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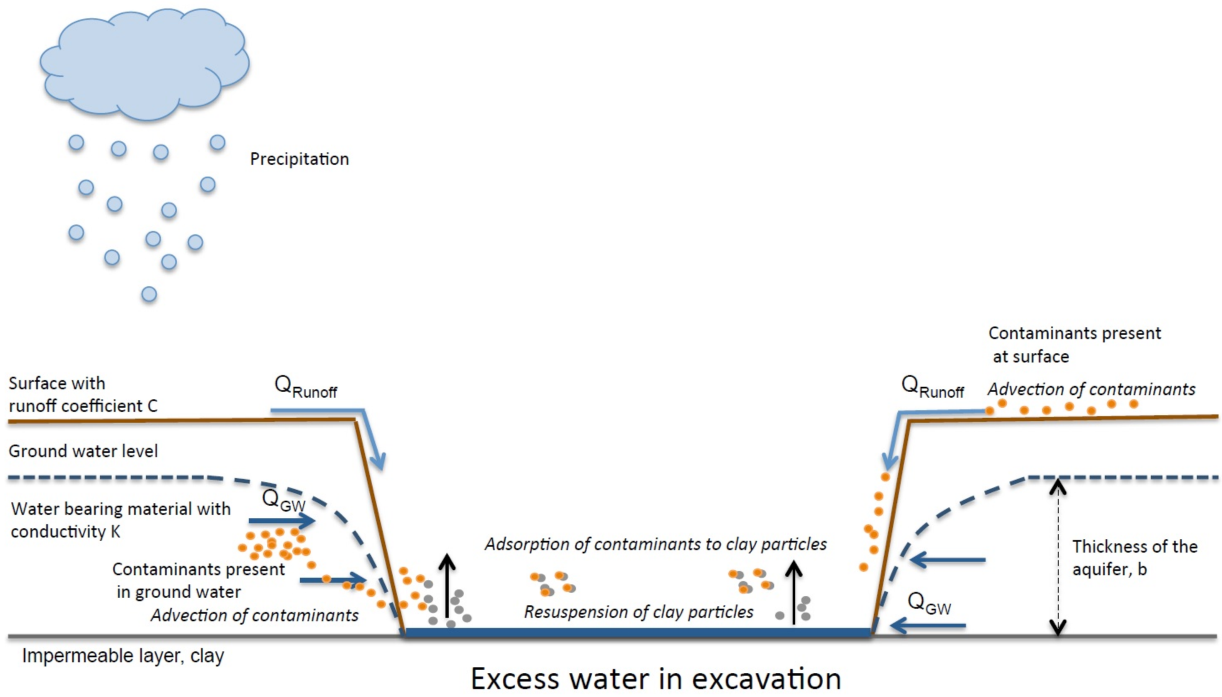

Prediction of Excess Water Quantity and Quality

Model framework enabling estimation of groundwater and stormwater inflow to excavations and assessment of contaminants in contributing flows

Master's Thesis in Master Programmes Infrastructure and Environmental Engineering and Industrial Ecology

TERESIA BÖRJESSON
JOHANNA SVENSSON

Department of Civil and Environmental Engineering
Division of Water Environment Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor: Karin Björklund, Department of Civil and Environmental Engineering
Assistant supervisor: Jenny Norrman, Department of Civil and Environmental Engineering
Examiner: Ann-Margret Hvitt Strömvall, Department of Civil and Environmental Engineering

Master's Thesis BOMX02-17-80
Department of Civil and Environmental Engineering
Division of Water Environment Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Conceptual model of quantity and quality of excess water.

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Abstract

In Gothenburg, excess water from excavations needs to fulfill the quality requirements set by the Environmental Agency before released into receiving waters. To determine remediation technique, the quantity and quality of the excess water needs to be estimated. There is currently no praxis for how to perform such estimations. The aim of this thesis was to develop a model framework to estimate quality and quantity of excess water in excavations by assessing groundwater intrusion, storm water inflow and contamination at site. The model framework was applied in a case study at Selma Lagerlöfs torg. To obtain further understanding of the issues surrounding excess water, interviews with stakeholders were held.

The groundwater intrusion was estimated by using the finite difference method as a numerical model in Microsoft Excel and the storm water inflow was estimated by using the rational method. To enable prediction of excess water quality, a framework model for qualitative assessment was developed. The model include for example sample strategies and a quality assessment matrix which describes how geochemical parameters such as pH and redox might affect contaminant fate. The storm water quality is estimated using standard values from the StormTac database.

Results of the case study are that correct assumptions of quantity parameters such as hydraulic conductivity, catchment area and runoff coefficients are crucial when estimating quantity of excess water. Regarding excess water quality, standard values from StormTac indicates that storm water contributes considerably to pollution of excess water. How groundwater affects the overall quality was found more complex to determine, but to facilitate estimations, structured sampling and consideration of geochemical properties are important factors.

Conclusively, estimations of excess water quantity and quality have potential to facilitate excess water management and hopefully the model framework can function as an aiding tool for stakeholders within the field. To enable improved predictions in the future, further research, monitoring and documentation of excess water quantity and quality are required.

Keywords: excess water, excavation, groundwater, stormwater, contamination, modelling, model framework

Bedömning av länsvattens kvantitet och kvalitet
Ramverk för modellering som möjliggör estimering av grund-och dagvatteninflöde till schakt och bedömning av föroreningar i bidragande flöden
Examensarbete inom masterprogrammen Infrastruktur och miljöteknik och Industriell ekologi
TERESIA BÖRJESSON
JOHANNA SVENSSON
Institutionen för Bygg- och miljöteknik
Avdelningen Vatten Miljö Teknik
Chalmers tekniska högskola

Sammanfattning

Länsvatten från schakt som släpps ut till recipienter och dagvattensystem i Göteborg måste uppfylla miljöförvaltningens kvalitetskrav. För att kunna bestämma lämplig reningsteknik, så måste kvantitet och kvalitet av länsvatten upskattas. I nuläget saknas praxis för genomförande av sådana uppskattningar. Syftet med rapporten var att utveckla ett ramverk för modellering som kan möjliggöra bedömning av länsvattens kvantitet och kvalitet genom att undersöka påverkan av grundvatteninträngning, dagvattenflöde och föreliggande föroreningssituation. Modelleringsramverket testats genom applicering på en fallstudie, Selma Lagerlöfs torg i Göteborg. För att fördjupa förståelsen för ämnet har intervjuer med berörda aktörer genomförts.

Flöden orsakade av grundvatteninträngning bedöms genom användning av finita differential metoden och dagvattenflöden uppskattas genom användning av rationella metoden. Bedömning av länsvattenkvalitet görs med hjälp av en ramverksmodell för kvalitativ uppskattning som inkluderar rekommendationer för provtagning av grundvatten och jord samt en kvalitetsbedömningsmatris som beskriver hur geokemiska egenskaper påverkar föroreningars beskaffenhet. Dagvattenkvalité bedöms med hjälp av schablonvärden från databasen StormTac.

Resultat från studien visar att korrekta uppskattningar av parametrar som hydraulisk konduktivitet och avrinningskoefficienter är avgörande när kvantitet av länsvatten ska bedömas. Angående länsvattnets kvalité så kan bedömning av grundvattnets påverkan på länsvattenkvalitete underlättas genom strukturerad provtagning och beaktande av geokemiska egenskaper. Schablonvärden från StormTac indikerar att dagvatten har potential att bidra avsevärt till förorening av länsvatten.

Slutsatser från studien är att bedömning av länsvattenkvantitet och kvalitet kan underlätta frågor som rör länsvattenhantering och förhoppningsvis kan modellramverket fungera som ett verktyg för berörda aktörer. För att möjliggöra mer precisa uppksattningar i framtiden, behövs förbättrad övervakning och dokumentation av länsvattens kvantitet och kvalitet samt fördjupad forskning inom ämnet.

Nyckelord: länsvatten, schakt, grundvatten, dagvatten, föroreningar, modellering, modellramverk

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Finally, we would like to thank our friends and families for their support.

Gothenburg, June 2017
Teresia Börjesson
Johanna Svensson

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1
Introduction

The release of polluted stormwater into natural water bodies may cause severe harm to ecosystems and biodiversity (NSW Government 2013). The urban environment consist mainly of impervious surfaces which reduces the amount of water infiltrating the soil and increases the proportion of precipitation converted into stormwater runoff. This leads to unnatural high flows that may cause flooding of urban areas or result in erosion of receiving waters (Victoria Stormwater Committee 1999). One particular type of urban stormwater is water accumulated in excavations at construction sites, here referred to as *excess water*. The excess water consist of either stormwater, groundwater or a mix of both. Before being released into receiving waters, excess water in Gothenburg should meet a certain level of quality, which in Gothenburg is determined by the city's Environmental Administration. Generally, the excess water is turbid and sometimes contaminated, and remediation is required. During construction projects it is usually the contractors' task to decide upon which remediation technique to use, depending on the quantity of excess water and its quality. However, there are currently no praxis in place for how to accurately predict excess water quantity and quality, which could lead to the release of insufficiently remediated excess water.

