Figure 9 shows the catchment area from where the possible inflow is estimated. An urban area in the south part of the catchment has connected drainage system that was removed from the system and does not amplify the inflow to the landfill. Some part of the catchment is estimated to be connected directly to ditches. These ditches make some of the water pass the landfill, without inflow to the contaminated masses in the landfill. The dredge and sludge are located above the surface level in the ditches surrounding the landfill. Therefore, the water that discharges to the ditches is assumed to not affect the landfill. This assumption was made due to the higher groundwater level in the landfill compared to the water levels in the ditches and the elevation below ground level of the different stratigraphic layers (Dinger et.al. 2016). Ditches around the landfill cut off the surface runoff from large parts of the catchment and inflow to contaminated material has therefore been assumed to be prevented.

Inflow to the model area was estimated as an interval with one lower and one higher value. The lower value was based on the minimum expected surface runoff from above the model boundary area. The higher value represents the possible groundwater inflow added to the expected surface runoff. The surface runoff was based on s the land surface elevation data of the area. Kretslopp och vatten has provided information of surfaces connected to storm water draining systems. A large part of the runoff was estimated to enter the ditches south and north of the model, which do not enter the landfill masses. Hence, that water does not become contaminated. However, the groundwater flow in to the model area was harder to predict partly due to the unknown properties of the filling material.

The sea level from SMHI (2018) has the monitoring point located at *Torshamnen* outside Gothenburg, which is located far from *Välen*, see appendix D. Due to that the sea level indicator was dry during several years at the time of monitoring occasions; the information has been gathered from SMHI instead. The variation at *Torshamnen* was regarded as low and due to the distance to *Välen* a seawater level of 0.3 m from a construction plan from 1976 was used.

Figure 9. Catchment area with potential inflow to the model area. The catchment area together with the sea bay and ditches was set to boundaries. The catchment described as a red line, the sea bay with a blue polygon and the blue lines as ditches.

5.4 Hydraulic features

The hydraulic characteristics of the landfill can be described as waste in form of dredge and sludge with low permeability. Especially the limed sludge cover of the landfill has been estimated to have had a hydraulic conductivity of approximately 10^{-9} m/s (Helldén et. al. 2006), which is regarded as adequate to use as cover material at landfills (Sveriges Riksdag 2018). However, at Välen, the hydraulic conductivity is likely not that low today due to aging of the material, potential dry cracks and root penetration. Dinger et.al (2016) also questioned the effectiveness of the limed sludge to be impermeable. Based on field observations from 2018, it was assumed that the yearly net recharge infiltrates through the limed sludge. Melica (2010) does not describe the permeability of the materials used in the landfill but states that the sludge and dredge is more compact than the embankments in and around the landfill masses.

The general understanding from earlier studies of the area is that the embankments kept water inside the landfill (Dinger et.al. 2016; Ramböll 2017). However, earlier investigations have indicated that the assumption could be incorrect. Since the embankments are constructed by various filling materials, including clay, sand, sludge, gravel and pieces of brick, these constructions might rather act as drains of the system. Dinger et.al (2016) mention parts of this, especially that the previously assumed permeability conditions of the embankments can be questioned. However, earlier studies have not mentioned the fact that the embankments can act as drains, which potentially changes the assumed hydraulic gradients. Ramböll (2017) even states that the embankments are compact and impermeable, except in some observed leakage points in the southern ditch. The assumption that the embankments can act as drains could not be verified without further investigations. Therefore, monitoring wells in the embankments were necessary to validate this condition. Figure 10 presents a schematic figure of the possible flow through the landfill with the assumption that the embankments act as drains. Table 3 describes different conceptual model scenarios used to evaluate the properties in the landfill.

The measured head values from the wells in the landfill indicate that the water level was lower in the embankments in some parts. However, in the south part (GV3, GV4 and GV5) of the landfill the gradient was not clearly affected by the presence of the inner embankments. Head values are presented in table 2 below. This indicates that the embankments do not prevent flow and that these potentially could have a draining function. This indicates that there could be a spatial variation of the water bearing capacity of the inner embankments in the landfill. Since the embankments were created with inhomogeneous filling material a variation in water bearing capacity is likely. The sloping gradient in the northern monitoring wells could potentially also be connected with the sloping ground elevation. The main conclusion from the measurements was that the gradient is not entirely towards the sea as assumed in earlier studies of the landfill. Figure 11 presents profiles of hydraulic gradient for an example section of the landfill.

Figure 10. Schematic flow through the landfill with the assumption that the embankments act as drains.

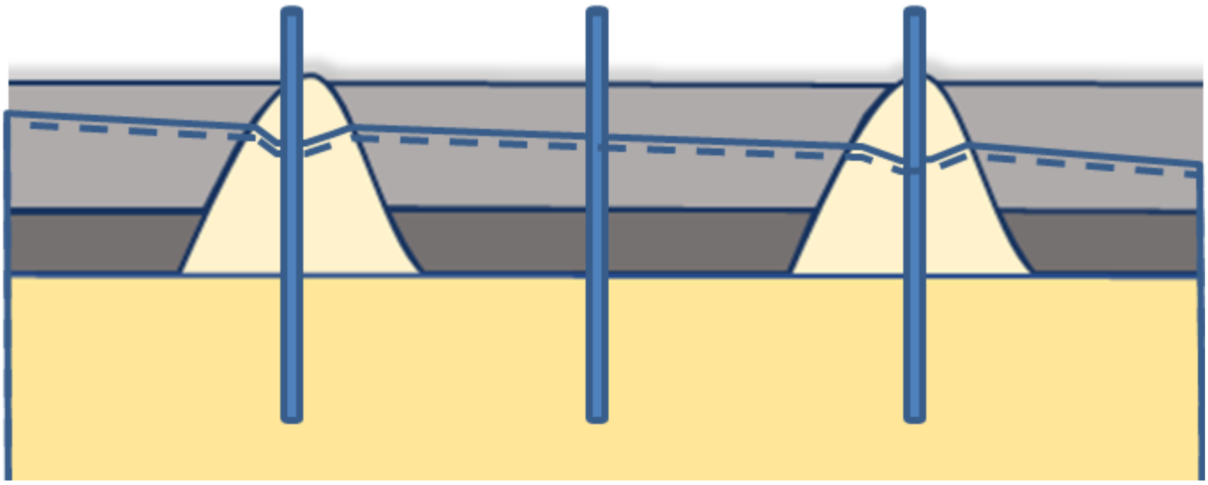


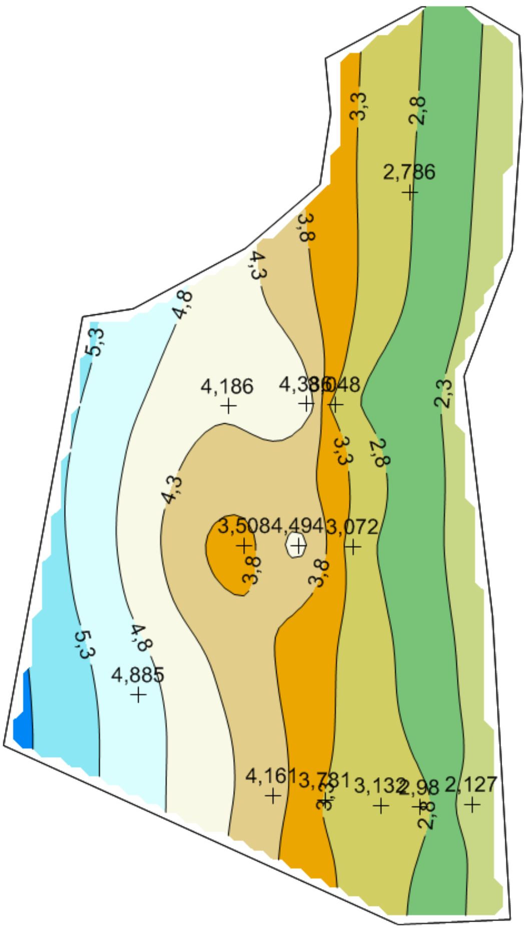
Figure 11. Example profile of the hydraulic gradients within the landfill.

Table 2. Observed heads in monitoring wells during the spring 2018.

Monitoring well	*GV5*	*GV4*	*GV3*	*Observation Date*
Observed head [m]	*4.16*	*3.78*	*3.13*	*12/04/2018*
	4.06	*3.46*	*3.10*	*23/04/2018*
	3.99	*3.24*	*3.03*	*09/05/2018*
Monitoring well	*GV8**	*GV7**	*GV6**	
Observed head [m]	*3.51*	*4.50*	*3.07*	*12/04/2018*
	3.64	*4.42*	*3.16*	*23/04/2018*
	3.63	*4.41*	*3.13*	*09/05/2018*
Monitoring well	*GV10**	*BH5**	*GV9**	
Observed head [m]	*4.19*	*4.39*	*3.05*	*12/04/2018*
	4.37	*4.47*	*3.23*	*23/04/2018*
	4.36	*4.45*	*3.24*	*09/05/2018*

**The three different columns represent the three monitoring wells showed in figure 11.*

The observed head values were used to interpolate an approximate water table in the landfill, see figure 12. The interpolation was made with minimum curve interpolation. The sink given by one of the monitoring wells indicates that the embankment affects the gradient. Some parts of the landfill are not represented with monitoring wells, giving that the water table in these parts is not represented sufficiently. The western part of the landfill is known not to be represented well in the interpolation.



The uncertainties of the hydraulic features in the landfill were considered by constructing different conceptual models with alternative hydraulic conductivity values to evaluate the sensitivity of the model. The variable features are the characteristics of the embankments and the sludge layer. The hydraulic conductivity of sludge from Gryaab AB in Gothenburg has according to lab tests a value of between 10^{-8} and 10^{-10} m/s (Carling et.al. 2006). However, this does not account for the ageing of the material from decades of outer influence and the tested material in the study was not the exact material used at Välen. The hydraulic conductivities for the alternatives of conceptual models for the Välen landfill is presented in table 2. The values are estimations based on soil samples and written information from earlier investigations and a few slug tests from 2016.

Figure 12. Interpolated groundwater levels from observed values. (Figure created by Jonas Sundell, Chalmers).

The slug tests by Dinger et. al. (2016) was assumed to represent the dredge layer. However, there were uncertainties of the construction of the monitoring wells used for the slug tests. Therefore, the material measured in these tests was uncertain and could possibly be a sand filter around the borehole instead of the landfill materials.

Table 3. Hydraulic conductivity of essential features in the dredge landfill Välen.

Layer or feature	*Conceptual Model 1*	*Conceptual Model 2*
Sludge	***10^{-7} m/s***	***10^{-7} m/s***
Dredge	*10^{-6} m/s*	*10^{-6} m/s*
Embankments	***10^{-7} m/s***	***10^{-6} m/s***
Natural clay layer	*10^{-9} m/s*	*10^{-9} m/s*
Surrounding (top layer)	*10^{-6} m/s ($K_z = 10^{-7}$ m/s)*	*10^{-6} m/s ($K_z = 10^{-7}$ m/s)*

Layer or feature	*Conceptual Model 3*	*Conceptual Model 4*
Sludge	***10^{-7} m/s***	***10^{-6} m/s*** *($K_z = 10^{-7}$ m/s)*
Dredge	*10^{-6} m/s*	*10^{-6} m/s*
Embankments	***10^{-5} m/s***	***10^{-5} m/s***
Natural clay layer	*10^{-9} m/s*	*10^{-9} m/s*
Surrounding (top layer)	*10^{-6} m/s ($K_z = 10^{-7}$ m/s)*	*10^{-5} m/s ($K_z = 10^{-6}$ m/s)*

The conceptual models included uncertainties in inflow to the model. Scenarios for the inflow were therefore combined with the hydraulic conductivity as described in chapter 5.5 and 5.6. An overview of all the input data and parameters are presented in appendix E.

5.5 Sources and sinks

The approach in earlier studies has been that infiltration was the main source of inflow into the system. However, groundwater flow has not been evaluated in detail during earlier investigations. Groundwater levels inside the landfill have been higher than the level in the ditches. Therefore, no groundwater inflow has been assumed (Dinger et.al. 2016). However, this is not true for the entire area and in some parts the groundwater level was higher outside the landfill than inside. Net inflow was therefore uncertain. This uncertainty will be controlled by setting up different recharge scenarios when modelled numerically.

The sinks from the landfill, where water discharges from the system, were complex to evaluate. Some leachate leaves the landfill through a drainage well, but according to Jamali and Skantz (2012), this only accounts for 0.3 % of the water assumed to enter the landfill and therefore a diffuse leakage was assumed to occur. The amount of surface runoff was uncertain both around and at the landfill area. Some water was estimated to be discharged at the land surface creating lime deposits visible as white spots in the terrain, as can be seen in figure 13.

Leakage pathways have not been identified at the south or north embankment by field observations during 2018 but it was assumed that the water diffusively leaves the landfill through the embankments. However, water at the surface close to the embankments has been observed at several locations. At the western embankment, a clear leakage pathway was observed at different occasions. At one occasion, the road was partly flooded with potential leachate that possibly originated from the pathway, showed in figure 14 and 15. Other locations with standing water at the south edge of the landfill has been located, see figure 16. An assumed location for discharge due to sloping land elevation was observed with water at some filed occasions. Drainage pipes found at construction plans and partly observed in field was further described in section 5.1. Figure 17 shows a visible flow from a visible drainage pipe in the south-east corner of the landfill observed when the frost in the ground thaws.

Figure 13. Lime deposit area at the landfill surface (23 April 2018 & 29 March 2018).

Figure 14. Pathway through the western outer embankment and the road partly flooded (6 April 2018).

Figure 15. Pathway through the western outer embankment. Green colour indicates area with standing water at the surface of the landfill (29 March 2018).

Figure 16. Standing water close to the southern embankment, this were one of several locations with standing water at the landfill surface (6 April 2018).

Figure 17. Flow from drainage pipe, in the south part of the east embankment, observed 11 April 2018. At most occasions, this pipe end was dry. See drawing in appendix B for location.

5.6 Water balance

The water balance is an important tool to estimate the possible water volume. A water balance requires several parameters to be considered. The important components of a water balance are to conclude what enter, leaves, and stay in the system (SMHI 2017 a.).

SMHI has provided the precipitation and evaporation data used in this project. The precipitation and evapotranspiration used were general values that SMHI provides on maps over Sweden (SMHI 2017 b.; SMHI 2017 c.). These values were not site specific but since data needed to make site specific estimations was not available and not possible to collect, more advanced methods were not possible to use. Dinger et.al. (2016) have performed evapotranspiration calculations with four different methods and compared them with precipitation. Their concluded value was higher than what SMHI presents. The SMHI value was therefore used since this would give the worst-case scenario of the leachate formed.

The net recharge was calculated as precipitation subtracted with evapotranspiration and a full water balance includes potential change storage and discharge as equation 1 represents (SMHI 2017 a.).

$$\Delta S = P - R - ET \qquad \text{(Eq. 1)}$$

ΔS = Storage, P = Precipitation, R = Runoff and ET= Evapotranspiration

All water in any contact with the contaminated landfill masses was assumed to produce leachate and can be described as all water that becomes polluted on-site for a given time. The water balance was important to identify inflow and outflow to reduce the amount of water getting contaminated and prevent contaminated water to escape the system without treatment. Figure 18 presents a schematic picture of the estimated water balance.

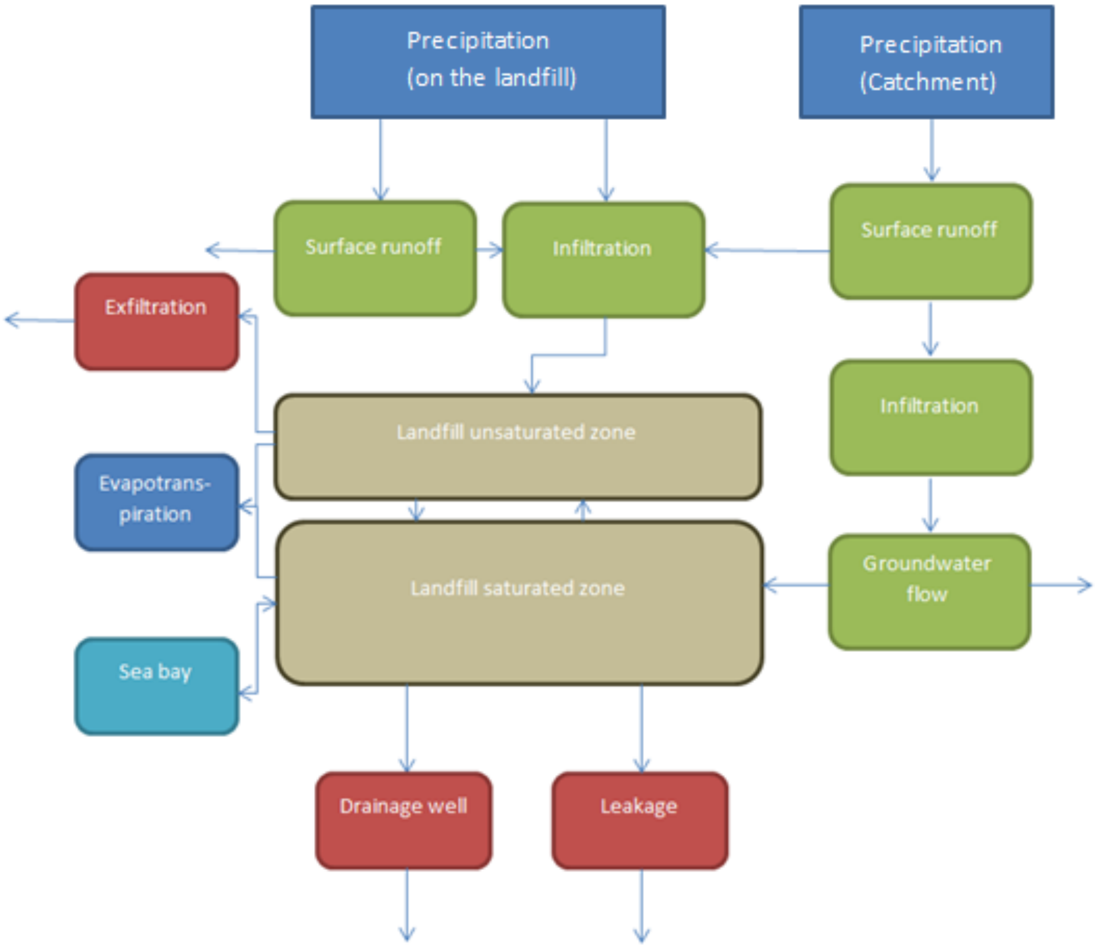


Figure 18. Water balance for the landfill system at Välen, inspiration from Dinger et.al. (2016).

The Välen landfill consists only of a smaller part of the catchment area, see appendix F. Therefore, the water balance includes inflow and outflow (SMHI 2017 a.). Equation 2 presents the water balance for a part of a catchment area.

$$Qout = Qin + P - ET - \Delta S \qquad \text{(Eq. 2)}$$

Q_{out} = Water flow out of the area, Q_{in} = Water flow in to the area, P = Precipitation, ET= Evapotranspiration and ΔS = Storage

At Välen, it was estimated that the storage capacity does not change in the system. The landfill has no extensive change in storage capacity over time and regarding the sea bay, it has been harder to estimate due to lack of information. The sea level can vary substantially, but it was not included in this water balance, due to lack of accurate monitoring and unknown correlation between the sea bay and the landfill. Precipitation in the area was estimated to an approximate value of 900 mm per year and the evapotranspiration to 450 mm per year (SMHI 2017 b.; SMHI 2017 c.).

The inflow was difficult to estimate due to the unknown surrounding properties of the area mainly due to that it mostly contains of filling masses and drainage pipes with unknown extent. The surface runoff into the landfill was from an area of approximately 5 500 m^2, which resulted in a yearly inflow of 2 500 m^3. The groundwater inflow was harder to estimate. The hill north of the landfill likely contributes to the groundwater inflow into the landfill. However, the recharge area is hard to delineate at Välen. The area of the hill north of the landfill was used to estimate a groundwater recharge area, which resulted in a groundwater inflow of approximately 10 500 m^3 yearly. The outflow has been assumed to equal the inflow and the net recharge of the system, since the system has similar groundwater heads with mostly low variation during the years of measurements (COWI 2012 a.; Ramböll 2014; Ramböll 2017). Regarding the outflow, it was known that little flow leaves the landfill through the drainage well in the south-east corner of the landfill, due to the low observed flow in the well. Therefore, leakage must represent a large part of the outflow.

5.7 Water chemistry

The water chemistry varies over the area at and around the dredge landfill (Ramböll 2017). Mercury is the main concern at Välen, with measurements showing that the mercury levels were highest in the dredge and sludge material and is lower in the embankment. Water quality measurements have only been carried out at two monitoring wells, one in the dredge and sludge material (GV2) and one in an outer embankment (GV1). Therefore, no information of spatial variation was available for groundwater. Surface water has been measured in ditches around the landfill. The chemistry varies between years and seasons in both groundwater and surface water, but generally the leachate exhibits very high pH, high organic content and high content of different forms of mercury (COWI 2012 a.; Ramböll 2014; Ramböll 2017).

No concentration of mercury has been identified in the monitoring well BH8, see appendix C, outside the landfill where an inflow is assumed, but in discharging groundwater mercury has been detected, as well as in the ditch south of the landfill (Ramböll 2017). However, no mercury can be detected upstream in the ditch at monitoring point Y2 or in GV1 placed in the exterior embankment, see appendix C. The locations of the monitoring wells were presented in figure 8. Other pollutants have been identified in L1, see appendix C, where concentration of nickel is severe and arsenic is moderate (Ramböll 2017) according to classifications from The Swedish Environmental Protection Agency (2004). Enviroplanning (2017) investigated water moss in the ditch south of the landfill and concluded that low or moderate levels of several metals can be found, but with high levels of mercury.

5.8 Pollution sources

Välen bay is, as mentioned, affected by several different sources of pollution of which the landfill is one (Magnusson et.al. 2014). According to Elisabet Porse (personal communication 2018, the area that nowadays is used as a sport centre with indoor halls and football fields was built on masses which are also potentially contaminated. This is supported by maps from SGU (2018), see figure 5, but the contents of these masses are mainly unknown. However, it was assumed that these masses are less contaminated since the content in surrounding ditches was less polluted than downstream where leachate from the landfill has entered (Ramböll 2017; Elisabet Porse personal communication 2018). These landmasses were added in 1976 before the dredge landfill was constructed, see figure 3. Some leachate seeps out from the embankment inside the dredge landfill and are indicated by lime deposits at the surface. Due to assumed diffuse leakage, the sources of pollution from the landfill to the surrounding ditches are likely to occur, but hard to identify. Electrical resistivity measurements can give some information of where the leakage is likely to occur. However, during the spring 2018 it was not possible to conduct resistivity measurements due to cold weather. The ground should not be frozen for resistivity measurements to be considered (Triumf 1992). The conditions at the site also prevent the possibility to gain clear results from resistivity measurements along the eastern embankment, due to the wet reed area close to the embankment.

6. Groundwater modelling in Visual MODFLOW

Groundwater models can be very useful tools for calculation and visualisation of groundwater flow, especially in aquifers with complex conditions (Von Brömssen et.al. 2006). Groundwater models can support decisions based on groundwater flow and particle transport in a cost-effective way. Sometimes groundwater flow models are in projects regarding to contaminated ground. Models are considered as pedagogical due to the possibilities to present results.

In Sweden, the most commonly used software systems for groundwater modelling are Visual MODFLOW and GMS (Von Brömssen et.al. 2006). Both software systems use the program code MODFLOW for calculation of fluxes, which is built on the finite difference method. Visual MODFLOW Flex 2013.1 was used as the software system in this project and the license provided by Ramböll. Tables with specific parameter values used in the numerical model are presented in appendix E.

6.1 Model construction

The groundwater model was created in Visual MODFLOW based on information from the conceptual model presented in chapter 5. The conceptual model information was used to describe and create spatial information files in QGIS that was used as input to Visual MODFLOW. These GIS files describe hydraulic features with other hydraulic conductivity than the general layers, as the embankments, but also ditches and other features in the model. Boundary conditions have also been assigned spatially by use of polylines and polygons created in the GIS programme. The engine used to run the model was MODFLOW-2005, which is the current standard version of MODFLOW (USGS 2018 a.). The coordinate system used to describe features for the landfill was given in the locally used coordinate system SWEREF 99 1200. However, this coordinate system was not compatible with Visual MODFLOW and all features described in shapefiles were therefore converted to the coordinate system UTM Zone 32N (WGS84).

Properties and boundary conditions were converted to a numerical model with features divided into grid cells based on spatial location relative to the grid assigned to the model domain. In the numerical step, some features could be edited and observation wells added before the numerical model was translated to fit MODFLOW. A larger number of iterations than the standard settings were used for the simulations due to that the model had problems to fulfil the convergence criteria. An option for rewetting of dry grid cells was tested, but it was concluded to cause instability and was not used for the model version used to produce the results.

6.1.1 Model discretization

The MODFLOW program code was developed as a finite difference method, but it was possible to assign the model with either a finite element grid or a finite difference grid in the Visual MODFLOW software (Waterloo Hydraulics 2013). For the finite element method, more complex geometries can be described, where the mesh can be programmed to comprise features like material and structural properties (Czichos et.al. 2006). For the finite element method, other codes than MODFLOW must be used to run the model, with FEFLOW being a choice for triangular meshes (Waterloo Hydraulics 2013). The finite difference method uses partial differential equations that are approximated directly instead of interpolated as for the finite element method (Czichos et.al. 2006). The finite difference method is represented by a finite number of sampling nodes, in difference to the finite element were the whole discretized domain contains of a finite number of interpolation functions. For this project, a finite difference grid was assigned to the model because the landfill could reasonably well be described with a simple rectangular grid.

The model describing Välen was discretized with the finite difference method and the grid had the settings of 100 rows and 89 columns, which resulted in squared horizontal grid cells of 6x6 m. A fine grid is not necessary to answer relevant questions for the project, but result in a more complex model. Therefore, grid with an approximate cell size 6x6 m was used in the simulations.

The model had problems to meet the convergence criteria, due to several different reasons. One problem was that the model had many dry cells, which resulted in problems to calculate head values. MODFLOW only handle saturated conditions and therefore large areas of dry cells cannot be controlled. To run MODFLOW, different solvers can be used. A solver that is better at managing unsaturated conditions is MODFLOW-NWT, which is an option to MODFLOW-2005 (USGS 2018 b). However, the Visual MODFLOW version 2013.1 used in this project did not support the use of NWT. The problem was concluded to partly be that the thin top layers were detached vertically in parts of the model where large changes of elevation occurred in a short distance. Due to steep hill sides in the north and south parts of the model this occurred. To solve the problems, both with dry cells and detached cells, the two top layers were merged to one layer. Problems with thin layers and detached layers, due to a large slope over a short distance, occurred in the model. The two top layers were assumed to partly be the problem of detached cells and of cells drying out in large parts of the modelled area. Therefore, these layers where merged into one layer in the model. That resulted in that the sludge and dredge layers were combined and that only one hydraulic conductivity parameter could be assigned to the layer.

The vertical discretization was set to give relatively thick layers to enable reasonable convergence criteria to be met. The top layer containing both the sludge and dredge from the conceptual model was set as one numerical layer, while the clay layer from the conceptual model was divided into four vertical layers in the numerical model. The top layer was slightly thinner than the lower clay layers.

6.1.2 Hydraulic characteristics

The hydraulic features of the area were assigned by imported polygons created in GIS. The polygons were used to assign different properties to the embankments and similar features that do not cover an entire layer. The hydraulic conductivity was important in this project due to the construction of the landfill. However, the hydraulic conductivity was uncertain for most of the features in the landfill area. Slug tests from 2016 gave values for the material inside the landfill, but the hydraulic conductivity was likely very variable and the method was not providing a robust result. The underlying clay layer was mainly assumed to be relatively impermeable and table values was used for the hydraulic conductivity. The embankments and the sludge layer were most uncertain in terms of hydraulic conductivity. The uncertainty, due to variability, was considered by constructing alternative conceptual models with different hydraulic conductivities as input to the numerical calculation. The values of the hydraulic conductivity for the features in the landfill are presented in *chapter 5.4*. Figure 19 shows a visualisation of the properties in the model.

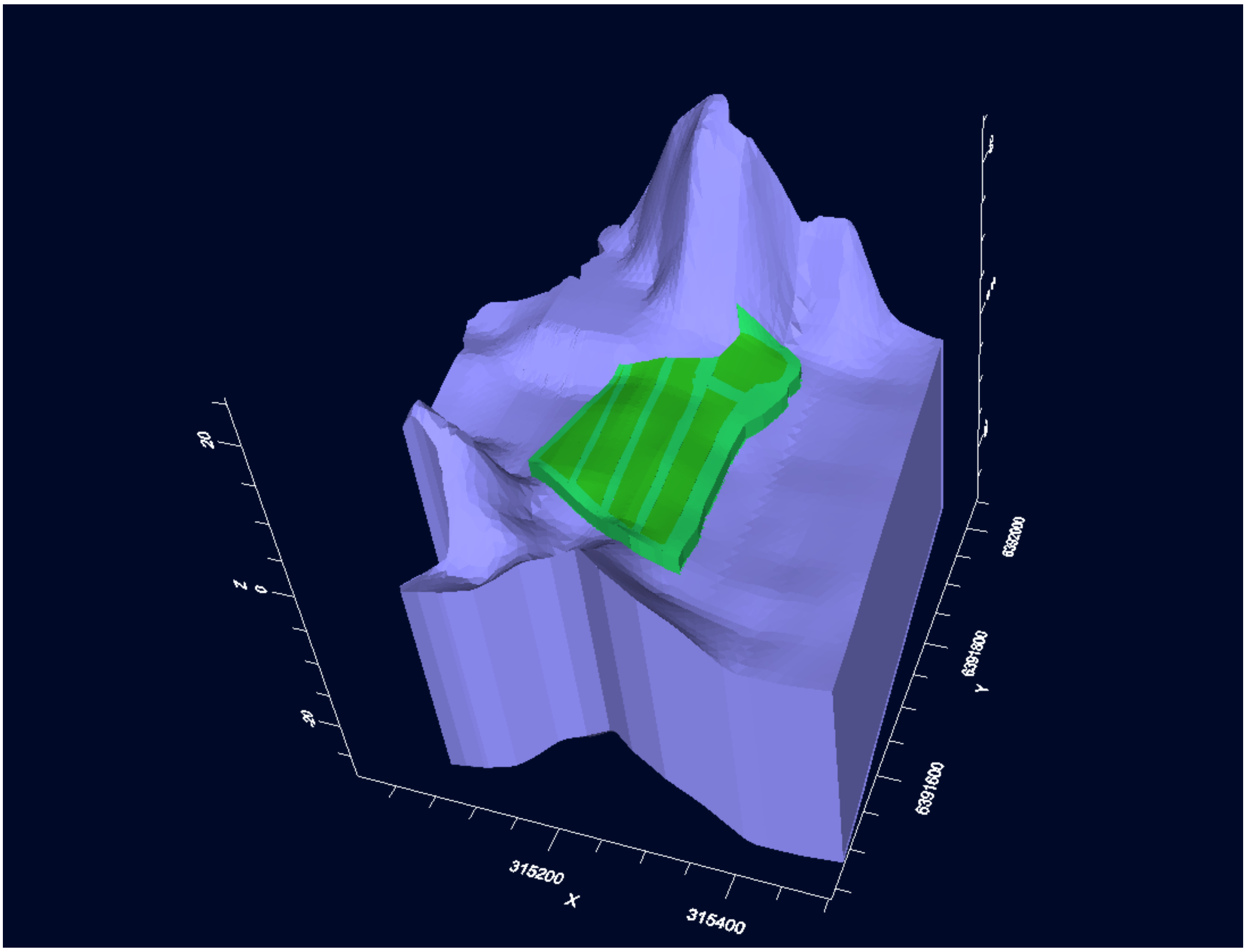


Figure 19. Variation of hydraulic conductivity for different parts of the landfill. The purple Zone 2 consisting of clay properties and the green the embankments and pond properties in Zone 1 (The surrounding part of Zone 1 were included in the model but hidden here to show the landfill properties in the same zone).