1.1 Background

Historically, monitoring of stormwater released into receiving waters and stormwater systems has been limited and no specific quality requirements for stormwater previously existed. However, national and international concern of the deterioration of watercourses has increased rapidly during recent years. This has led to the development of regulations for release of stormwater, including excess water originating from excavations, in some regions.

Since 2008, the Environmental Administration, EA, of Gothenburg provides water quality guideline values for all water released into receiving waters and stormwater systems. In 2013, the guideline report was updated in order to be coherent with the European Union Water Framework Directive and Swedish legislation (Carlsrud and Mossdal 2013). The report presents guidance on threshold values for heavy metals, oil, particles, suspended particles and common organic pollutants.

The responsibility to fulfil the quality requirements and remediate polluted excess water lies on the business operator, which during a turnkey agreement is the contractor and during a general agreement the developer. During the procurement of a turnkey agreement, the contractor needs to estimate how much the remediation of excess water will cost and include this in the total budget. The developer should, with the help of consultants, be able to provide data regarding the expected quality and quantity of excess water in the project so that the contractor in turn can present a price estimation (Magnusson and Norin 2013). As mentioned, there is currently no praxis in place of how to predict quantity or quality of excess water, leading to inaccurate price estimations and insufficient remediation. Hence, there is a need for a tool to forecast the quantity of excess water. Moreover, the level of pollution varies between different sites depending on soil type, surrounding activities and historical land use. To be able to choose treatment technology and thereby make reasonable cost estimations, as well as lower the amount of insufficiently treated water reaching nearby recipients of building sites, the tool should also be able to predict the overall quality of the water.

Research within the area of excess water quality and quantity is limited. NCC published a report in 2013 on how to manage and remediate excess water (Magnusson and Norin 2013), and a few master theses on the subject have been conducted during recent years, for example Biscevic and Olofsson (2015), which shows an increasing need for research.

1.2 Aim

The aim of this study is to estimate the quantity and quality of excess water in excavations at construction sites. The aim will be fulfilled by the development of a model framework that estimates groundwater intrusion, stormwater inflow and the contamination at site. The goal is to enable cost estimations for remediation of excess water in excavations for consultants and contractors within the building sector. This can hopefully prevent that insufficient solutions are installed and in turn decrease the amount of contaminated water reaching nearby receiving waters. To further investigate the issues surrounding excess water management, opinions and views of relevant stakeholders will be gathered and presented.

1.3 Research Questions

- How much excess water can be expected in an excavation depending on conditions at the site and size of the excavation? How can the quantities be estimated?
- What quality can be expected of the excess water with regards to particles, organic pollutants and metals?
- To enable accurate predictions, what investigations (groundwater and soil sampling, geotechnical investigations etc.) are required?
- What are the views and opinions about the current managing of excess water in Gothenburg among affected stakeholders?

1.4 Delimitations

This is study is limited to address the concerns regarding excess water management in Gothenburg. Other locations are not specifically considered, although comparisons might occur. Further limitations regarding the model framework are presented in each sections.

1.5 Thesis Outline

Chapter 1 of the thesis introduces the subject, and contains the aim and research questions for the study.

The study's theoretical background is described in chapter 2 and 3, where chapter 2 describe the theory behind excess water such as important parameters for quality and quantity, and different remediation techniques. Chapter 3 outline the theory behind modelling of groundwater and stormwater.

The methods for stakeholder interviews and modelling of excess water quantity and quality are presented in chapter 4.

Chapter 5 presents the case study, Selma Lagerlöfs torg, where the model is applied.

The result are presented in chapter 6, followed by discussion in chapter 7. The conclusions of the study are presented in chapter 8.

2
Excess Water in Excavations

The subject for this thesis is *excess water* in excavations, which is an ill-defined term. In Sweden, this water is referred to as *länsvatten*, as the water is pumped and removed from the excavation. The Swedish word *läns* is defined by the Swedish Academy as 'free from water' or 'empty', and the verb *länsa* as 'to empty' or 'to pump' (Svenska Akademien 2015). It has historically been used mostly when discussing water leaked into a ship, but in recent times it has also been applied to water in excavations at construction sites. In USA, the term *construction stormwater* is commonly used (Sjöberg 2017). Excess water in excavations is primarily runoff water originating from precipitation in combination with groundwater that might reach the excavation through the soil (Figure 2.1).

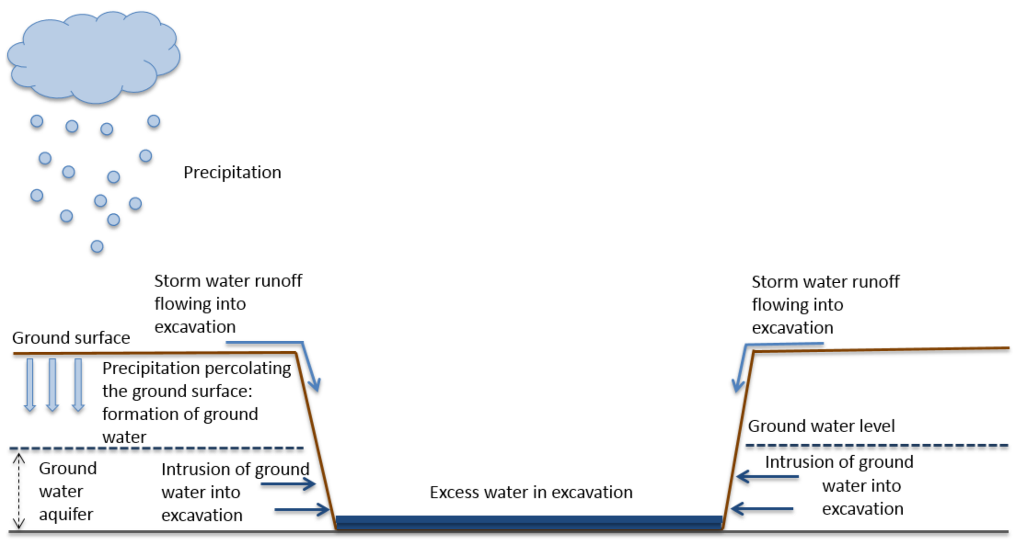

Figure 2.1: Formation of excess water in excavations.

When conducting excavations in construction projects, there are currently large uncertainties regarding the quantity and quality of excess water. The contractor has the responsibility to manage excess water and beforehand assess whether there will be any excess water and which treatment that will be needed. Since there is no tool available for this kind of assessment, management of excess water is a difficult task.

Generally, excess water in Gothenburg is turbid and contains high levels of suspended particles since it is mixed with the fine soil grains in the excavation (Magnusson and Norin 2013). Depending on the construction site it may also contain different environmental contaminants. Currently, separation of particles through sedimentation is the most common treatment method for excess water. Particle separation is considered to be of major importance since particles are often carriers of contaminants such as persistans organic pollutants and heavy metals (Biscevic and Olofsson 2015). The use of sedimentation tanks has however often shown to be insufficient, especially for water with high clay content as clay particles settle very slowly (Magnusson and Norin 2013). Excess water from construction sites is pumped to nearby receiving waters or stormwater systems, and has to meet the requirements for wastewater discharged to surface water and receiving waters, set by the Environmental Administration in Gothenburg. The requirements are the same for all types of wastewater discharged to stormwater systems or receiving waters, including for example process water from industries and water from washing of facades and roofs (Carlsrud and Mossdal 2013). The requirements include guideline limits for concentration of certain environmental contaminants such as heavy metals, organic pollutants and suspended soils. The requirements are found in Appendix A.

2.1 Water Quantity Parameters

Water in excavations can consist of both stormwater runoff and groundwater percolated through the soil. Many parameters affect the total amount of water accumulated in the excavation, some of which are presented in this section.

2.1.1 Precipitation and Surface Type

In Sweden, precipitation falls all year round but mostly during summer and autumn (SMHI 2017b), (Figure 2.2). Most of the low pressures hit Sweden from the west, leading to heavier precipitation in Sweden's western parts. In southwestern Sweden, where Gothenburg is located, average annual rainfall is 1000-1200 mm whereas annual precipitation in parts of eastern Sweden can be as low as 400 mm.