The hydraulic features were assigned with the real thickness and shape through the import of GIS files. However, the resolution of the grid used in the model did not represent the extent of the embankments sufficiently. Therefore, the width of the embankments was doubled to better describe the landfill as a system. Different parts of the embankments in the numerical model consisted of either one or two grid cells, which affected the width to vary between 6 to 12 meters. The real width of each embankment varies between 2 to 3 meters. Therefore, this could affect the transmissivity differently depending of the properties of the embankments.

6.1.3 Boundary conditions

The boundary conditions in the numerical model were assigned as constant head and a net recharge constantly distributed over the entire top layer of the model. Due to the uncertainties of the characteristics of the fillings under the sport areas next to the dredge landfill, as described in the conceptual model, the infiltration capacity is unknown. A hydraulic conductivity value was assigned to the entire surroundings even though large variations are known. The recharge was assigned a constant value equally distributed over the model area and all recharge was at first assumed to infiltrate to lower layers in the model. Due to very high head values, this assumption had to be modified and a surface runoff was assumed, which lowered the head values to more reasonable levels. Two different net recharge values were tested with several different combinations of hydraulic conductivities in the landfill and it was concluded that more surface runoff than expected was likely. The net recharge was set close to 50 mm/year to give the most reasonable results in the numerical model, which could not handle a higher precipitation due to low infiltration capacity in the clay layers.

The shoreline was given a constant head value, which was regarded as reasonable due to low variation in sea level that was assumed to not affect the model result significantly. The constant head boundary was assigned to all layers and not only the top one. Since the shoreline was from the sea bay this assumption was assumed to describe the system better than if only a constant head at the top layer was assigned. However, this could affect the flow in the bottom layers and the model should therefore not be used to the purpose of evaluating these flows.

The effect of the shoreline on the landfill was unknown and therefore its features have been simplified. This was due to the complexity of modelling the change in boundary condition and that other tools would be needed since Visual MODFLOW as a groundwater modelling tool could not be used for surface water simulations. The shoreline was therefore assigned a constant head with a value of 0.3 m with information of variation collected from SMHI (2018) and an explicit value from plan drawings from 1976. The boundary condition was assigned by using a polygon describing parts of the shape. When a polygon was used the constant head could not be assigned to all layers and therefore one side of the polygon at the edge of the model was added to represent the sea bay depth. Figure 20 presents the combined shape of the sea bay in the model as a constant head boundary. The flow lines in the bottom of the model were possibly not described optimally. Therefore, the model should not be used for estimations of the flow in the bottom of the clay layer or below the sea bay.

In the model created in Visual MODFLOW, the ditches were represented by constant head boundaries, see figure 20. Due to the coarse elevation information used in this project the ditches were not represented reasonably by only use of the elevation. Therefore, the nodes of the polylines used to create the two ditches were assigned approximated values manually with only a few known elevation values. The flow has been measured twice a year since 2011 and it was usually very low, sometimes too low to measure or estimate. A ditch along the hillside north of the landfill was dry during all the field visits during the spring of 2018 and was therefore not included in the conceptual or numerical model. It was assumed that a low constant flow reasonably well could describe the function of the ditches with a visible water level. In the numerical model, the ditches were described as a constant head boundary and the flows were therefore not used, but was still of conceptual importance in the evaluation of the boundary condition.

In the north-east, surface runoff and groundwater was assumed to enter the landfill since there is no construction preventing inflow, see figure 8. However, in the Visual MODFLOW version used, an inflow could not be assigned to the model without causing an error in the translation to MODFLOW. Therefore, the model area was extended to include the entire catchment area. The properties of the extended area around the landfill were very simplified due to lack of information of especially the filling material covering large parts of the area. The soil around the landfill was assumed to be homogenous in two different layers, even if that was not the case. The surrounding area consists of bedrock, till, clay, filling materials and some parts are covered with impermeable surfaces like houses or pawed ground. The complexity could not be accounted for here and the model should therefore not be used to evaluate conditions outside the extent of the landfill.

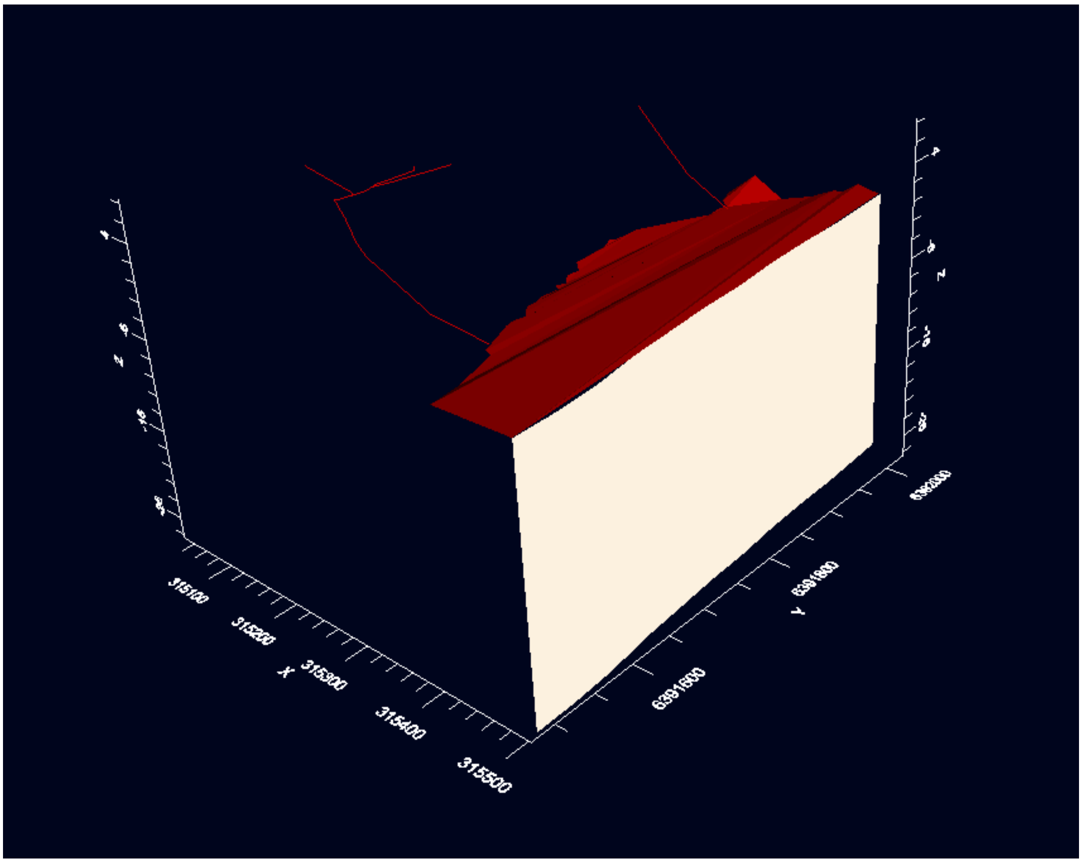


Figure 20. The sea bay constant head boundary in the Visual MODFLOW model. The red area represents the horizontal extent of the sea bay (the part inside the model domain) and the white area represents the vertical boundary at the edge of model domain. The red lines represent ditches described as constant head.

Drainage pipes from the construction of the landfill were identified from construction drawings, documents and as field observations. The conditions of the drainage pipes were uncertain and it is unknown if the pipes were plugged or crushed when the landfill was covered or if these could be possible leakage ways. Since a flow from the visible south drainage pipe was recognised in field only at a few occasions and mostly was dry it was difficult to evaluate the function of the drain. Therefore, the assumption is that these drainage pipes could be a possible location of leakage. However, the drainage pipes were not included in the numerical model due to lack of information. Extended investigations would be necessary to understand if the parts of the pipes affect the groundwater level inside the landfill.

6.1.4 Assumptions, simplifications and parameterisation

Assumptions and simplifications were made in the creation of both the conceptual and numerical model. All main assumptions and simplifications are listed here:

- The elevations of different geological features have been assigned by using the ground surface elevation. The elevation has been estimated by use of elevation data from laser scanning, provided by Lantmäteriet. The point cloud from laser data was sparse and the ground elevation resolution in the area was therefore relatively low compared to surrounding areas.
- The elevation data was used to create surfaces in Visual MODFLOW. Additional surfaces were created by subtracting a constant value from the ground elevation data. These surfaces were used to define the main zones consisting of sludge, dredge and clay. The constant of lowering was estimated from available groundwater borehole data and an average value were assumed to describe the system reasonably well for this project.
- The hydraulic conductivity was assumed to be homogenous within each hydraulic feature. This is a simplification since the material in the masses was known to be spatially distributed.
- The assumption of a constant sea level was used in this project. The boundary condition was simplified due to limitations in the used software.
- The constant head values for the ditches were estimated from only a few known levels.
- At the south border of the model, a ditch was according to the watershed estimations receiving all the flow from the hillside south of the modelled area. The water level in the south ditch was assumed to always be lower than the lowest level of contaminated material in the landfill. Most runoff from the catchment was assumed to enter the south ditch. Due to a residential area connected to the local authority’s drainage system some of the runoff to the south ditch was reduced.
- The entire surrounding area of the landfill was simplified to be homogenous within in the two separate property zones used in the model.
- The flow in the ditches was simplified to be a low constant flow.

- Drainage pipes in the eastern embankment of the landfill were not included in the numerical model due to lack of information about its function. It is uncertain if these pipes affect the groundwater in the landfill.
- The shape of the embankments was simplified to squares in the numerical and conceptual model, due to that the shape was imported as a 2D file and that the layers were described as squares.
- To change the width of the embankments, affect the transmissivity. The hydraulic conductivity of the embankments was not changed to represent the changed transmissivity, which was a major simplification.
- A new cover was assumed to be possible to add to the landfill. However, geotechnical stability was not considered, which potentially could be a problem if more masses are placed at the landfill site.
- Transport and natural attenuation processes have not been included in the model in Visual MODFLOW or in the conceptual model.
- Seasonal variation was not accounted for in this project and the model was only steady-state. Transient modelling would require long records of data that was not available in this project due to the time frame of the thesis.
- The groundwater model could only handle saturated flows, which simplifies the area that is in hydraulic connection to the sea and also partly have an unsaturated top layer at land.

6.1.5 Calibration parameters and goals

Calibration was performed with hydraulic conductivity values of the embankments, sludge cover and top layer of the surrounding area to ensure to reduce the uncertainty of this parameter. The goal was to evaluate how these parameters affect the model so that it could be adjusted for. The goal of this study was to evaluate countermeasures for the landfill and the exact features was therefore not essential to simulate different countermeasures in the model.

6.2 Calibration and validation

Calibration and validation is important in all modelling. In this project, long measurement series has not been available and therefore a validation of the model was not possible. Calibration by setting up different conceptual models with varying hydraulic conductivity and net recharge was used, calibrated by head observations from 2018.

The model was calibrated by comparing observed head values to head values calculated in the model. Hydraulic conductivity was the main uncertainty that was evaluated in the sensitivity analysis. Unfortunately, a model which represented the area sufficiently could not be composed within the assigned project time frame. The modelling had to be ended even if several errors could not be solved. The best correlations with observed values were from the conductivities presented in table 3 and the correlation plot in figure 21. However, the head values in other parts of the model were very high, much higher than the ground elevation.

Table 3. Hydraulic conductivities for the landfill at Välen with the net recharge 50 mm.

Feature	Embankments	Landfill Masses	Surroundings (top layer)
K_x, K_y [m/s]	10^{-5}	10^{-6}	10^{-5}
K_z [m/s]	10^{-5}	10^{-7}	10^{-6}

The recharge was supposed to be a part of the sensitivity analysis, but caused unrealistic results and errors. Therefore, a value of 50 mm/year was used. All versions of the model experienced calculated head values of several hundred meters, which is not reasonable at Välen where the landfill have elevations of less than 10 meters above sea level. This was assumed to indicate that the infiltration capacity in the model was too low and that the net recharge could not be handled. Since Visual MODFLOW does not handle surface runoff the calculated heads rise above the ground elevation. To lower the calculated heads the recharge was lowered and a recharge of 50 mm, which gave the most reasonable results. However, net recharge values, both higher and lower, caused convergence criteria problems due to dry grid cells and the software had problems to change the recharge without causing errors in the translation.

The hydraulic conductivities were, before the modelling, assumed to be lower. The conceptual models suggested in chapter 5.4 resulted in very high calculated head values at the landfill, see figure 22. Conceptual model 1 had high head values at the landfill site but the rest of the model domain was better represented. Figure 21 shows a map describing the flow lines for conceptual model 1. The shape of the flow lines is close to the expected results, but the head values are above ground level. To lower the net recharge was tested but did not result in a better correlation.

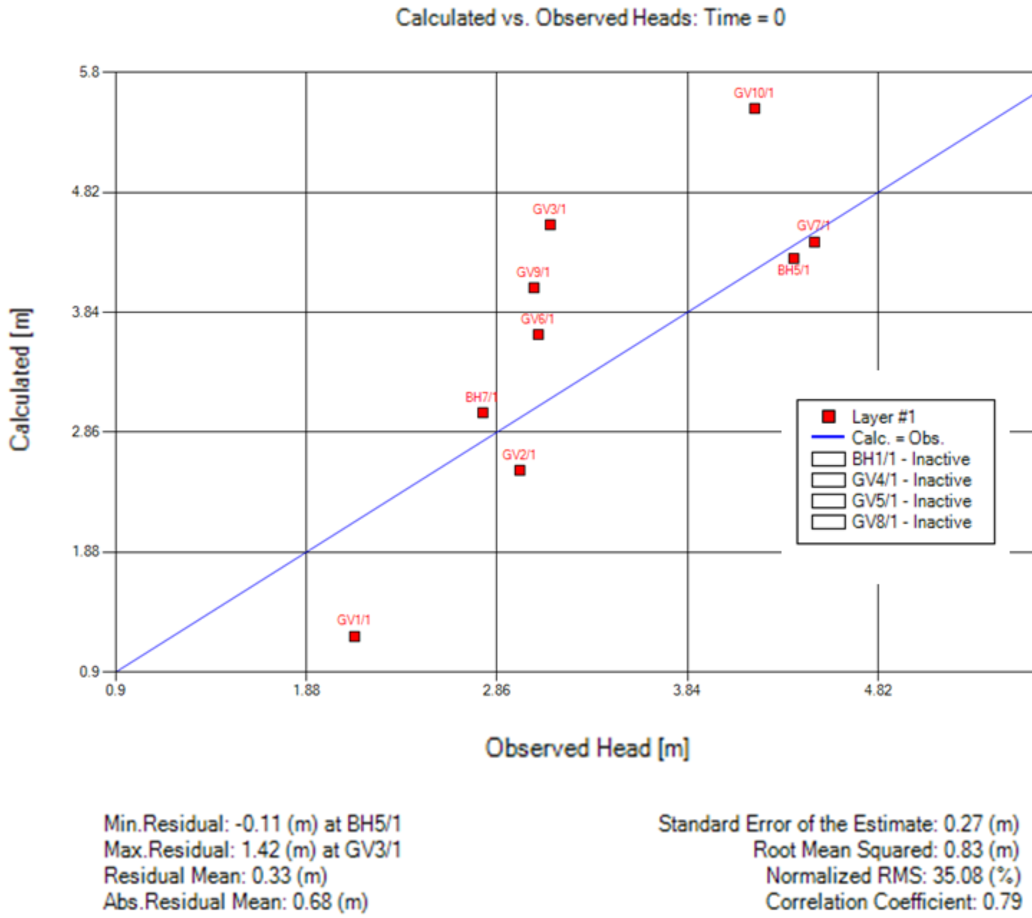


Figure 21. Correlation plot for one of the conceptual model 4 with conductivity values presented in table 3. Four monitoring wells were inactive in this simulation due to dry cells at the location of the wells. A larger plot is presented in appendix G.

The sensitivity analysis showed that different combinations of hydraulic conductivity could give similar results. Especially the layer representing the sludge and dredge in combination with the values of the embankments could give similar results. Therefore, the results from the sensitivity analysis could only give an approximate value of the properties for the different features in the landfill. Since the correlation was relatively poor and since some cells at monitoring wells were inactive because they were dry, the model could not be said to represent the landfill as required. The main reason to this was that the software was problematic to work in and that needed functions were not available. Many of the problems with this software were described to have been solved for newer versions of the software.

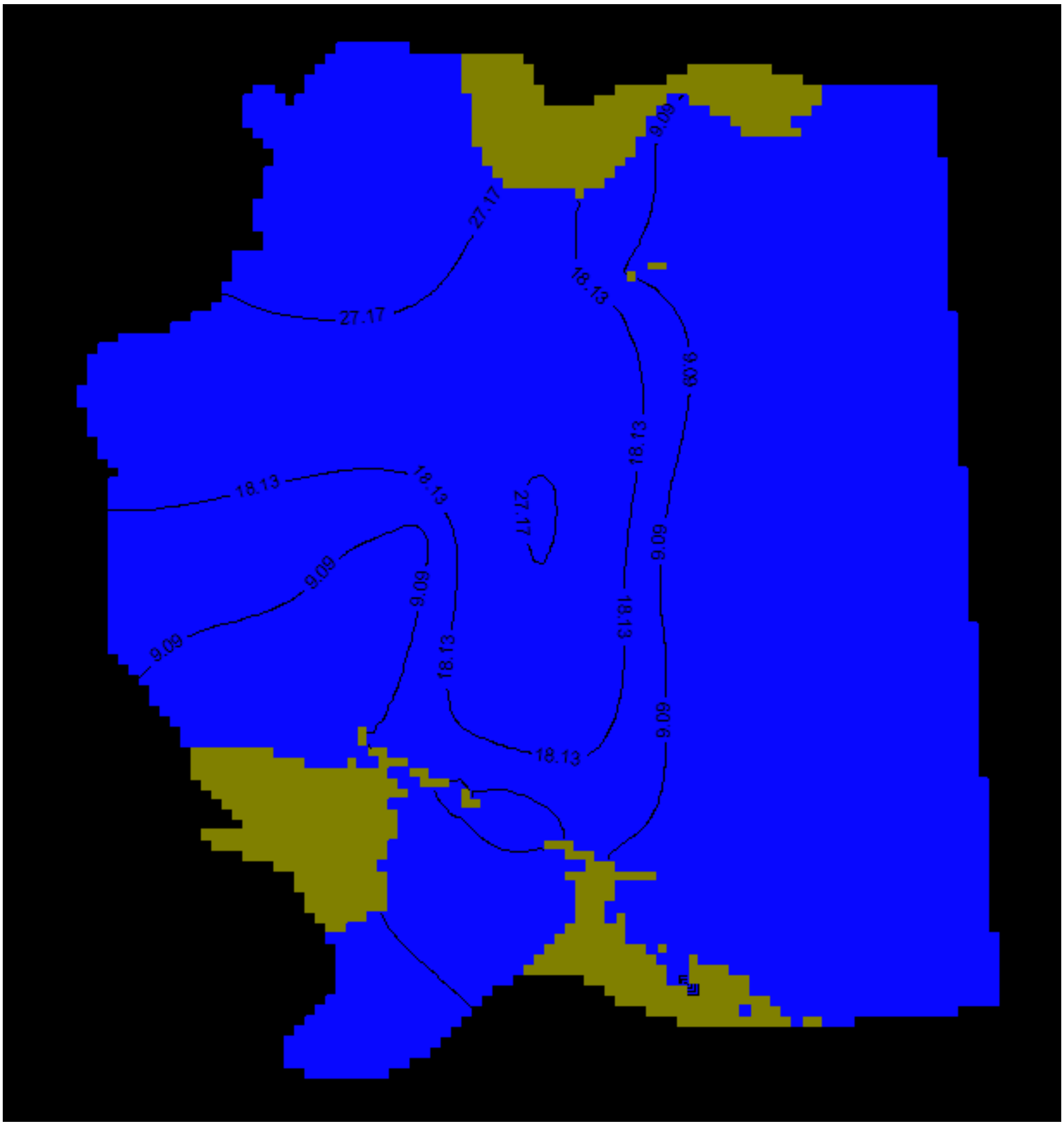


Figure 22. Calculated head values for conceptual model 1. Blue areas contain active cells while brown areas represent inactive dry areas.

6.3 Result of simulations with implemented countermeasures

Countermeasures could not be installed in the model due to errors and that no calibrated model with reasonable conditions could be achieved. The used Visual MODFLOW version 2013.1 did not support vertical barriers to be installed as a wall. An area with lower permeability was planned to be installed, but due to either high head values or dry cells the barrier hand no clear effect in the model. The cover could not be implemented without replacing the contaminated landfill material, due to that thin layers caused detached grid cells in the model. To replace the contaminated material with a cover material was regarded to change the model in a way that it could not be used to evaluate the effect a real cover would have. Due to these issues, a numerical result of implemented countermeasures could not be evaluated.

6.4 Problems and potential solutions

This chapter summarises the main problems in the numerical groundwater model and potential solutions or reasons to why some solutions could not be applied in this model.

- An inflow could not be assigned in the conceptual or numerical step in Visual MODFLOW 2013.1 without causing an error in the translation to MODFLOW.
  - Solution: To extend the model to include the entire catchment area.
- Calculated large head values were a problem. It was assumed to be caused of too impermeable layers that could not receive the net recharge. The infiltration capacity was lower than expected and Visual MODFLOW cannot handle surface runoff, which was the assumed reason to large head values.
  - Solution: To assign a drain layer to the entire model area that could represent surface runoff. Version 2013.1 could not assign a drain to a polygon due to errors in the assignment of surfaces to the drain.
  - Solution: To lower the net recharge. This method was used, but the software had problems to change the recharge and often closed the software when a recharge was assigned.
- Problems to meet set convergence criteria were experienced. A model could fail to meet convergence criteria due to several different reasons. One of the problems in this model was due to detached grid cells.
  - Solution: One solution could be to assign a child grid, which is a finer grid in a limited part of the model domain, to areas with detached vertical grid cells. However, Visual MODFLOW 2013.1 only supports child grids horizontally.

  The problem was also that the model had many dry grid cells in the top layer. If many cells in an area get dry during a simulation the head values in adjacent cells cannot be calculated.
  - Solution: Use rewetting of dry grid cells. It was concluded to cause instability in the model and was therefore not included in the final setup of the model.
  - Solution: To use MODFLOW-NWT instead of MODFLOW-2005 since that engine better represent unsaturated conditions. However, MODFLOW-NWT is not supported in Visual MODFLOW 2013.1.
  - Solution: The two uppermost layers were merged to one layer to solve the problem with both dry and detached grid cells.
  - Solution: The number of iterations was increased for the convergence criteria to be met.
  - Solution: A possibility could be to increase the convergence criteria. This was used before the two uppermost layers were merged. However, the head change and residual criteria needed to be increased to a higher value than accepted for the model to converge. Therefore, the merged grid cells were used instead and the convergence criteria could be low.
- The merging of the uppermost layers gave the result that a cover as a countermeasure could not be installed in the model without replacing the contaminated materials in

the landfill. Head values calculated with those properties could not represent the situation in the landfill sufficiently. To add a new thin layer for the cover would result in convergence criteria problems as the reason to why the uppermost layers were merged. Therefore, an improved cover was not tested in the model.

  - Solution: No relevant solution was evaluated.

- An impermeable wall could not be installed in the model for the used Visual MODFLOW version, since it is only supported in newer versions.
  - Solution: To install an impermeable barrier by assigning low hydraulic conductivity to an area in the model. This did not give changes and it was assumed due to that the calibrated models either had dry cells in the area or had to high head values. Neither of these scenarios represents the conditions in that part of the landfill sufficiently.
  - Solution: Use another version of Visual MODFLOW or GMS.
- The main reason to why an accepted solution was not reached was that the software warned for errors that were unreasonable. An example was that surfaces created in the programme was said not to cover the entire polygon it was created with. Other errors were that only a few runs could be performed before the software had problems to run simulations or to change or create new structures in the model.
  - Solution: To create several different model files with only a few different conceptual models or numerical simulations in each. This solution was tested and it was very time consuming. However, some problems still appeared and the modelling therefore had to be ended since there was no time for the solution below.
  - Solution: Use another version of Visual MODFLOW or GMS.

7. Countermeasures suggested for the Välen landfill

The countermeasures most suitable for Välen are probably a combination due to the complexity of the landfill. As mentioned in chapter 4, countermeasures that solve the core of the problem are preferred and in the case of Välen, the options are to remove the masses, which would probably only move the problem, or to prevent water to transport contamination out from the landfill. There are countermeasures that could be beneficial at other locations mentioned in chapter 4, but that is not a possibility at Välen. Countermeasures which require land are not sustainable from either a social or environmental aspect due to the environmental and recreational importance of the nature reserve. If nothing is to be done or only short time solutions are implemented, it also threatens both environmental and social interests in the area.

Vertical barriers and improved cover were the two countermeasures evaluated in this project and both are in alignment with the recommendations from The Swedish Environmental Protection Agency. Since these countermeasures could not be tested in the numerical model as planned, no comparisons of different extents of vertical barriers or covers needed at Välen could be evaluated. However, the conceptual models indicate that a new cover or a vertical barrier is needed if inflow should be reduced, see figure 23.

A vertical barrier would need to be combined with drainage or ditches, which could lead the water around the landfill. To ensure that infiltration from potential ditches is reduced, ditches should be constructed with clay or other materials with low hydraulic conductivity.

The countermeasures need to handle the environmental and social interests, which means that if a new cover would be applied, the area need to be re-planted with species that is not a threat to the nature reserve and cannot penetrate the cover and create cracks. To keep a new cover from aging, the vegetation needs to be maintained. That maintenance would be lower compared to many other countermeasures that treat contaminated water. The main vegetation types to prevent from being established at the site are larger tree and bushes that could easily cause root penetration of the cover. To create areas with low points that could cause standing water should also be avoided to prevent infiltration.

Vertical barriers could potentially be implemented in other areas than evaluated in this report. Along the hillside north of the landfill, a dry ditch was observed, which indicates that recharge of groundwater occurs in that location. If this ditch would be properly sealed with clay then the inflow of surface water from the hillside to the landfill would probably be minimised. An additional benefit could also be that less water would pass the filling material below the football fields, see figure 23, which is less contaminated but still could contribute with some pollutants. As Karlsson (2014) mentioned, the dredge landfill is not the only source of pollution of the bay at Välen. Countermeasures at the dredge landfill are needed. However, it might also be needed at other locations that have not been investigated in this project.

Countermeasures which relocate or reveal the sludge could potentially cause some social issues due to that it concerns people nearby. However, to ignore the problem could also cause social concern due to that a sewage odour occasionally is unpleasant in the area.

Figure 23. Suggested countermeasures for a reduced leachate in the landfill.

Because it was estimated that both inflow from the surroundings and precipitation that falls at the landfill area contributes to the problem, it was expected that a combination of different countermeasures would be most effective. Since the numerical groundwater modelling failed, it was not possible to evaluate which one of the countermeasures that would give the largest reduction in water volume. The water balance estimated that the catchment area for the inflow is smaller than the landfill area, which theoretically causes a smaller water volume. Combined with the assumption that not all water from that catchment area for the inflow actually enters the contaminated masses in the landfill, it was estimated that a cover would reduce the water volume more than a vertical barrier.

8. Discussion

The numerical model was constructed as steady-state, which was estimated to be reasonable with respect to the aim of the project. However, a steady-state model excludes seasonal variation from the model. The reason to this was that sufficient series of observed heads were not available. The monitoring wells installed 2018 could have given more data that could have been used validate the model. However, the cold weather during February and March 2018 delayed the installation of the monitoring wells and the collected data was not as complete as expected in the beginning of the project.

Due to the many problems described in chapter 6.4, the conclusion was that the model does not represent the conditions in the landfill sufficiently. The heads are either too high, but with a reasonable shape of the assumed heads in the landfill, or assumed too low with dry cells in some of the cells containing monitoring wells.

It is hard to estimate the effect of simplifications as the assumption that all materials in the landfill are homogenous or that the two materials, sludge and dredge, were merged to enable the model to fulfil convergence criteria. Conceptually, the sludge and dredge were assumed to have different properties, which could not be represented in a single homogenous layer.

Transport and decomposition processes have not been included in this project due to the complexity of these processes. However, this limitation of the model is a problem since cracks in the sludge layer and other features most likely affect the aged material in the landfill. It has been assigned by using scenarios for the homogenous hydraulic conductivity in the sludge layer that was assumed to be most affected. Transport and decomposition processes are neglected in this project due to complexity, but should, if possible, be included in a more complex model to better represent soil properties.

The grid size could affect the results in a model. In this project, the grid sizes were not tested in a sensitivity analysis, due to that the uncertainties in hydraulic conductivity and inflow to the landfill were more important to evaluate. The grid size affected the embankments in the numerical model, since these for a coarse grid was not represented sufficiently without doubling the width of the embankments. A finer grid cell could have described the embankments better without any need to widen them. However, a finer grid would result in a larger and more computationally challenging model to run and since even the coarse grid resulted in problems to run several simulations, a finer grid was not an option.

The estimation of the level in the ditches described as constant heads in the model was very simplified. The uncertainties could have been met by measurement of the level in additional locations to reduce the uncertainty of the levels. This data was not collected because it from the beginning was not used to describe the ditches. The ground elevation was used from the beginning, but had to be changed due to that the ground from laser data did not slope towards the sea at the location of especially the south ditch. A water level in one of the ditch ends and an approximate sea level was the basis for other estimated levels in the ditches. Therefore, the levels cannot be too high or too low for the total length of each ditch, but at specific locations an error should be considered. This error was estimated to not affect the model results severely since it was assigned within the interval of the start and end values.