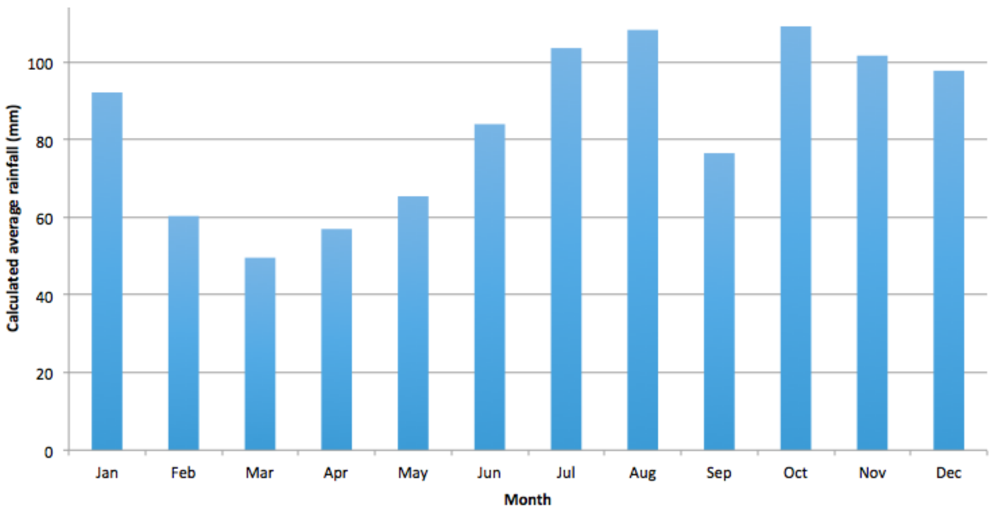

Figure 2.2: Monthly average rainfall in Gothenburg 2000-2016 (SMHI 2017a).

Precipitation at construction sites is likely to accumulate in excavations, since an excavation is a low point to which water flows. When rainfall exceeds the ground's capacity to infiltrate water, runoff is produced and water begins to flow downhill (Sustainable Agriculture Research and Education 2012). The proportion of the rain that will infiltrate into the soil depends on the permeability of the ground surface. Materials like sand and gravel have larger ability to infiltrate water compared to finer soils such as clay. The water that infiltrates will percolate through the ground and eventually become groundwater. In urban areas, many surfaces are of impermeable materials, such as asphalt and rooftops, which increases the amount of surface runoff (Clean Water Education Partnership 2017). Moreover, filling materials are commonly found and these are known to be very heterogeneous and therefore have varying infiltration capacity. Since many building projects are carried out in cities, surface runoff from less permeable surfaces is an important parameter to consider.

2.1.2 Hydraulic Conductivity, K

When predicting the flow of groundwater into excavations, the governing parameter is *hydraulic conductivity.* Soil materials consists of both solid material and pores, and in the pores there are room for air or water (Fetter 2001). When the pores are connected, water can move and flow through the soil. Water's ability to move through the material is referred to as hydraulic conductivity. In the 19^{th} century, Frenchman Henry Darcy conducted a study on water's movement through a porous media by using water filtrations through sand. His conclusion was that the water flow is proportional to the hydraulic head and to the studied cross-sectional area, as well as inversely proportional to the flow length. The flow also depends on the hydraulic conductivity, K, which magnitude depends on the material's properties. This resulted in the so called Darcy's law (equation 2.1).

$$Q = -KA\frac{dh}{dl} \tag{2.1}$$

Q - Flow (m^3/s)
K - Hydraulic conductivity (m/s)
A - Cross-sectional area (m^2)
$\frac{dh}{dl}$ - Hydraulic gradient (-)

The magnitude of K depends on the material's properties, mainly the average size of the pores (Knappett and Craig 2012). The pore size is influenced by the size of the grains leading to a generally lower permeability in soils with smaller grains. The permeability also depends on the shape of the grains. For example, the permeability of clay can be highly variable due to the orientation of the oval clay grains. If the grains are aligned in a similar direction, the permeability will be higher than if they are aligned in different directions. Typical hydraulic conductivities for different soil materials can be seen in Table 2.1.

Table 2.1: Hydraulic conductivities and grain sizes for different soil fractions (SGI 2008).

Material	**Hydraulic conductivity (m/s)**	**Grain size (mm)**
Clay	$<10^{-8}$	< 0.002
Medium silt, fine silt	$10^{-6} - 10^{-8}$	0.002 - 0.02
Coarse silt	$10^{-4} - 10^{-6}$	0.02 - 0.063
Fine sand	$10^{-3} - 10^{-5}$	0.063 - 0.2
Medium sand	$10^{-2} - 10^{-4}$	0.2 - 0.63
Coarse sand	$10^{-1} - 10^{-3}$	0.63 - 2.0
Fine gravel	$1 - 10^{-2}$	2.0 - 6.3

If table values are not sufficient or accurate enough, the site-specific hydrailic conductivity can be determined e.g. through established empirical relations. One example is the Hazen method, which estimates the hydraulic conductivity from the effective grain size for sands (Hussein and Nabi 2016). This method has been further developed to be applied for different types of soil using the mean grain size.

Field tests can also be used to determine the hydraulic conductivity at site. Aquifer test is a method to find out the hydraulic characteristics by pumping water from a well and observe the draw-down in the well, close-by observation wells or both (Fetter 2001). Aquifer tests can be expensive to conduct and problematic if the water is contaminated, as the water then might need treatment before disposal. An alternative method to aquifer tests at site is the slug test. During a slug test, a known quantity of water, or other type of slug, is added to or drawn from a monitoring well, and the response is monitored by continuously measuring the water level in the monitoring well. The data collected can then be analysed to find the hydraulic conductivity. The slug test however only evaluates the permeability at a smaller area around the monitoring point, whilst the aquifer test evaluates a larger part of the aquifer (Ohio EPA 2006).

Soil samples can also be evaluated in laboratory tests to determine the hydraulic conductivity. However, laboratory tests on small samples might not give representative values of the permeability of the soil as soils usually are layered, which affects the hydraulic conductivity but might not be observed in a small sample (SGI 2008). When dealing with dry crust clay it is important to consider cracks, which may increase the hydraulic conductivity several times compared to what can be shown from a small sample.

2.1.3 Radius of Influence, R_0

The radius of influence is the area where a draw down is occurring around a well or excavation. This is also called the cone of depression (Der Smedt 2009), outside of the radius of influence the groundwater level will be undisturbed.

The radius of influence is most reliably determined from analysis of a pumping test (Cashman and Preene 2013), but if no test has been conducted the radius of influence needs to be calculated using other methods. Thurner's equation (SBEF 1985), sometimes referred to as Sichardt's formula (Cashman and Preene 2013), gives an approximate estimation of the maximum radius of influence based on the hydraulic conductivity (equation 2.2).

$$R_0 = 3000s\sqrt{K} \tag{2.2}$$

R_0 - Radius of influence (m)
s - Drawdown in well (m)
K - Hydraulic conductivity (m/s)

If the radius of the studied well is large, the equation can be modified (equation 2.3). It is assumed that excavations behave like larger wells, and the latter equation is more appropriate to use.

$$R_0 = R_b 3000s\sqrt{K} \tag{2.3}$$

R_0 - Radius of influence (m)
R_b - Radius of well (m)
s - Draw down in well (m)
K - Hydraulic conductivity (m/s)

To not use too unrealistic values, it is stated in SBEF (1985) that the radius of influence should not be smaller than 30 m or larger than 5000 m.

2.2 Water Quality Parameters

The quality of excess water depends on the conditions at the site of the excavation. This section presents some of the most common contaminants as well as important transport processes.

2.2.1 Contamination of Soil

Contaminants usually mean harmful substances introduced by humans into the environment (van der Perk 2014). Release of anthropogenic contamination can be divided into two categories, point sources and diffuse sources. Point sources refer to contaminants released at one fixed point whilst a diffuse source is released over a larger area. According to Sveriges Geologiska Undersökning (2017), approximately 80 000 sites in Sweden are potentially, or confirmed contaminated. It is known that around 1300 of these sites pose serious risks to humans and the environment.

Contaminants in soil often originate from industrial, chemical-technical activities that increased rapidly during the first half of the 20th century, such as material processing and production, agriculture and mining. Since the harmful effects of contaminants were previously unknown, many old industrial sites and buildings are heavily contaminated and industrial waste was disposed into land and water without remediation. Moreover, already contaminated soil from e.g. old landfills or harbours where commonly used as filling material when building housing areas and infrastructure facilities (Naturvårdsverket 2005). Contaminants were then spread to places that normally would not be affected, leading to the problematic current situation where prediction of contamination of an area is difficult.

2.2.1.1 Heavy Metals

Metals and semi-metals with toxic characteristics are often referred to as heavy metals, although the definition of the term may vary (van der Perk 2014). Many pollutants addressed in the guidelines of the Environmental Agency of Gothenburg are categorised as heavy metals, for example zinc, copper, lead and mercury. Some of the heavy metals are essential in soil for biological growth but become toxic in larger quantities, especially to humans and animals. Many heavy metals are bioaccumulative i.e., they have the tendency to accumulate in organic tissue. Moreover, biomagnification may occur, leading to transfer across the food chain and potential harm to top predators.