The estimation of pathways was connected to uncertainty, due to lack of information of especially found drainage pipes. The pipe from the test pound could potentially be a pathway for the water to pass without infiltrating the eastern embankment that was estimated to function as a filter. The function of the visible south concrete drainage pipe is also uncertain, but observations indicates that flow through the pipe possibly occur during wet conditions. To make any conclusions of the functions of the drainage pipes, further investigations are needed. To evaluate if the water level inside the landfill affect the flow in the visible drainage pipe, an additional monitoring well closer to the pipes would be useful. Locations of leakage are estimated to reduce in importance if countermeasures are correctly installed. Countermeasures should lower the water table and less water could be contaminated, which potentially can reduce leakage of leachate.

Geophysics could be an option for distinguishing water “pass ways” in the embankments around the landfill. However, geophysics measurements require the ground conditions to be unfrozen which during the spring 2018 did not occur until late April close to the end of the thesis project. Hence, no geophysics measurements could be included in the project due to the time limit and the long winter conditions. However, geophysics measurements are associated with some uncertainty when used in areas were the resistivity is low, not only for the pass ways, but in other layers as well.

The water in the catchment that enters contaminated masses is assumed to form leachate. However, the depth of the ditches around the landfill makes I likely that most of the surface runoff to discharge to one of the ditches. If countermeasures are installed at the site, the water quality in the ditches would hopefully improve over time due to less discharge of leachate. Better water quality in the ditches is assumed to contribute to less spreading of mercury and reduced sewage odour in the area.

Further investigations are recommended to ensure geotechnical stability with installed countermeasures. Investigations are also needed to dimension new countermeasures, both an improved cover and a vertical barrier with a ditch or a drain. Considering, leakage further investigations can clarify the condition of the outer embankment and found drainage pipes. Measurement pipes outside the outer embankment could potentially be used for calculation of mass transport. However, installation of monitoring wells outside the landfill requires approval since it is located in a nature reserve and it is uncertain if it is possible to find decent locations to install monitoring wells.

9. Conclusion and Recommendations

The following main conclusions were made from this study:

- The leakage probably occurs around the entire landfill, which is partly the reason why earlier countermeasures have failed
- Monitoring and observations indicates that the gradient is not towards the sea in parts of the landfill but is affected by structures in the landfill.
- Embankments in the landfill probably act as drains in the system, or at least do not act as impermeable barriers.
- Välen landfill is complex and there are still some uncertainties about how it correlates hydraulically with the surroundings.

Derived from the main conclusions it is recommended that *Kretslopp och vatten* consider the following countermeasures, further investigations and improvements for the dredge landfill at Välen:

- Countermeasures that reduce water input should be prioritized. The recommendation for Välen would be an improved cover and a maintenance plan to protect the cover combined with a vertical barrier and a ditch or a drain.
- Further investigation is recommended to better understand the system.
    - Geotechnical investigation to ensure stability with installed countermeasures.
    - Monitoring wells outside the eastern embankment could be used for groundwater sampling to facilitate calculations of mass transport from the landfill to the sea.
    - Groundwater recharge and extent of surface runoff should be investigated in more detail.
- Improve the groundwater model by creating a new model in a newer version of Visual MODFLOW or GMS.

The numerical model created in this project could not give acceptable results in the sensitivity analysis. Therefore, different countermeasures could not be tested in the model. Nevertheless, countermeasures based of the conceptual model were suggested to reduce the water volume in the contaminated masses. Countermeasures are recommended to reduce the negative social and environmental influence of pollution in the area.

References

Abbas, A.A. ; Jingsong, G. ; Ping, L.Z.;Ya, P.Y.; Al-Rekabi W.S. (2009) Review on Landfill Leachate Treatments, ISSN 1546-9239, American Journal of Applied Sciences

Avfall Sverige. (2017). Svensk Avfallshatering. Malmö: Avfall Sverige.

Carling, M. Ländell, M. Håkansson, K. and Myrhede, E. (2006) Täckning av deponier med aska och slam. Svenskt vatten AB: Stockholm

Chen, Y., Wang, Z., Nai, C., & Dong, L. (2012). Computer Simulation of Transmission Line Model for Landfill Leakage Location. Switzerland: Trans Tech Publications.

COWI (2012) a. *Riskbedömning av Välens mudderdeponi*. Göteborg: Göteborgs Stad Kretsloppskontoret

COWI (2012) b. *Beskrivning av lagerföljd i borrhål för miljöprover och grundvattenrör*. Retrived from Kretslopp och vatten

Czichos, H. Saito, T. and Smith, L. (2006) *Handbook of Materials Measurement Methods*. Springer Science Business Media Inc

Dinger, J., Barkestedt, A., & Geuze, I. (2016). Hydrogeological investigations at the Välen landfill. Göteborg: University of Gothenburg.

Enviroplanning (2017). *Metaller i vattenmossa – undersökning av biotillgängliga metaller i vattendrag i Göteborg 2017*. Göteborg: Miljöförvaltningen

Flodin, J. (2015) *Rening av lakvatten från nedlagda kommunala deponier – Med St. Hans i Lund som fallstudie.* Lund: Lunds Tekniska Högskola

Golder Associates (2004) *16 nedlagda deponier i Göteborgs kommun*. Göteborg: Kretsloppskontoret

Göteborgs vatten och avloppsverk (1977) *PM Restaurering av havsviken Välen Åtgärder för täckning av deponeringsplatsen*. Retrieved from Regionarkivet Göteborg 12 March 2018

Helldén, J. Juvonen, B. Liljedahl, T. Broms, S. and Wiklund, U. (2006) *Åtgärdeslösningar – erfarenheter och tillgängliga metoder*. Stockholm: Naturvårdsverket

Jamali, A. and Skantz, C. (2012) *Evaluation of Treatment Techniques for Mercury Contaminated Leachates*. Göteborg: Chalmers University of Technology

Karlsson, M. (2014) *Characterisation of leachate and implementation of recipient control – A case study on Välen deposit site.* Göteborg: University of Gothenburg

Lantmäteriet (2018) Spatial data retrieved 20 February to 25 March.

Länstyrelsen Västra Götaland (2013) *Hantering av massor – kort information om olika hateringssätt*. Retrived 20 February 2018 from http://www.lansstyrelsen.se/vastragotaland/SiteCollectionDocuments/Sv/djur-och-natur/skyddad-natur/tillstand/hantering-av-massor-20131115.pdf

Magnusson, M., Cato, I., Hilvarsson, A., & Hammar, J. (2012). *Undersökning av Välens miljökemiska och biologiska status 2012.* Lysekil: Marine Monitoring AB.

Mattson, J. (2015) *Miljörapport Ryaverket 2014*. Göteborg: Gryaab (Rapport 2015:4)

Melica (2009) *Välens mudderdeponi – Årsrapport 2008*. Göteborg: Kretsloppskontoret

Melica (2010) *Välens mudderdeponi – Årsrapport 2009*. Göteborg: Kretsloppskontoret

Modin. H, (2012) *Modern landfill leachates – quality and treatment*. Lund: Lund University

Ramböll (2014) *Årsrapport 2013 Välen Mudderdeponi. Göteborg*: Kretslopp och vatten

Ramböll. (2017) *Årsrapport 2017 Välen Mudderdeponi*. Göteborg: Kretslopp och vatten.

SGU (2018) *Geologi i 3D*. Retrieved 13 February 2018 from http://apps.sgu.se/sgu3d/

SMHI (2017) a. *Vattenbalans*, Retrieved 7 Mars 2018 from https://www.smhi.se/kunskapsbanken/hydrologi/vattenbalans-1.124695

SMHI (2017) b. *Normal uppskattad årsnederbörd, medelvärde 1961-1990*, Retrieved 3 March 2018 from http://www.smhi.se/klimatdata/meteorologi/nederbord/normal-uppskattad-arsnederbord-medelvarde-1961-1990-1.6934

SMHI (2017) c. *Årsavdunstning medelvärde 1961-1990*, Retrieved 3 March 2018 from http://www.smhi.se/klimatdata/hydrologi/vattenstand-2-2-338/arsavdunstning-medelvarde-1961-1990-1.4096

SMHI (2018) Data. Retrieved 3 March 2018 from https://www.smhi.se/klimatdata

Stadsbyggnadskontoret. (2013). *Beslutshandling Naturreservatet Välen*. Göteborg: Göteborgs Stad.

Sveriges Riksdag (2018) *Förordning (2001:512) om deponering av avfall*. Retrieved 20 February 2018 from https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-2001512-om-deponering-av-avfall_sfs-2001-512

Sweco (2013) PM Välen deponi Hydrogeologi mm.

Swedish Environmental Protection Agency (2004) *Deponering av avfall – Handbok2004:2 med allmäna råd till förordningen (2001:512) om deponering av avfall och till 15 kap. 34 § miljöbalken (1998:808)*. Stockholm: Naturvårdsverket

Swedish Environmental Protection Agency (2008) *Lakvatten från deponier*. Stockholm: Naturvårdsverket

Swedish Environmental Protection Agency (2009) *Att välja efterbehandlingsåtgärd – En vägledning från övergripande till mätbara åtgärdsmå*l. Stockholm: Naturvårdsverket

Triumf, C-A (1992). *Geofysik för geotekniker metoder och tillämpningar*. Byggforskningsrådet: Stockholm

USGS (2018). *MODFLOW and related programs*. Retrieved April 18, 2018 from https://water.usgs.gov/ogw/modflow/

USGS (2018) b. *MODFLOW-NWT: a Newton Formulation for MODFLOW-2005*. Retrieved 9 May 2018 from https://water.usgs.gov/ogw/modflow-nwt/

VA-verket Göteborg (1975-1979). Archived material from the region archive in Gothenburg. Retrieved from Regionarkivet Göteborg 12 March 2018

Von Brömssen, M., Gunnemyr, L., Lindstrand, O., & Jonasson, S. (2006). *Modeller för transport och spridning av föroreningar fas 1*. Stockholm: Naturvårdsverket.

Waterloo Hydrogeologic (2018), Retrieved 8 March 2018 from https://www.waterloohydrogeologic.com/2018/03/02/retiring-visual-modflow-classic

Waterloo Hydrogeologic (2013) *Goundwater Modelling Numerical Methods: Which one should I use?* Retrieved 26 Mars 2018 from https://www.waterloohydrogeologic.com/2013/08/26/groundwater-modelling-numerical-methods-which-one-should-you-use/

Waterloo Hydrogeologic (2015). Retrieved 16 March 2018 from http://novametrixgm.com/help/vmod-flex/index.html?quick_start_tutorials.htm

Appendix A – Construction photographs

Appendix A presents pictures from the construction of the landfill 1976-1980.

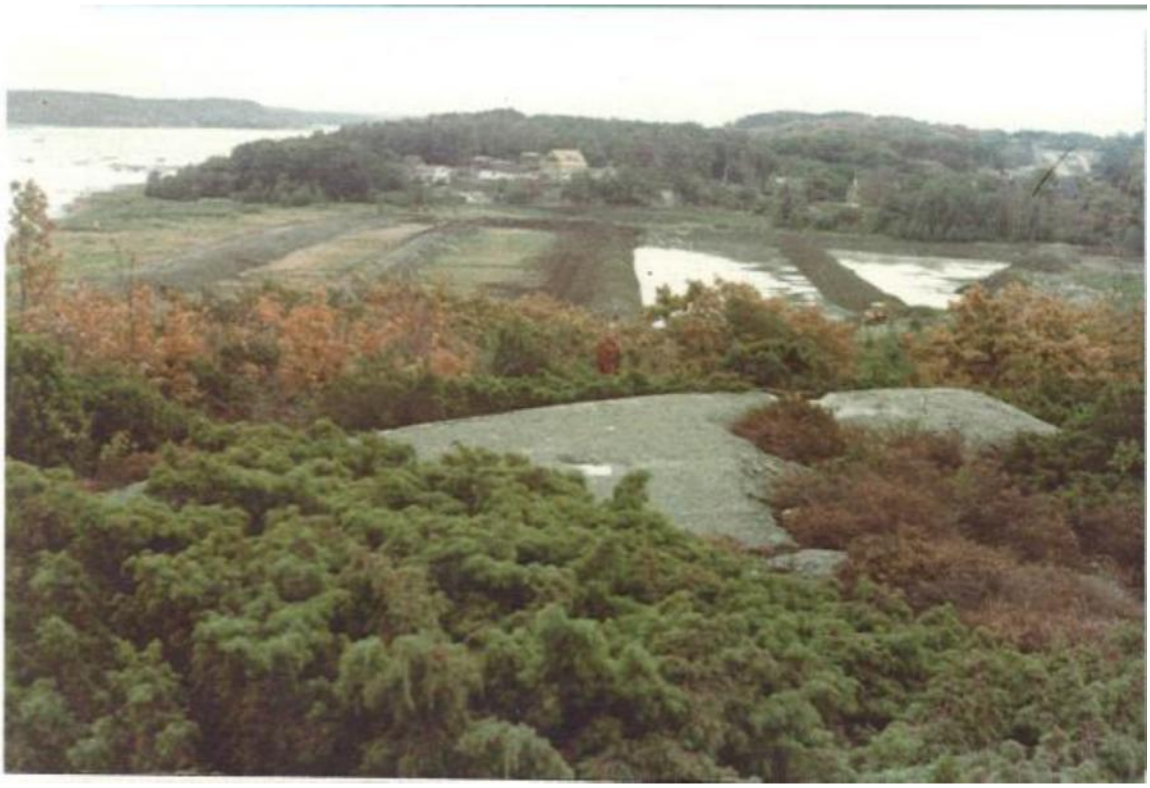


Figure 1. Overview Välen Dredge Landfill from hill north of the area.

Figure 2. Overview facing south.

Figure 3. Dredge pool facing north.

Figure 4. Outflow drainage pipes in the south east corner of the landfill.

Figure 6. Dredge material being transported to the ponds separated of embankments at the landfill site.

Figure 7. The dredge material was filled in ponds separated by embankments to separate dredge material from water through sedementation.

Figure 8. The dredge material was filled in ponds separated by embankments to separate dredge material from water through sedementation.

Figure 9. The dredge material was filled in ponds separated by embankments to separate dredge material from water through sedementation.

Figure 10. Outflow drainage pipes in the south east corner of the landfill.

Figure 11. Boulders at a part of an embankment constructed for overflow.

Figure 12. *Outflow drainage pipes and a constructed ditch in the south east corner of the landfill.*

Figure 13. Constructed overflow in the south part of the middle inner embankment.

Figure 14. The covering of landfill with sludge from the waste water treatment plant, Ryaverket.

Figure 15. Cover of the north east part of the landfill.

Figure 16. *The covering of landfill with sludge from the waste water treatment plant, Ryaverket.*

Figure 17. Cover of the north west part of the landfill.

Appendix B - Construction drawings

Appendix B presents plan drawings from the construction of the dredge landfill. Please note: None of the figures showed in this appendix have the scale presented in the figures, use original for scale information.

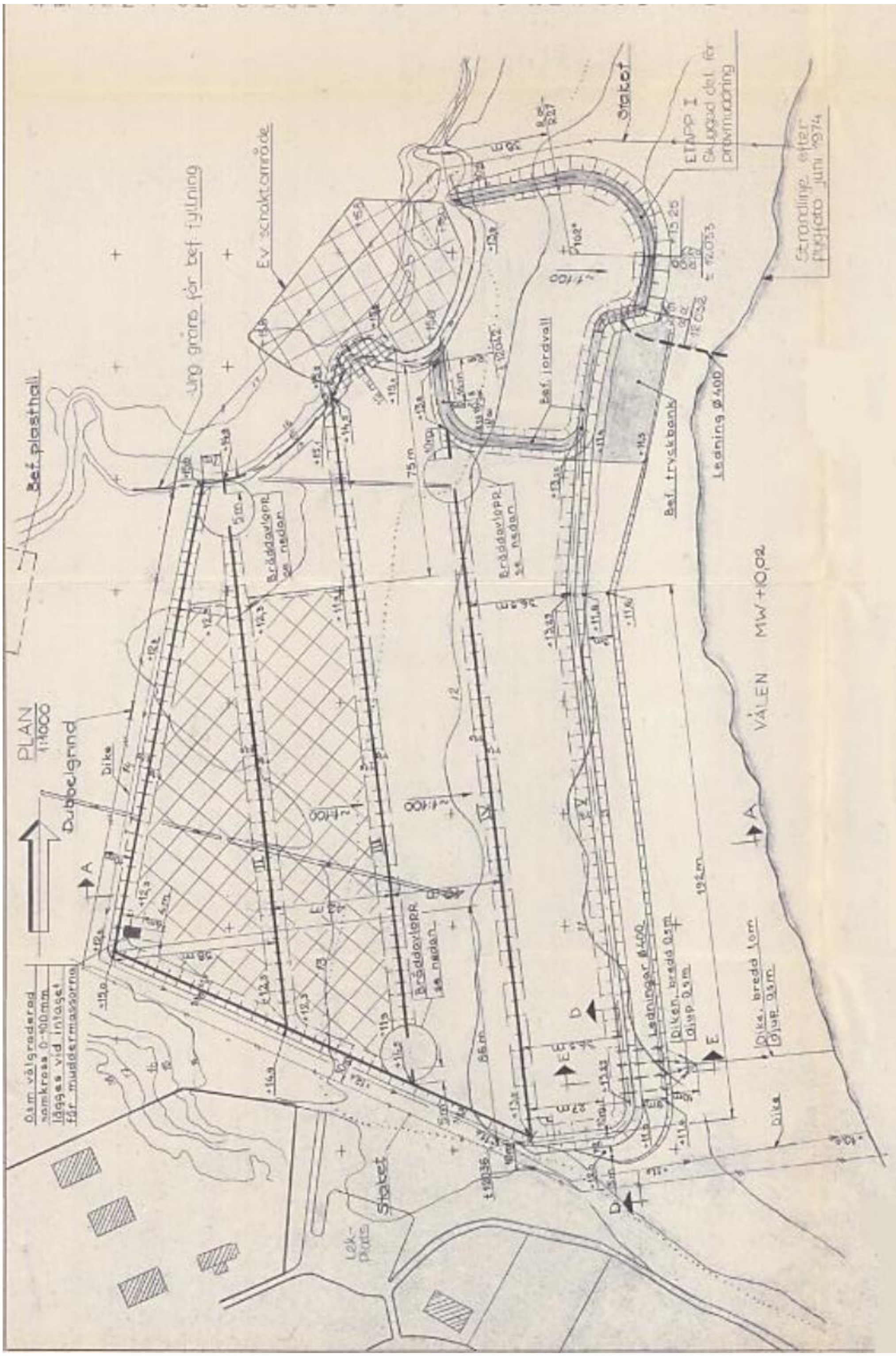


Figure 1. Construction plan of the Välen dredge landfill from 7 July 1976.

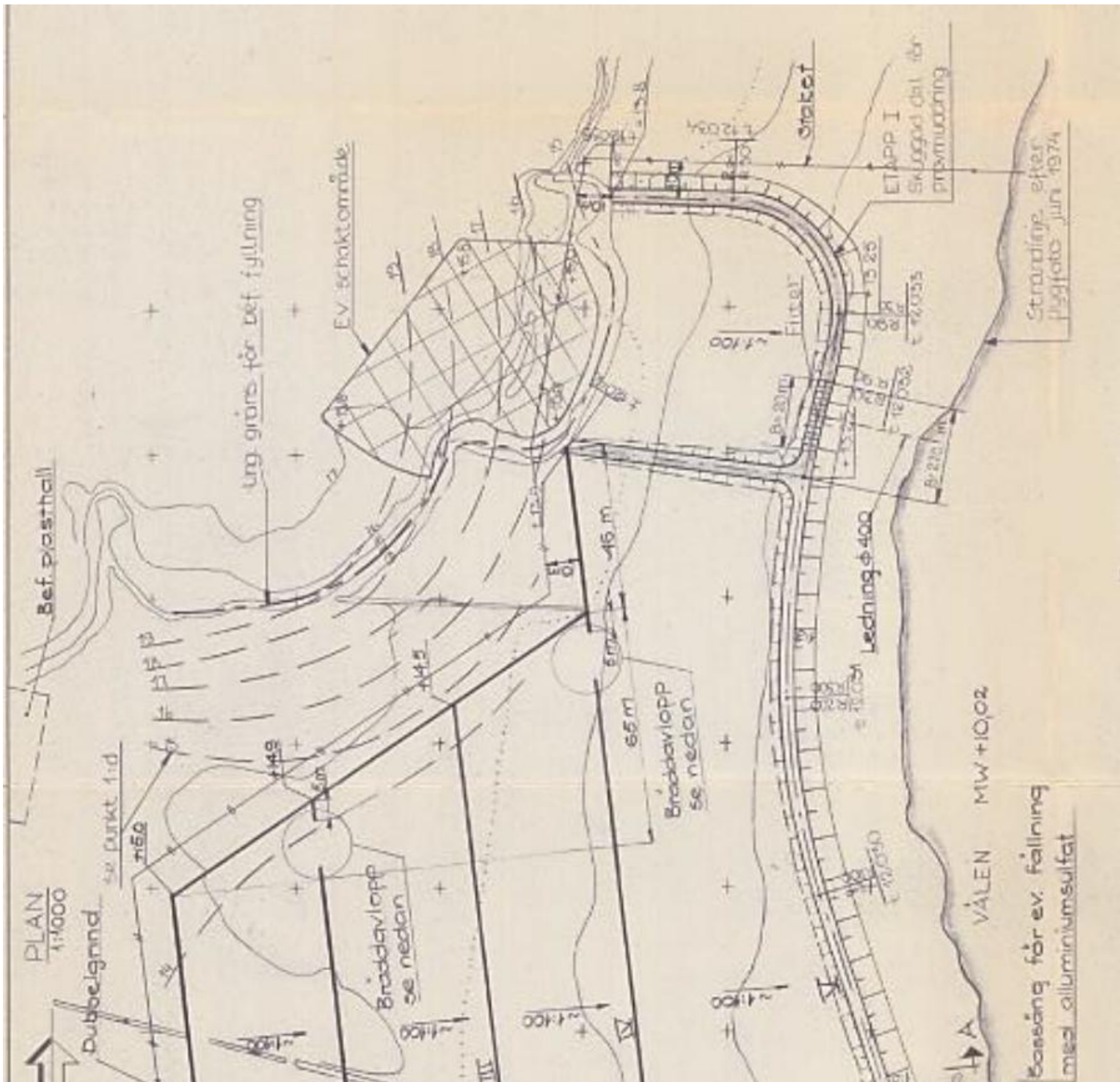


Figure 2. Construction plan of the Välen dredge landfill from 20 February 1975.

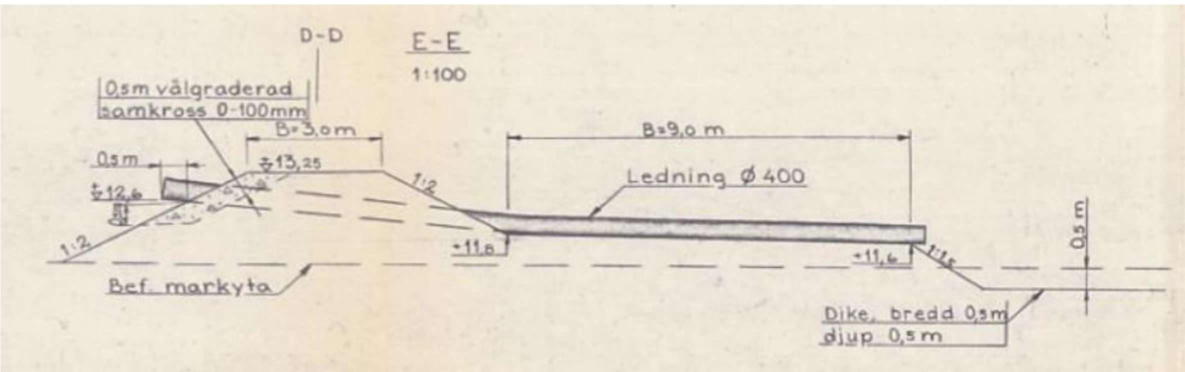


Figure 3. Drainage plan drawings from the south east corner, see figure 1 in this appendix for overview from 7 July 1976.

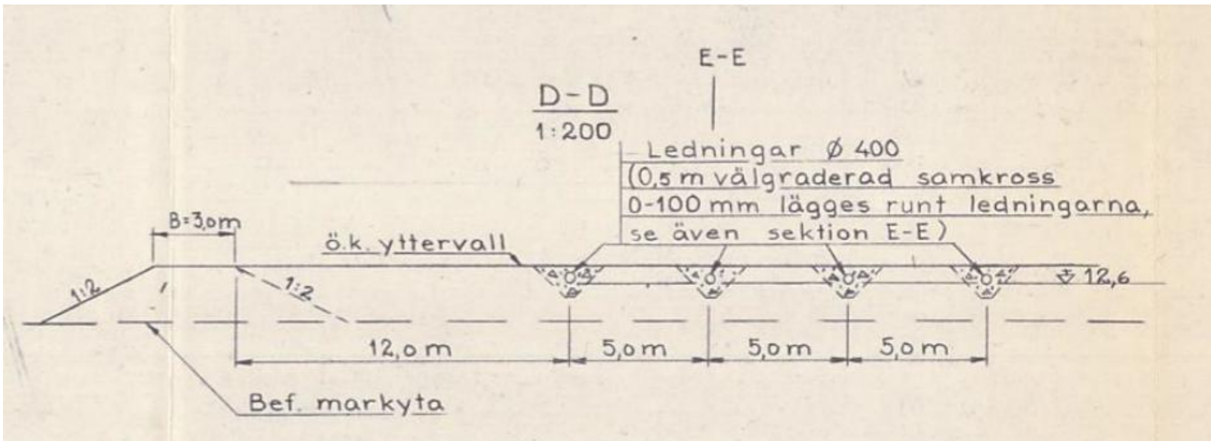


Figure 4. Drainage plan drawings from the south east corner, see figure 1 in this appendix for overview from 7 July 1976.

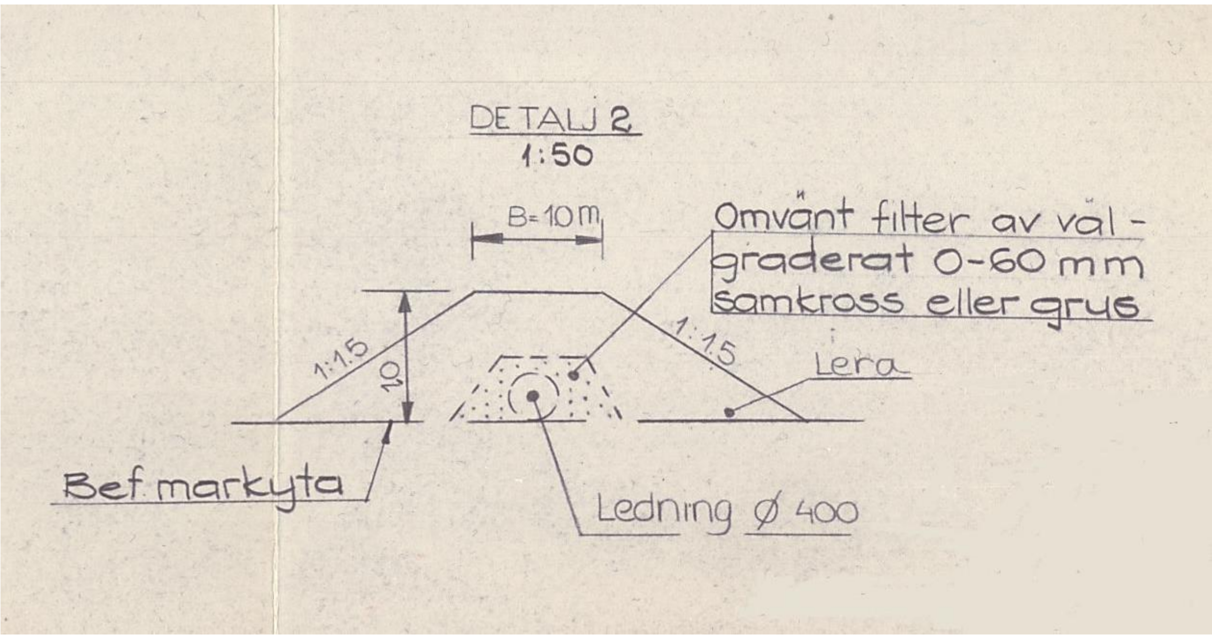


Figure 5. Drainage from the north test dredge pond from 20 February 1975.

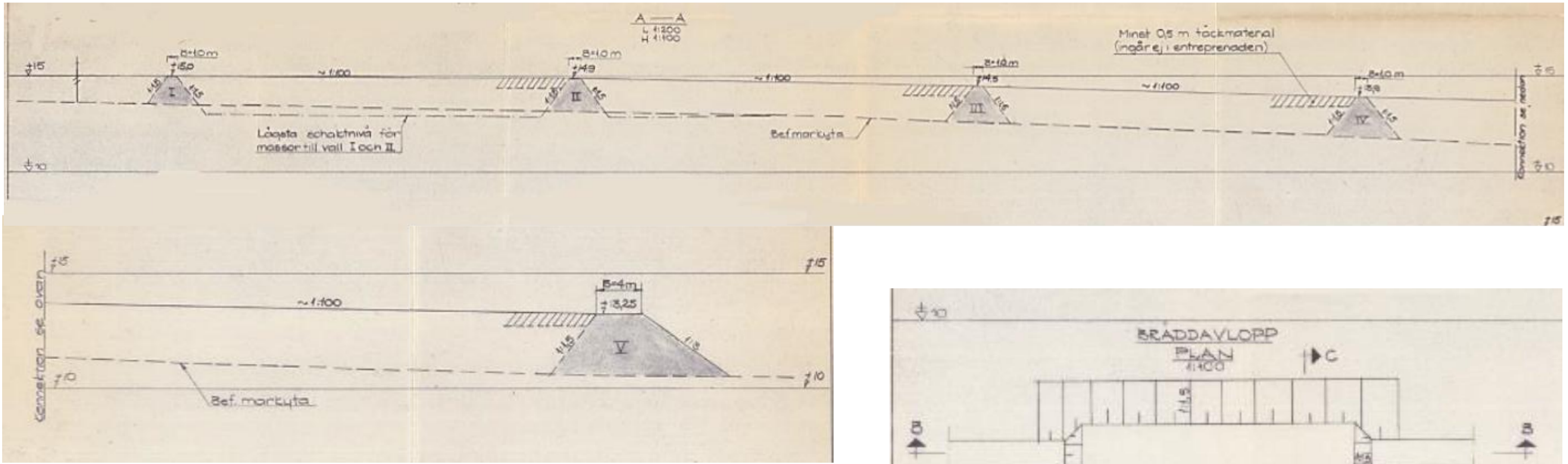


Figure 6. Embankments in profile from 7July 1976.