Heavy metals occur naturally in the earth's crust and natural events like volcanic eruption can cause abnormally high concentrations of metals in the soil(van der Perk 2014). Anthropogenic sources are for example mining, spreading of sewage sludge on land, leaching from building materials and discharges from industries, which contribute to increased heavy metals in the environment. In Sweden, industries such as paper and glass production, have been the largest contributor to elevated concentrations of heavy metals in soil (Naturvårdsverket 2017). The factor with the largest influence on the metal's soil absorption is pH, where lower pH leads to decreased absorption(van der Perk 2014).

2.2.1.2 Persistent Organic Pollutants

Persistent organic pollutants, POPs, are industrially produced toxic chemicals that do not degrade and therefore accumulates in the environment (US EPA 2009). The three main categories are pesticides, industrial chemicals and unintentionally produced by-products (Stockholm Convention 2008). Generally, POPs are carbon-based, semi-volatile, have low solubility in water and have an inherent toxicity (Fiedler 2003). In combination, these properties results in long-range transport and bioaccumulation, which leads POPs being found in areas far from where they were originally released. Similarly to heavy metals, POPs biomagnify in the food chain and high concentrations has occasionally been identified in animals and humans.

Examples of well-known POPs are Diklordifenyltrikloretan (DDT), Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs) and Tributyltin (TBT) (O'Sullivan and Megson 2014). The commercial production of many POPs began during the years 1930-1950, and the negative effects related to the release of these substances was first highlighted in the book *Silent Spring* by Rachel Carson in 1962. Today, many of these substances are banned or regulated by environmental authorities, but due to their long lifetime they are still found in the environment, especially in industrial areas.

2.2.1.3 Suspended Solids

Total suspended solids, TSS, are all fine particulate matter that are larger than 2 µm (Fondriest Environmental 2014). Particles smaller than 2 µm, such as colloids, is considered a dissolved solid (Fondriest Environmental 2014).

Suspended solids refers to organic and inorganic matter drifting and floating in the water such as sediment, silt, sand, plankton and algae. The concentration of TSS affects the clarity of the water, the more solids present, the less clear and more turbid is the water (Fondriest Environmental 2014). Under natural conditions, all streams carry some suspended solids but the concentrations can be enhanced due to anthropogenic perturbation which may lead to changes in the physical, chemical and biological properties of the water body (Biolotta and Brazier 2008). Examples of physical changes connected to an increased concentration of suspended solids are reduced penetration of light, infilling of channels when solids are deposited, reduced navigability and decreased lifetime of dams and reservoirs. Chemical alterations include increased concentrations of contaminants and pathogens due to adsorption into the water body. Moreover, if the suspended solids consists of matter with high organic content, decomposition of these might cause depletion of dissolved oxygen. The biological effects are connected to how biota is affected by the physical and chemical changes, e.g. reduced penetration of light and oxygen depletion.

2.2.1.4 Oil

Crude oil, also referred to as petroleum, is a thick, dark brown combustible liquid, formed by the anaerobic decay of organic matter in enclosing sedimentary rocks (van der Perk 2014). The chemical compounds found in crude oil have various properties from very volatile light compounds like pentane and benzene, to heavy compounds such as bitumens and asphaltenes. Around 95 % of the compounds are hydrocarbons i.e. organic compounds consisting of only carbon and hydrogen. However, small amounts of oxygen, nitrogen, sulphur and traces of heavy metals might occur. Extraction of oil is conducted by drilling and pumping and refined by distillation. Environmental pollution of oil occur due to extraction, refinement, transport and spills of refined products such as diesel and petrol, which pose threat to soil and water quality, plant and animal life and human health.

2.2.2 Transport and Fate Processes of Contaminants in Soil

Fate processes determines the life cycle of a contaminant, i.e. what will happen after it is released into the environment. One highly relevant fate process when assessing transport of contaminants in soil is *sorption* (Vallero 2004). Sorption is when a contaminant becomes associated physically or chemically with a solid sorbent, and is important to consider when evaluating a compound's bioavailability. Sorption is caused by different attractive forces between the contaminants and particles in soils and sediments (Gratwohl 1998). There are four basic mechanisms of sorption; adsorption, absorption, chemisorption and ion exchange (Vallero 2004). For clay particles where little carbon is available, such as in groundwater, the most common sorption process is adsorption. During adsorption, the dissolved chemical attaches to a solid surface. Absorption instead occurs in porous materials when the chemical is sorbed onto the inside of the particle. Chemisorption might occur as a result of a covalent reaction between a mineral surface and a contaminant, and ion exchange is when charged ions are attached to particle surfaces of opposite charge. Contaminants will eventually establish a balance between the mass on the solid surfaces and the mass in the solution, and molecules will migrate from one phase to another to maintain this balance. According to Gratwohl (1998) the process of adsorption is relatively fast.

Other important fate processes are *advection*, *diffusion* and *dispersion* (van der Perk 2014). Advection refers to the process of substance transport through water or soil with the movement of the water itself. Diffusion is when contaminants spontaneously move from areas of higher concentration to areas of lower concentration. Dispersion, also referred to as mixing, occurs when the flow velocity varies within and between the pores. In addition, mechanical dispersion occurs due to the tortuosity of flow paths in an environmental media as well as the velocity gradient (Figure 2.3) (van der Perk 2014).

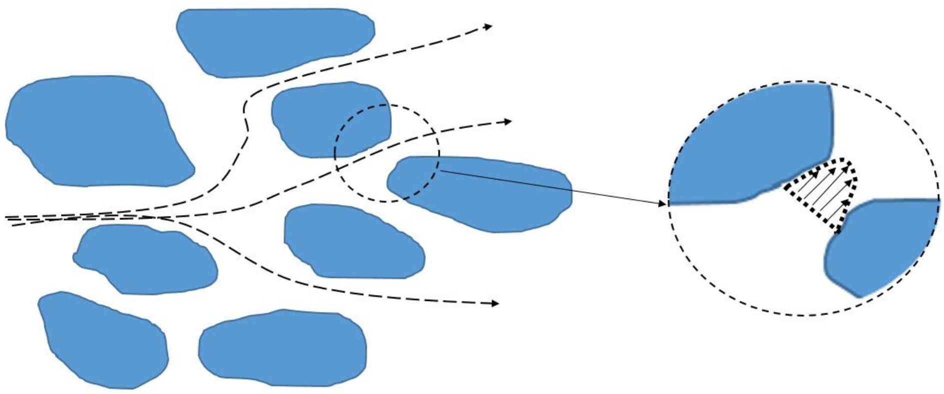

Figure 2.3: Illustration of dispersion. Adapted from van der Perk (2014).

2.2.3 The partition coefficient, K_D

When assessing sorption, the partition coefficient K_D is highly relevant. Contaminant transportation greatly depends on the contaminants partition between different phases (Naturvårdsverket 2009). Substances generally exist in either solid, liquid or gas phase and the ratio between two phases can be described with a partition, or distribution, coefficient K_D (equation 2.4) (van der Perk 2014).

$$K_D = \frac{C_{phase1}}{C_{phase2}} \tag{2.4}$$

K_D = Distribution coefficient
C_{phase1} = Equilibrium concentration of the contaminant in phase 1
C_{phase2} = Equilibrium concentration of the contaminant in phase 2

Balance between the mass on the solid surfaces and the mass in solution is achieved through contaminant migration between phases. Partition between the phases depends on the properties of both the contaminant and the soil (Vallero 2004). Soil properties that might affect partition are grain size, organic content of the soil, soil pH and redox relations (Naturvårdsverket 2009). Grain size refers to the diameter of the individual grains in soil or water. Organic content in the soil is the fraction of the soil that consist of residues of plant or animal tissue in various stage of decomposition (Fenton et al. 2008) and generally, organic pollutants bind harder to soil particles if the organic content in the soil is high (Naturvårdsverket 2009). Soil pH is a measure of the acidity or alkalinity of the soil (Bickelhaupt 2017) and is defined as the negative logarithm of the hydrogen ion concentration. The pH interval are from 0 to 14 with pH 7 as the neutral point. As the amount of hydrogen ions in the soil increases, the soil pH decreases i.e. the soil is becoming more acidic. According to Chuan et al. (1996) solubility of heavy metals increase if pH in the soil decrease. Redox potential is a measure of the redox conditions, i. e. availability of electrons, the in the soil (Hindersmann and Mansfeldt 2014). Soil conditions under which oxygen is accessible, aerobic conditions, are characterised by low availability of electrons and referred to as oxidising. Anaerobic soil conditions, where no or little oxygen is available are referred to as reducing conditions which are characterised by high electron availability. Solubility of heavy metals are affected by the prevailing redox conditions and according to Chuan et al. (1996) the solubility generally increase as redox potential decrease, i.e increased availability of electrons and decreased accessibility of oxygen.

The sorption balance relationships are known as *sorption isotherms* and can be determined experimentally (Vallero 2004). Isotherms are not always entirely linear, especially at high concentrations of a contaminant, which should be considered when sorption is analysed. A linear chemical partitioning can be expressed as in equation 2.5.

$$K_D = \frac{C_s}{C_w} \tag{2.5}$$

K_D = Distribution coefficient (l/kg)
C_s = Equilibrium concentration of the contaminant in the solid phase (mg/kg)
C_w = Equilibrium concentration of the contaminant in the water (mg/l)

The relationship between solid and liquid phase are described with the distribution coefficient K_D (van der Perk 2014), where a high K_D value indicates *low* solubility. K_D can be laboratory determined by leaching test. If the concentrations are unknown, and laboratory tests can be conducted, K_D can be estimated from the *organic carbon partition coefficient*, K_{OC}, and the amount of organic matter in the particular soil, OC, see equation 2.6 (Vallero 2004). The solubility of organic substances in subsurface water depends greatly on the amount of organic carbon in the soil, as these pollutants tend to sorb to organic carbon through hydrophobic interactions. A substance with a high K_{OC} bond strongly to the organic carbon and less will be dissolved in water.

$$K_D = K_{OC}OC \tag{2.6}$$

K_D = Distribution coefficient (m^3/kg)
K_{OC} = Organic carbon partition coefficient (m^3 water/kg organic carbon)
OC = Soil organic matter (kg organic carbon/kg soil)

K_{OC} can be calculated using the specific partition coefficient of octanol and water, the *octanol-water partition coefficient*, K_{OW}. K_{OW} is a measure of a chemical's tendency to partition between the organic and aqueous phase, and is especially useful when assessing transport and fate of organic compounds. Hydrophobic compounds prefer to bind to octanol (log $K_{OW} > 3$) whereas hydrophilic organic compounds prefer to bind to water. Values of K_{OW} for many chemicals are available in the literature and can be used to estimate other parameters, e.g. K_D. Regarding the special case of volatilisation of contaminants from liquid to gas phase, the distribution constant is often referred to as Henry's law constant, K_H (van der Perk 2014).

2.3 Remediation of Contaminated Excess Water

Groundwater and stormwater in excavations usually needs to be remediated before being release into receiving waters, and often the focus is on removal of finer particles that cause turbidity and might carry contaminants (Magnusson and Norin 2013). In some cases, dissolved contaminants such as organic compounds and heavy metals also need to be removed. Besides quality the preferred remediation technique depends on the expected volumes of excess water as the treatment facility needs to have sufficient capacity.

There are several different remediation techniques available, ranging in both price and complexity. Magnusson and Norin (2013) divided the different techniques into five different levels, with the cheapest and simplest solutions at level 1 and then increasing cost and complexity with each level.

Magnusson (2017) states that one of the issues with remediation of excess water is that from the simplest remediation techniques, where only sedimentation is used, to the more complex remediation techniques the step is very large. The more complex remediation techniques require more user knowledge, at the same time as the cost increases.

2.3.1 Sedimentation

Sedimentation is the process when particles sink by gravity in the water and it is a way to remove suspended particles, and thereto bound contaminants, from turbid water. Once the particles have settled, they can be removed from the bottom of the container (Magnusson and Norin 2013). A particle's settling velocity depends largely on the particle's diameter, larger particles will settle more quickly than smaller. Stoke's equation describes the setting velocity (equation 2.7).

$$v_s = \frac{1}{18}\frac{g}{\nu}\frac{(\rho_s - \rho_w)}{\rho_w}d^2 \tag{2.7}$$

v_s - Settling velocity (m/s)
g - Gravitational force (m/s^2)
ν - Viscosity (m^2/s)
ρ_s - Particle density (kg/m^3)
ρ_w - Water density (kg/m^3)
d - Particle diameter (m)

The limiting settling velocity depends on the vertical flowrate and the dimensions of the sedimentation tank or pond. Lower flow and larger dimensions will settle more particles. A commonly used remediation technique at construction sites are sedimentation tanks (Figure 2.4). Clay particles have, due to their small diameter, a very low settling velocity and are therefore difficult to remove.

Figure 2.4: Photography of sedimentation tank.

There are ways to increase the efficiency of sedimentation, for example by using a facility with larger area such as a pond (Magnusson and Norin 2013). This allows for particles with lower settling velocity to settle or possibilities to remediate larger volumes of water. Sedimentation ponds however require large areas adjacent to the construction site. An alternative could be the use of *lamellas* in the sedimentation tank. The lamellas are plates which are placed in the tank at an angle around 60° to increase the settling area as well as making the settling distance smaller (Figure 2.5). The sludge created on the lamellas then slides down to the bottom of the container. Lamella sedimentation can be up to 20 times more efficient than using a regular sedimentation tank, and does not require larger area.

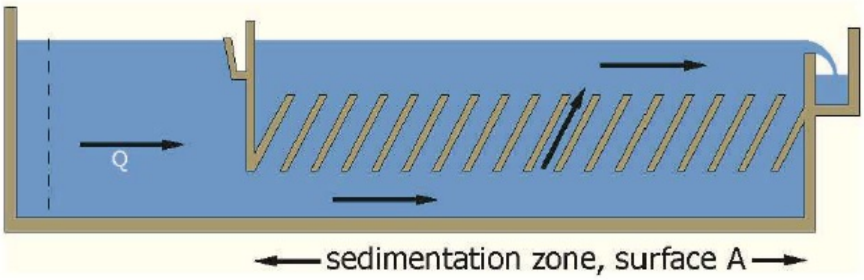

Figure 2.5: Sedimentation tank with lamellas (TU Delft Open Course Ware 2016). Creative Commons licence: CC BY-NC-SA.

Sedimentation is a simple technique that does not require any special skills to operate. However, it does not give sufficient remediation for waters with high content of clay or dissolved pollutants, as these particles will not settle.

2.3.2 Oil Separation

Oil separation is, like sedimentation, accomplished by differences in density: oil has a lower density than water and will float (Magnusson and Norin 2013). An oil separator can be combined with a sedimentation tank where the oil, accumulated at the top layer, is stopped and separated at the outflow (Figure 2.6).

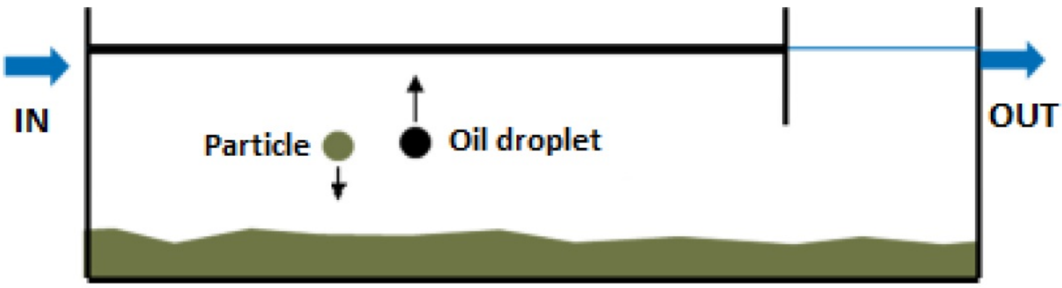

Figure 2.6: Oil separation in a sedimentation tank (Magnusson and Norin 2013). Published with permission.

2.3.3 Precipitation and Flocculation

While many contaminants are removed by sedimentation, smaller particles like clay are not. By making the smaller mineral particles flocculate to larger aggregates, they are more easily removed by either sedimentation or floatation. This method is well suited for turbid water with a high content of fine particles (Magnusson and Norin 2013).

The use of iron or aluminium salts as precipitants, neutralise the positive charge on the particle surface which enables particles to form larger aggregates (Figure 2.7).

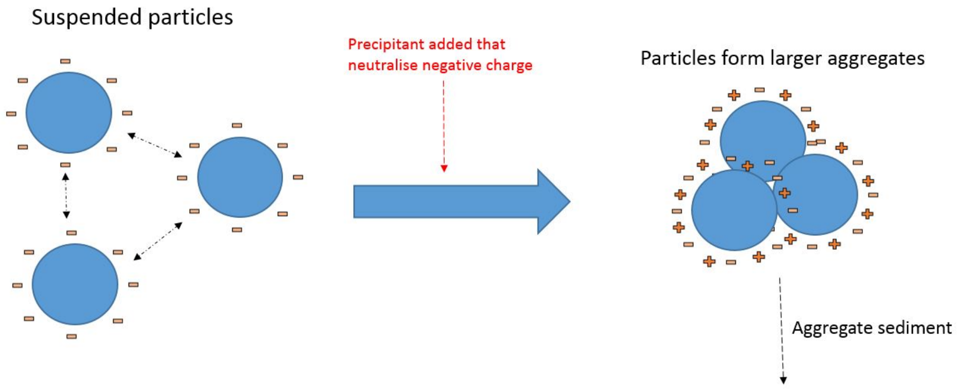

Figure 2.7: Particles form larger aggregates after addition of precipitant.