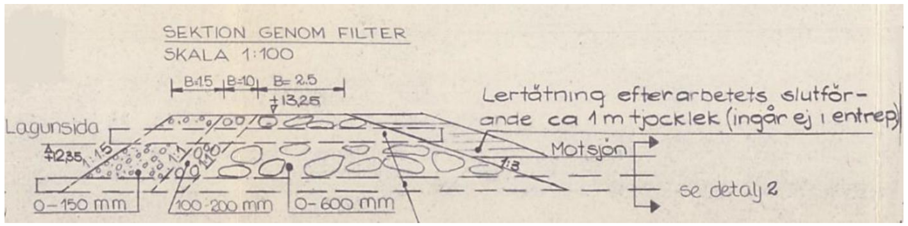


Figure 7. The profile of the east embankment from 20 February 1975.

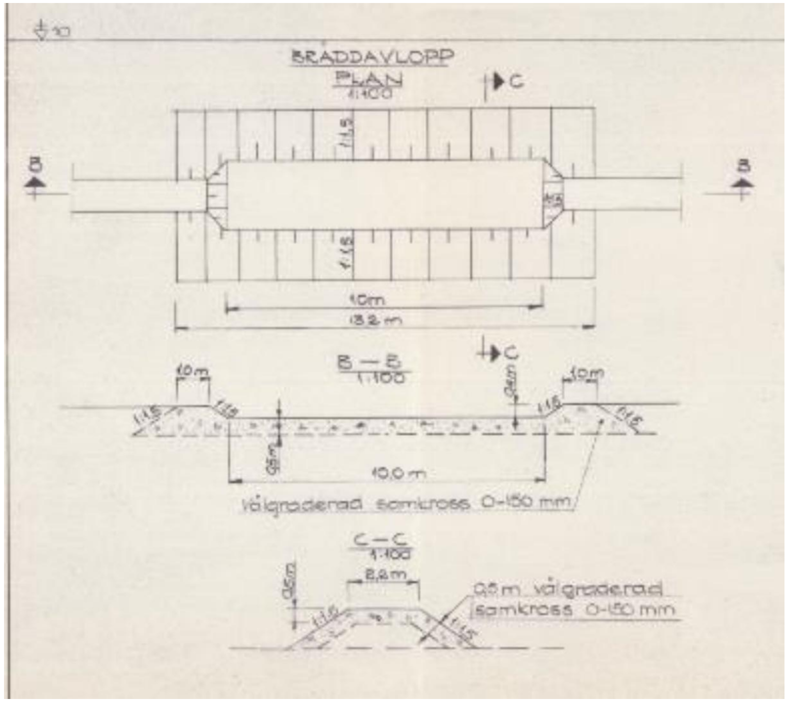


Figure 8. Spillway plan drawing from 20 February 1975.

Appendix C – Previous countermeasures

Appendix C presents countermeasures at Välen dredge landfill that have previously been implemented.

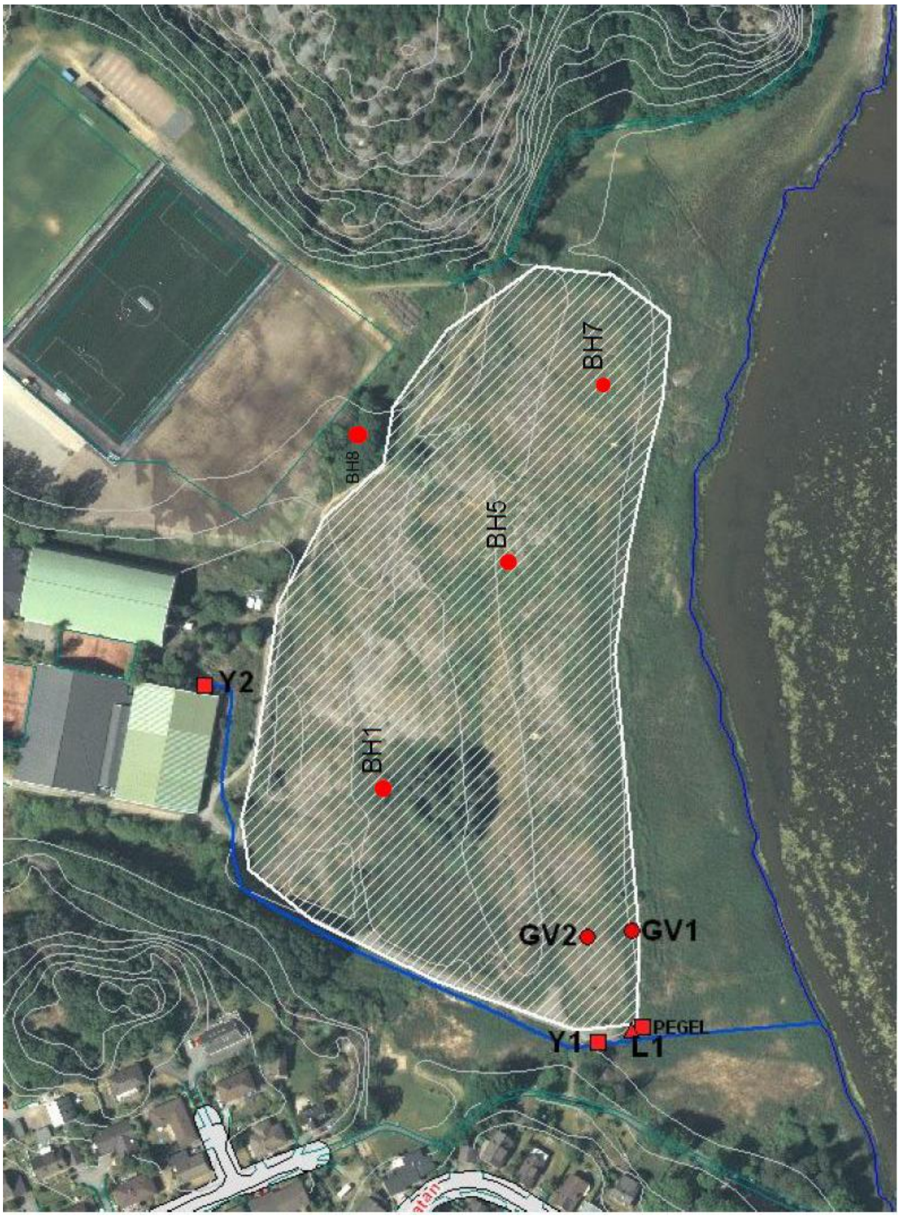


Figure 1. Locations of groundwater measurement pipes installed 2012 or earlier. The location of the sludge well L1 and surface water measurement.

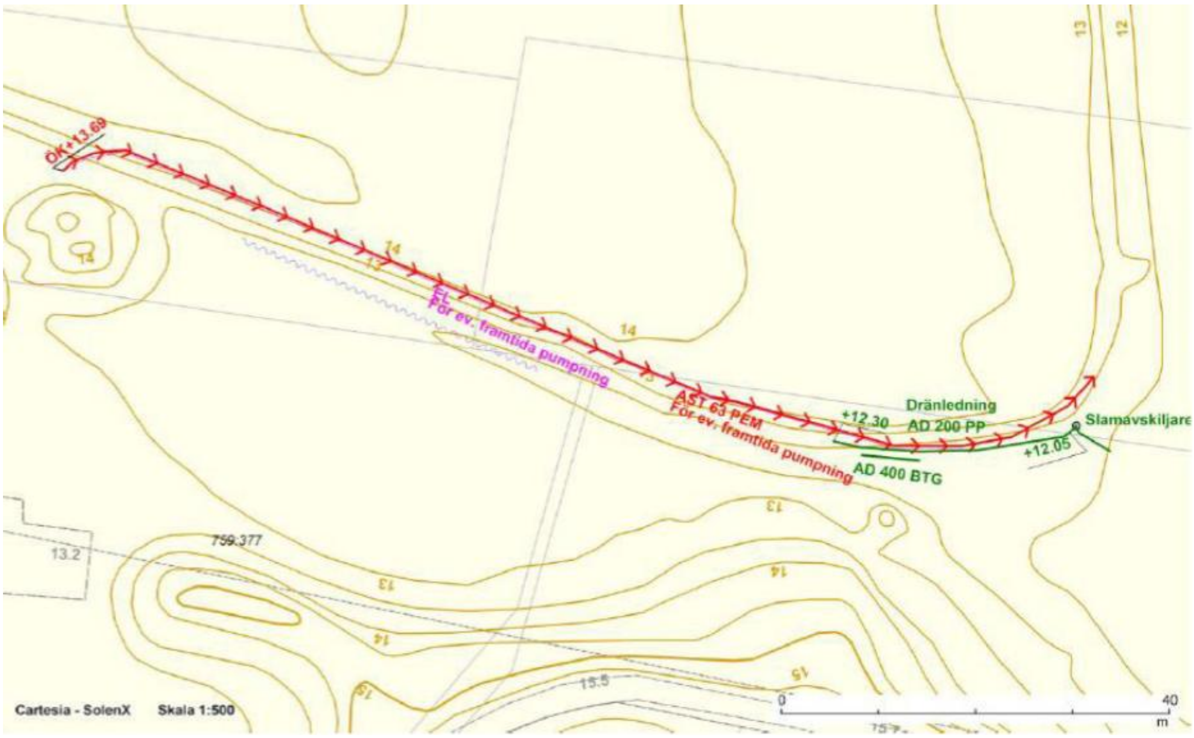


Figure 2. Overview of the screen and drain installed in the south embankment close to L1 (slamavskiljare) picture provided by E. Porse 2018.

Figure 3. The screen at installation 2005, which later was covered. Photograh provided by E. Porse 2018.

Appendix D – SMHI measurement locations

Appendix D presents the SMHI measurement locations.

Figure 1. Sea water level measurement location at Torshamnen outside Gothenburg.

Figure 2. Askim D measurement location close to the dredge landfill. Location of the landfill area marked with a red square.

Appendix E – Parameters in Visual MODFLOW

Appendix E presents parameter settings used in Visual MODFLOW.

General parameters	
Steady state simulation date	2016-05-02
Coordinate system	UTM Zone 32N (WGS 84)
Engine	MODFLOW-2005
Simulation type	Groundwater flow
Flow type	Saturated (constant density)
Input shape files	Inspector_point.shp, Boundary_new.shp, Sea_bay_new.shp, Embaankment_dubbel.shp, Pools_for_dubbel_embankment.shp, South_ditch.shp, North_ditch.shp, Observation_wells_valen_steady_state.shp
Created and used surfaces	Ground, Sludge bottom, Dredge bottom, Clay 2
Bulk Density (kg/m^3)	1700*
Initial Heads (m)	100*
Longitudinal Dispersion (m)	10*
Effective porosity	0.14*
Specific Storage (1/m)	1E-05*
Specific Yield	0.2*
Total Porosity	0.3*

* Default value

Units	(Standard settings was used)
Bulk Density	kg/m^3
Concentration	mg/L
Conductivity	m/s
Length	m
Mass	kg
Pumping Rate	m^3/d
Recharge	mm/yr
Specific Storage	1/m
Time	day

Appendix F – Catchment area and surface runoff estimations

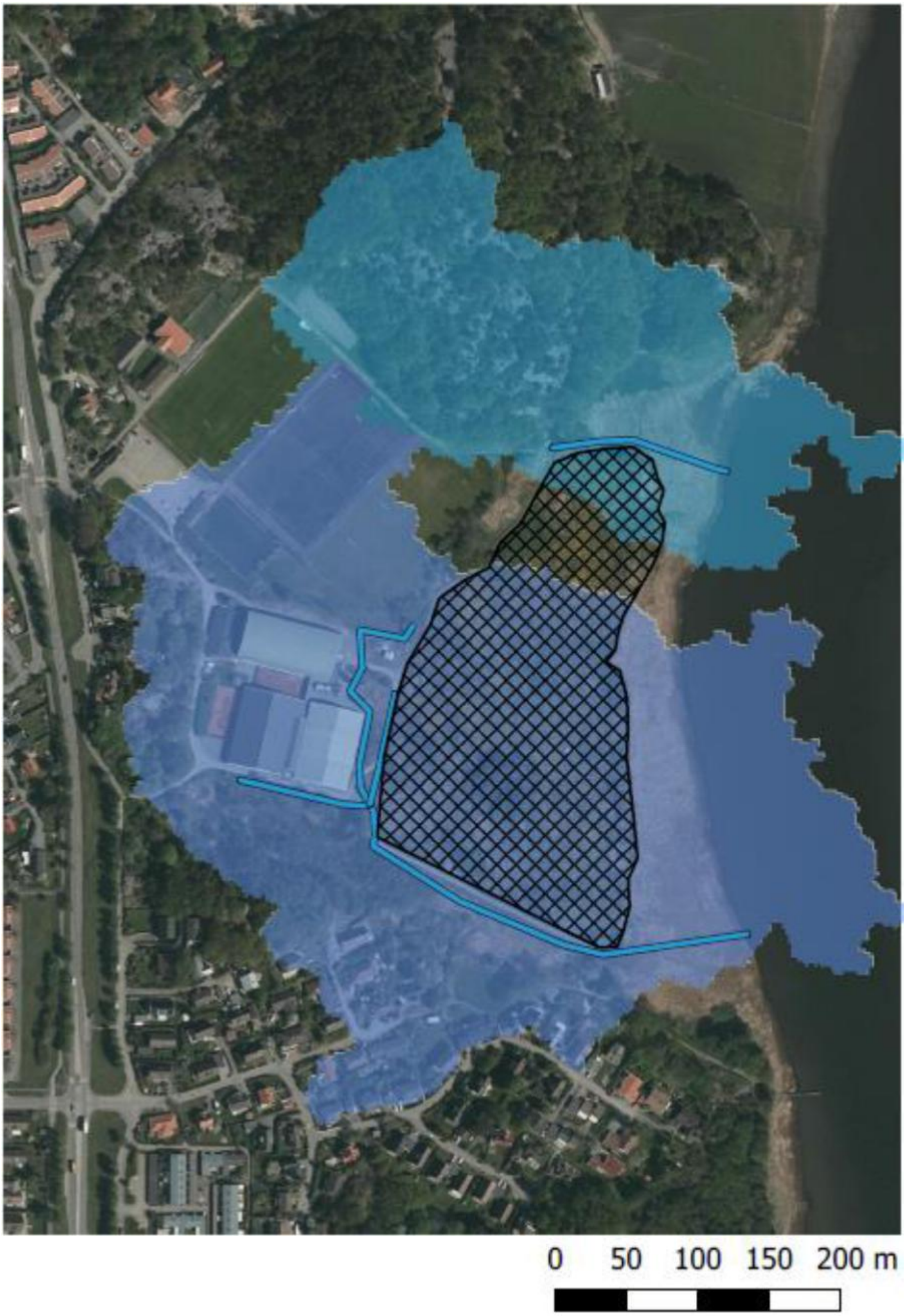


Figure 1. Catchment area divided into subareas.

Appendix G - Visual MODFLOW simulations

Maps and plots from simulations in Visual MODFLOW.