The precipitation process requires a certain pH interval, and additional pH adjustment might be needed. The pH adjustment is followed by the flocculation process where a high molecular polymer is added to make the particles bind together. The larger aggregates are then removed by sedimentation. Compared to regular sedimentation, this technique is much more efficient for turbid waters with high clay content, however special skills are needed during operation to apply the right amount of chemicals.

Some new technologies has entered the Swedish market in recent years, for example the use of the chemical chitosan (Swedish Hydro Solutions 2017). Chitosan can be extracted from by-products from the food industry, e.g. crab shells, and is therefore biodegradable. The method is established in USA where it has been more or less standardised (Sjöberg 2017). Chitosan helps the particles flocculate to larger aggregates.

2.3.4 Filtration

Filters can be used to remove particles and contaminants, either physically or by sorption to the filter media. During filtration, water is lead through a filter while the particles are physically retained by the filter media (Magnusson and Norin 2013). There are several different types of filters. Pressurised rapid filters consist of a tank filled with for example sand, where the water flows from the top and down through the filter. The filter needs to be back flushed regularly to remove the particles retained in the filter. Another type of filter is continuous filter where the filter media, usually sand, is circulated and cleaned continuously.

A different type of filters is active carbon. Active carbon has, due to its large surface area, the ability to adsorb different types of contaminants, for example dissolved organic matter. An active carbon filter needs to be preceded by another process that removes larger particles, such as sedimentation, otherwise the filters risks to be clogged.

Membrane filters separates contaminants by size, where the pore size of the filter decides which particles are let through (Blecken 2016). Membrane filters are categorised into micro, ultra and nano filters, depending on the pore size. Membrane filters are commonly used for waste and drinking water remediation, but use has so far been limited when it comes to stormwater and excess water remediation. Some trials have been conducted for stormwater, with positive results.

3
Modelling

A model is, as described by Bear and Cheng (2010), *"a selected simplified version of a real system and phenomena that take place within it, which approximately simulate the system's excitation-response relationship that are of interest"*. Modelling is essentially a way to predict how systems react in different scenarios. A model needs to be simple in order to not require excessive amounts of input data, but it must still be sophisticated enough to solve the particular problem. The relation between simplification and sophistication is crucial, and thorough descriptions of model assumptions and boundary conditions are essential. To facilitate the description of a model and its assumptions and boundaries, a so called *conceptual model* can be constructed.

3.1 Conceptual Model

Conceptual models function to define and identify important components of a system (Burgman 2005). Examples of important components are input and output parameters, flows, pathways, cycles and system boundaries. Conceptual models can be in forms of verbal models, diagrams, logical trees or sets of mathematical equations. The context together with the problem formulation decide how detailed the model needs to be. An example of a simple framework for a conceptual model is presented in Figure 3.1.

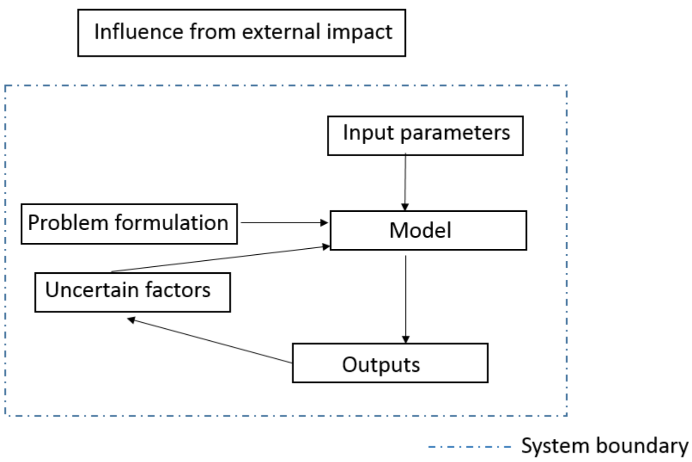

Figure 3.1: Example of a simple conceptual model.

Conceptual models should be constructed in the beginning of the modelling process and function to clarify the most important parameters of the situation. They could also be helpful when problem are to be communicated to concerned stakeholders. To analyse the importance of the parameters, and how they interrelate, sensitivity and scenario analyses can be conducted.

3.2 Sensitivity and Scenario Analysis

A sensitivity analysis explores how the model output change due to a change in one of the input parameters, and thereby pinpoint the parameters that affect the outcome the most (Burgman 2005). This can be expressed as the equation 3.1

$$s_p = \frac{\Delta V/V}{\Delta P/P} \tag{3.1}$$

s_p - Sensitivity
P - Input parameter
ΔP - Change in input parameter
V - Output variable
ΔV - Change in output variable

The model is sensitive to a parameter if s_p is larger than 1, and proportional to the parameter if s_p is equal to 1. For values closer to 0, the model is less sensitive to the parameter. A scenario analysis evaluates hypothetical sequences of events. Common examples of scenarios are *best case scenario* and *worst case scenario* and in a scenario analysis, combinations of different input parameters that might have extraordinary consequences are tested strategically.

3.3 Hydrological Modelling

The science of hydrology describes the system of water on earth, including its occurrence, circulation, and properties (Gayathri et al. 2015). The purpose with hydrological modelling is to simplify the complex reality of water and enable prediction of water-related processes such as precipitation patterns, runoff flows and groundwater occurrence. It is also of importance when assessing how the environment and its hydrological systems is affected by anthropogenic activities such as urbanisation, industrialisation, land cover change and irrigation. Moreover, hydrological modelling plays an important role when analysing climate change and its impact on our built society (Praskievicz and Chang 2009).

When modelling groundwater flow and contamination transport, there is generally not enough data to calibrate the often heterogeneous ground conditions or enough information about the processes concerning contaminants. One might then wonder what is the point of a model, if there is not enough data to create reliable predictions? Bear and Cheng (2010), argue that even without models decisions will be made, and a model can still give some knowledge of how the system works even without complete accuracy. Therefore, especially for areas where there is not enough knowledge of how the system in place work, modelling can be a useful tool to increase the level of understanding.

3.4 Groundwater Modelling

Groundwater is created by precipitation that percolates vertically through the unsaturated zone in the ground until it reaches the groundwater table, under which all pores all filled with water. The groundwater flows from areas with a high potential to areas with a low potential. Groundwater may eventually discharge as springs, in surface water bodies or in the ocean (Bear and Cheng 2010).

A material is homogeneous if the permeability is the same at every point, which is usually not the case since the ground often is very heterogeneous(Bear and Cheng 2010). The permeability may also change with direction. A material is referred to as anisotropic if the vertical permeability is different from the horizontal permeability. If the permeability is the same in different directions it is called isotropic. In nature, materials are never truly isotropic even if that is a common assumption in modelling.

Groundwater flow occurs in all directions and is therefore three dimensional, but can often be approximated to only flow horizontally, disregarding the vertical flow (Bear and Cheng 2010). This assumption has shown to only give small errors during modelling. If there is a permeable boundary in an aquifer, water will flow through it, and the magnitude of the flow will depend on the water table's gradient across the boundary.

3.4.1 Governing Equations

Models are usually based on a *governing equation*, and for groundwater models, the governing equation is derived from the conservation of mass and Darcy's law. The resulting general governing equation, 3.2, describes three dimensional flow in an anisotropic and heterogeneous aquifer.

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) = S_s\frac{\partial h}{\partial t} - W^* \tag{3.2}$$

K_i - Hydraulic conductivity component in i direction
$\frac{\partial h}{\partial i}$ - Gradient component in i direction
S_s - Specific storage
W^* - Volumetric inflow rate

Equation 3.2 can be simplified by applying certain assumptions. For example, for an unconfined aquifer which assumes 2D flow (only horizontal flow) and where the aquifer is seen as heterogeneous and anisotropic, equation 3.3 can be used (Andersson et al. 2015)

$$\frac{\partial}{\partial x}(K_x h\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y h\frac{\partial h}{\partial y}) = S_y\frac{\partial h}{\partial t} - R \tag{3.3}$$

K_i - Hydraulic conductivity component in i direction
$\frac{\partial h}{\partial i}$ - Gradient component in i direction
S_y - Specific yield
R - Recharge rate

Equation 3.3 represents flow under *Dupuit-Forchheimer* approximation, which essentially means that the flow is mainly horizontal whereas the vertical flow is negligible (Andersson et al. 2015). When using Dupuit-Forchheimer approximation for unconfined aquifers, the head at any given point is equal to the water table. Another example is if the aquifer instead is assumed to be homogeneous and isotropic with no recharge and in steady state conditions. In this case, the flow can be described by *Laplace equation*, 3.4.

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{3.4}$$

3.4.2 Boundary Conditions

There are different ways to simulate the conditions at the boundary of the model and typically three different boundary conditions are used (Andersson et al. 2015). *Dirichlet condition* is when the boundary has a known value, and the boundary is therefore called a specific head boundary. The value can vary, or be the same along the boundary. *Neumann condition*, of specified flow boundary describes the flow rate across the boundary. Neumann could also be applied when there is an impermeable boundary. The third boundary type, *Cauchy conditions* or head-dependent boundary, uses a specified head outside the boundary and the value of a node located near the boundary to calculate the gradient.

3.4.3 Analytical Models

Analytic solutions are exact and continuous in time and space. They generally use simplified governing equations and require simple geometry and boundaries (Andersson et al. 2015). Even if analytic models are approximations of the field data they can be highly useful for some modelling purposes as well as verifying numerical models.

Thiem's well equation, 3.5, provide a simple analytical solution for steady-state radial flow to a well, which can also be used for inflow calculations to underground facilities like excavations (Gustafsson 2012). The drawdown can be estimated to be the same as the depth of the excavation.

$$Q = \frac{2\pi T s}{\ln(\frac{R_0}{R_b})} \tag{3.5}$$

Q - Inflow (m^3/s)
T - Transmissivity (m^2/s)
s - Drawdown (m)
R_0 - Radius of influence (m)
R_b - Radius of well (m)

3.4.4 Numerical Models

When using numerical models, many calculations and iterations might be needed and as computer capacity has increased, it has also become increasingly useful to use numerical solutions for groundwater modelling (Igboekwe and Achi 2011). Analytic solutions for groundwater flow assume homogeneous aquifers and highly idealised parameters and boundaries, and since this might not be the case, numerical methods can be very useful. Numerical models give approximate solutions, when it is too complicated to find exact solutions with analytic models.

There are several different numerical solutions that can be used for modelling groundwater flow. Some examples are *finite difference method*, FDM, *finite element method*, FEM and *finite volume method*, FVM.

In FDM, the aquifer id divided into a grid of squares (Figure 3.2a). The head at each node in the grid can be determined by the values in the adjacent nodes (Knappett and Craig 2012). FDM is considered one of the easiest numerical methods to implement, but can be limited for more complex geometries, for example curves.

In FEM, the modelled domain is divided into smaller and simpler geometries, e.g. triangles (Figure 3.2b). This gives FEM the advantages of flexibility when applying the grid. The mesh can easily be refined to improve accuracy, or applied to advanced geometries. Since the method is quite advanced, it does however require a certain amount of knowledge to use this model appropriately.

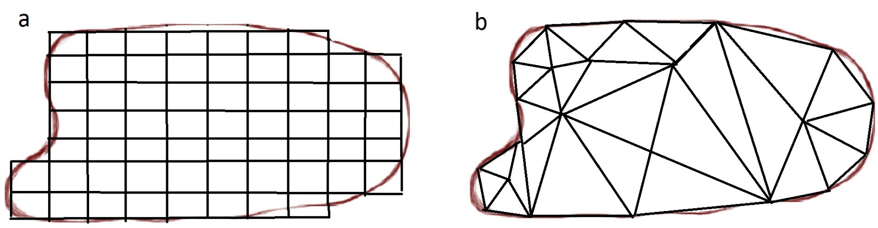

Figure 3.2: Examples of grids for a) FDM b) FEM and FVM.

The division of the modelled domain in FVM is similar to FEM, but instead of using elements, FVM uses cells, where each cell is a controlled volume. FVM modelling applies the fact that conservation is true for many physical laws, and thus what goes into one cell on one side also needs to leave it on the other side. FVM can therefore be quite powerful when computing fluid dynamics.

3.5 Stormwater Runoff Modelling

Urban stormwater and wastewater management is a complex issue. Rapid urbanisation, population growth, changing rainfall patterns, increased sea levels and stricter environmental regulations are some of the challenges that need to be considered and that can be addressed with stormwater modelling (DHI 2017). Stormwater modelling, also referred to as rainfall-runoff modelling, is mainly used to predict runoff flows when, for example, designing stormwater and wastewater systems or analysing risks of flooding (Beven 2012).

3.5.1 Runoff Models

Runoff models are classified depending on their different characteristics and features. Classification of hydrological runoff models can be done as presented in Figure 3.3.

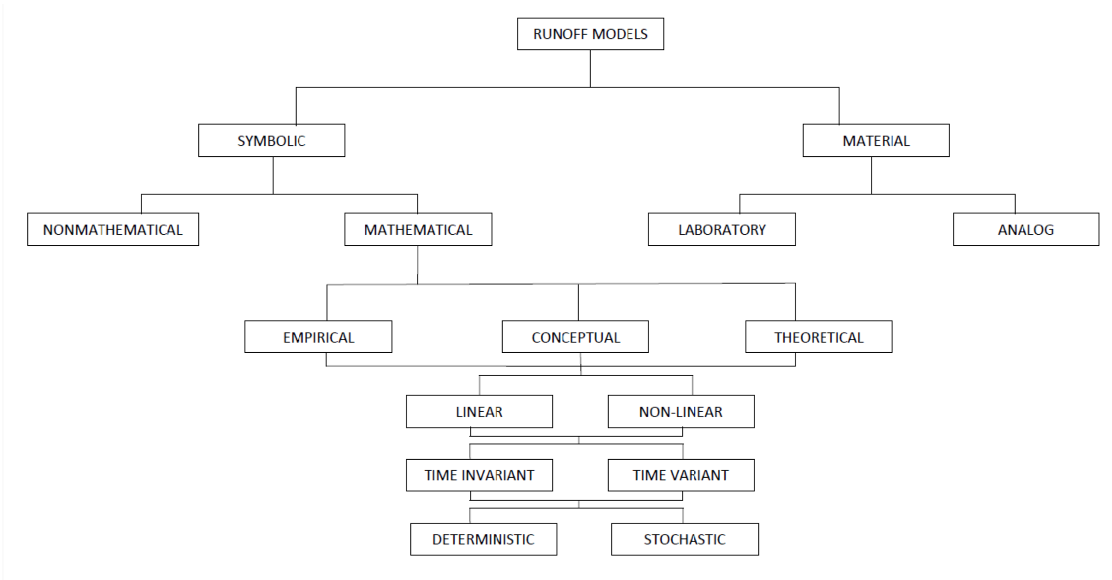

Figure 3.3: Classification of hydrological models. Adapted from Xu (2002).

In material models, the larger system is represented by a smaller prototype model, for example laboratory watersheds or hydraulic models of dams (Xu 2002). In contrast to the material models, symbolic models are logic expressions representing the original system. Symbolic models could be of mathematical nature were the system behaviour is expressed by a set of equations and perhaps analytical parameters and statements.

Furthermore, hydrological models can be theoretical, empirical and conceptual. Theoretical models, or white-box models, are physically based models that describe the consequences of the laws that govern the phenomena, and the model has a logical structure that is similar to the real-world system that it simulates. This is unlike the empirical models, black-box models, were the physical understanding is not facilitated but the model contains parameters that can be estimated through measurements. Conceptual models are somewhere in between the theoretical and the empirical models using simplified physical laws in combination with functions of equations. All three types of mathematical models are useful but for different applications and contexts (Xu 2002). Regardless of whether the model is theoretical, empirical or conceptual, it can be linear or nonlinear. One common definition of linearity is that a model is linear if the principle of superposition holds, i.e that y1(t), y2(t) are the outputs corresponding to inputs x1(t), x2(t), or that x1(t) + x2(t) corresponds to y1(t) + y2(t). Moreover, models can be both time-variant or time-invariant, depending on whether the input-output relationship changes with time or not.

Regarding spatial covering, models can be lumped, semi-distributed or distributed, Figure 3.4. In lumped models, spatial variability is disregarded and the area is taken as one homogeneous unit (Sorooshian et al. 2008). Spatial processes, patterns and organisation of characterisation are disregarded, which lowers the complexity of the model. Semi-distributed models aim to calculate contributions from separate areas and in turn, handle these sub-areas as homogeneous. This makes the model more accurate compared to lumped models. The most sophisticated models are distributed were the whole area is divided like a grid net and spatial variability is taken into account (Xu 2002). The last division for hydrological models is whether they are deterministic or stochastic. Deterministic models always give the same output for a special set of input parameters, whereas stochastic models might give different output values even if the input are the same (Gayathri et al. 2015).