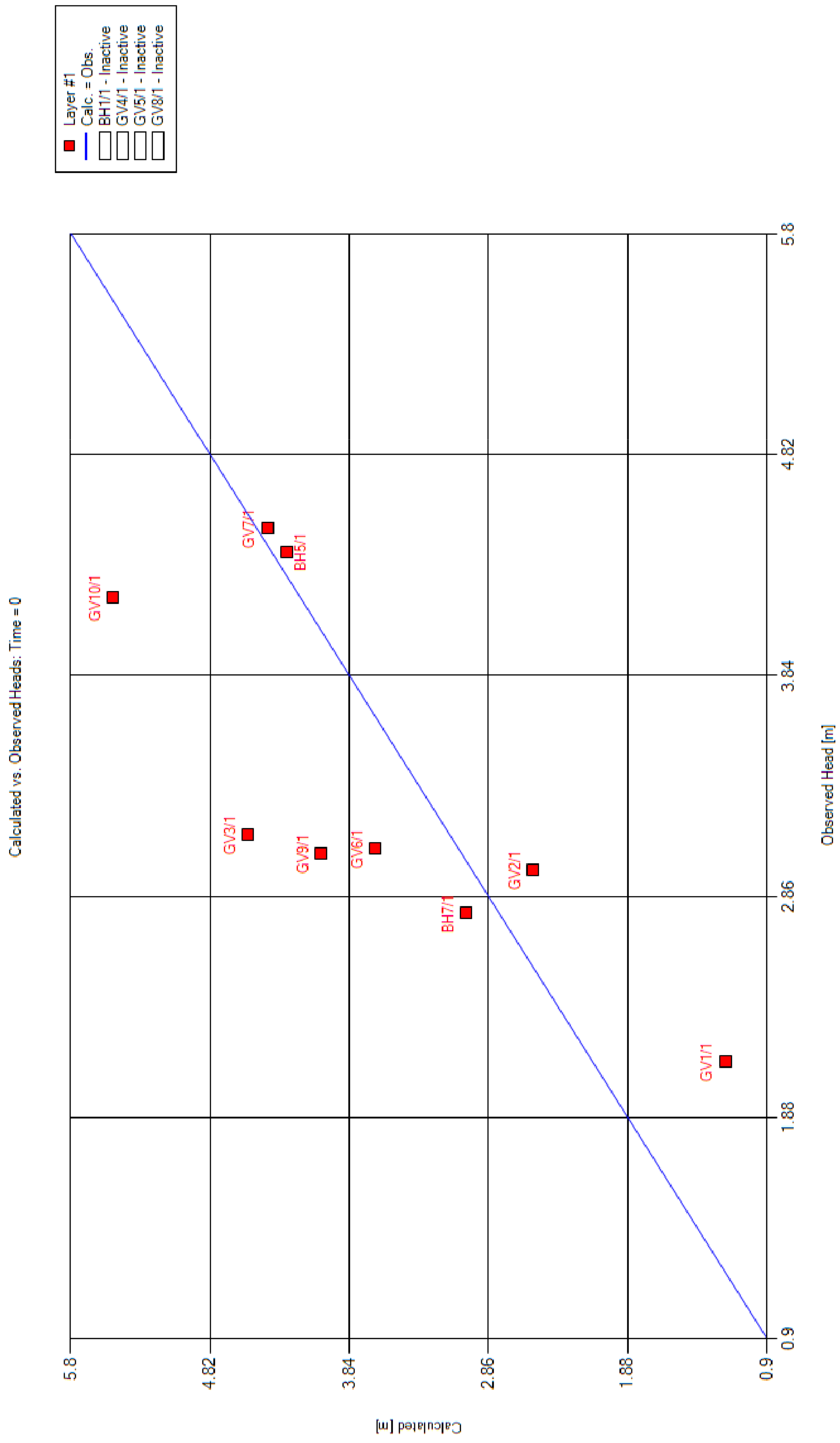


Figure 1. Correlation plot for one of the conceptual model 4.

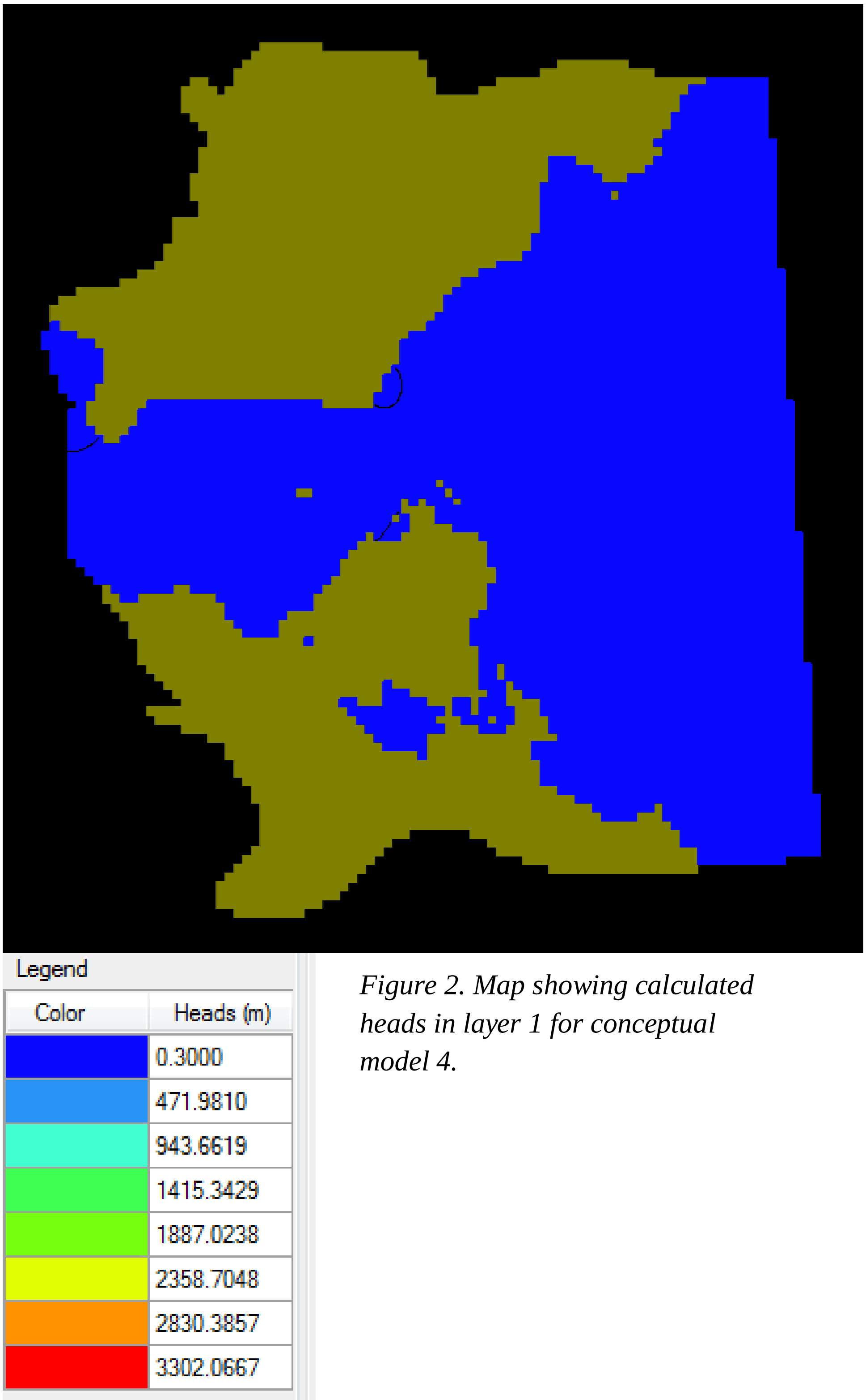


Figure 2. Map showing calculated heads in layer 1 for conceptual model 4.

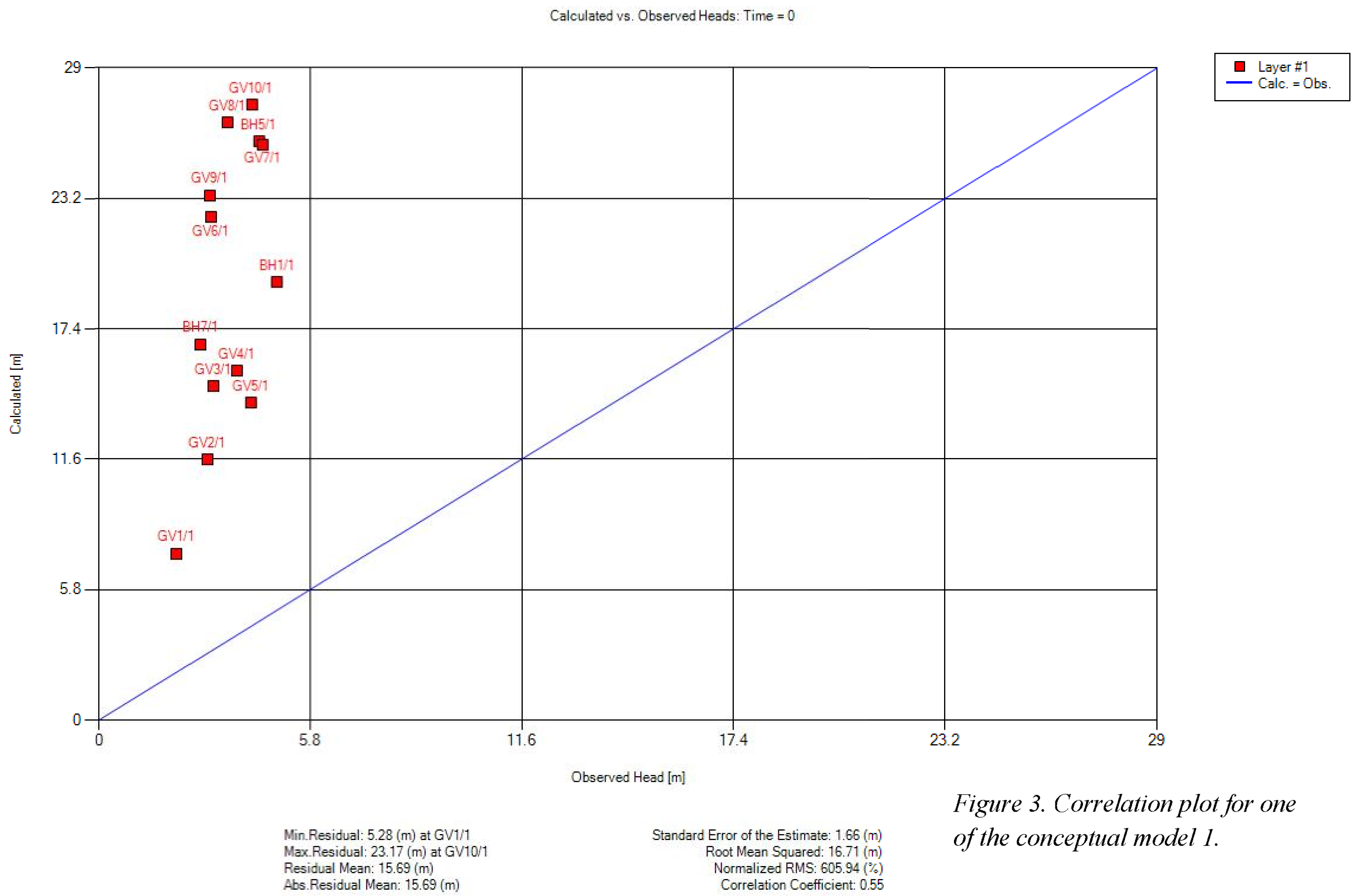
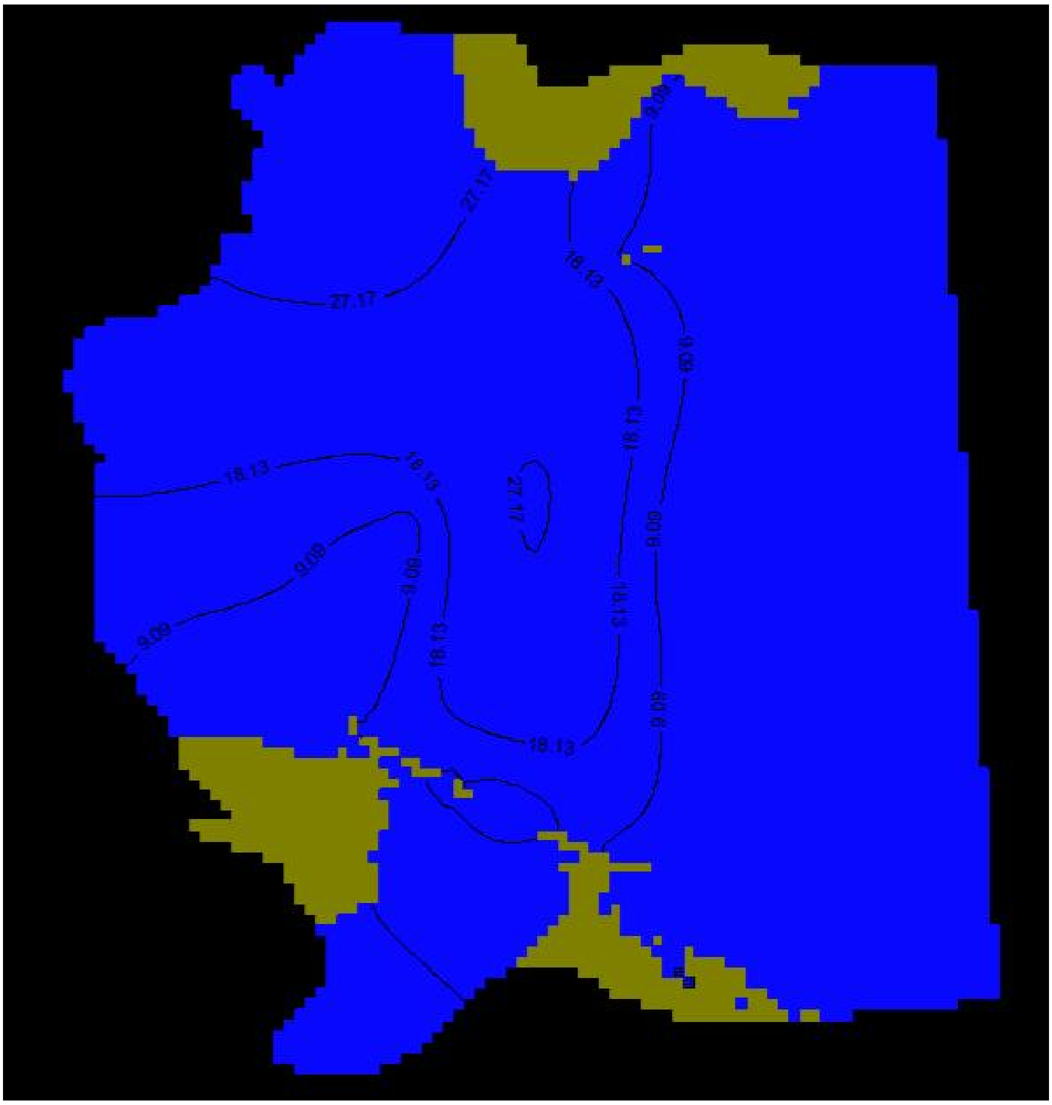


Figure 3. Correlation plot for one of the conceptual model 1.



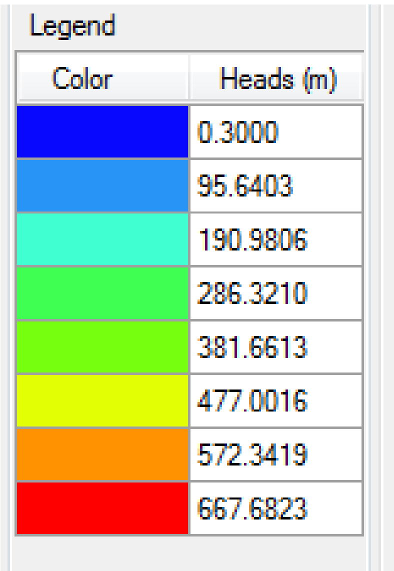


Figure 4. Map showing calculated heads in layer 1 for conceptual model 1.