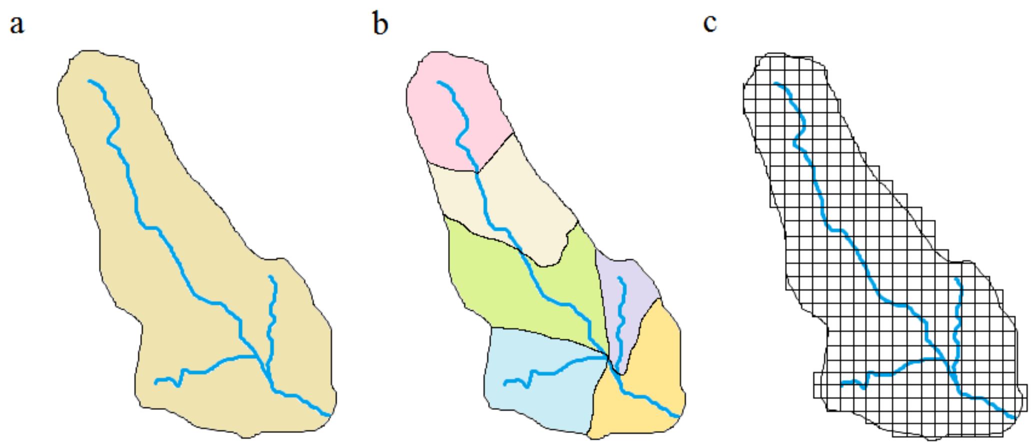

Figure 3.4: a) Lumped model, b) semi-distributed model c) distributed model.

3.5.2 The Rational Method

The rational method is a mathematical, lumped, deterministic model that can be used to estimate stormwater flows in urban areas. The method was first introduced in 1889 (Urban Drainage and Flood Control District 2016), and it still widely used to dimension stormwater pipes for smaller catchment areas. When the built environment requires larger areas for anthropogenic activities, the natural water cycle is affected (Lyngfelt 1981). Since many urban areas are entirely or partially impermeable, excess rain water is accumulated. The traditional way of handling surface runoff is through gutters and pipes that form a stormwater sewer system. The governing equation used in the rational method is described in equation 3.6 (Svenskt Vatten 2016).

$$Q = \varphi i(t_r)Akf \tag{3.6}$$

Q - Dimensioning flow (l/s)
φ - Runoff coefficient (-)
t_r - Rain duration (min)
$i(t_r)$ - Rain intensity (l/s*ha)
A - Catchment area (ha)
kf - Climate factor (-)

3.5.2.1 Runoff Coefficient

The partition between pervious and impervious land is important in urban hydrology (Urban Drainage and Flood Control District 2016). For stormwater planning and management, the probable future percent of different surfaces must be estimated. The estimations are used to determine the runoff coefficient. The runoff coefficient is an expression of the proportion of precipitation that will contribute to runoff, considering the effects of evaporation, infiltration and absorption in vegetation (Svenskt Vatten 2016). The runoff coefficient depends on several factors, such as how exploited the area is, partition of impermeable area and slope. General runoff coefficients suggested by Svenskt Vatten (2016) for different types of surfaces are presented in Table 3.1.

Table 3.1: Runoff coefficients for different surface types (Svenskt Vatten 2016).

Type of surface	**Runoff coefficient φ**
Roof without storage facility	0.9
Concrete-and asphalt surface	0.8
Paved surface with gravel joints	0.7
Gravel road	0.4
Exposed rock with no sharp slope	0.3
Gravel surface, unbuilt area	0.2
Park with vegetation or hilly forest land	0.1
Cultivated land, grass land, meadow	0.05
Flat forest land	0.05

If the area consists of several types of surfaces, weighted runoff coefficients can be calculated using equation 3.7 (Svenskt Vatten 2016).

$$\varphi = (A_1\varphi_1 + A_2\varphi_2 + \dots A_n\varphi_n)/(A_1 + A_2 + \dots + A_n) \tag{3.7}$$

φ - Weighted runoff coefficient (-)
A_1 - Subarea 1 (ha)
A_2 - Subarea 2 (ha)
A_n - Subarea n (ha)
φ_1 - Runoff coefficient for subarea 1 (-)
φ_2 - Runoff coefficient for subarea 2 (-)
φ_n - Runoff coefficient for subarea n (-)

For rough estimates, weighted coefficients for different type of built areas such as residential areas can be used (Table 3.2).

Table 3.2: Runoff coefficients for different types of built areas (Svenskt Vatten 2016).

Type of built area	**Runoff coefficient** φ
Flat industrial area	0.5
Flat open housing area	0.4
Townhouse area	0.4

3.5.2.2 Rain Duration and Time of Concentration

In the rational method, the rain duration is equal to the time of concentration, Tc, which is the time it takes before the entire area contribute to the flow in the point of calculation (Lyngfelt 1981). In other words, the time of concentration is the time required for the water to travel from the most hydraulically distant part of a catchment area to the calculation point (Thompson 2006). Time of concentration can be calculated by dividing the longest flowing path distance, which has to be measured or estimated, by the velocity of water. The velocity of water varies depending on the underlying material (Table 3.3).

Table 3.3: Flow velocity for different materials (Svenskt Vatten 2016).

Type of material	**Velocity** (m/s)
Regular pipe	1.5
Tunnel or bigger pipe	1
Ditch and gutter	0.5
Ground	0.1

Tc can also be derived from the empirical relations connected to the specific characteristics of an area (Lyngfelt 1981). For a general approach, equation 3.8 can be used to calculate the time of concentration. Tc is then used as duration time, t_r, when deriving the rain intensity, i (equation 3.6).

$$Tc = \frac{d}{v60} \tag{3.8}$$

Tc - Time of concentration (min)
d - Longest flowing distance (m)
v - Flow velocity (m/s)

3.5.2.3 Return Time

The return time indicates the expected occurrence of a particular flow. The return time is the mean time interval that passes between every time a flow occurs or is exceeded, and common discussed return periods are 2, 5 and 10 years (Lyngfelt 1981). The return time is derived from statistics of rain events, and different return intervals are required for different types of structures depending on how often it can be accepted that the flow is exceeded. According to Magnusson and Norin (2013), 2-years return time and 5-years return time is common as designing requirement for excess water treatment facilities.

3.5.2.4 Rain Intensity

The rain intensity is derived from the relationship between rain duration and return time. It is possible to use statistics for specific sites, where data have been collected for a long time, to derive the rain intensity. Specific rain intensities for Gothenburg and Stockholm are presented in Appendix B.

If there are no statistics available for the site, the intensity is calculated using equation 3.9 (Svenskt Vatten 2016).

$$i(t_r) = 190\sqrt[3]{T}\frac{\ln(t_r)}{t_r^{0.98}} + 2 \tag{3.9}$$

$i(t_r)$ - Rain intensity (l/s ha)
t_r - Rain duration (min)
T - Return time (months)

3.5.2.5 Climate Factor

The world's climate is affected by anthropogenic green house gases, and more rain and higher intensities are expected in Sweden in the future (SMHI 2014). Therefore, the risk of flooding of urban area is increased and structures that are supposed to last for a longer time must be adapted to this new climate. This is why Svenskt Vatten (2016) suggests that a climate factor K_f, should be added to the rational method (equation 3.6) when predicting the maximal dimensioning flow. The climate factor should be calculated with current state knowledge and in correlation to the installations expected life time. Updated values of K_f are available in publication P110 (Svenskt Vatten 2016).

3.5.3 Time Area Method

The time area method is a development of the rational method and is a more sophisticated methodology for estimation of stormwater runoff. The time area method uses a unit hydrograph to determine the relation between the travel time of the runoff and the specific portion of a catchment area that may contribute with runoff during the given travel time (NWS 2017). Commonly, the unit hydrograph puts 1 mm effective precipitation in relation to the duration time 1 hour (Pettersson 2015). When using the time area method, the bigger catchment area are divided into sub-areas and the runoff traveling time is related to that area . The hydrograph curves for all the individual sub-areas are then accumulated and the runoff contribution from the entire area can be calculated. The method is suitable when more detailed estimations of runoff is needed and is specifically useful when the rain duration is shorter than the time of concentration (Pettersson 2015).

3.6 Contamination Modelling

Environmental modelling complements environmental measurements and is useful when assessing environmental conditions such as spreading of contaminants (Vallero 2004). In cases where measurements cannot be conducted, for example due to cost and time constraints, models function to *"fill in the gaps"* and extend the available information. Environmental models can predict movement and change of compounds in the environment and aim to represent a real system in a comprehensive way.

Since water participates as a reagent for several fate processes and is the conveying medium for dissolved ions, colloids, and particulate matter through soil, understanding of hydrology and hydrological pathways is of importance when modelling contaminants (van der Perk 2014). A useful strategy when studying hydrological pathways is to think of the modelled area as a system with clearly defined boundaries that exchanges mass and energy with its surroundings. Models can be designed in several ways but often begins with conceptual models that helps to identify the major pathways and processes that influences the fate of a chemical in the environment. An example of a conceptual model for environmental modelling is presented in Figure 3.5.

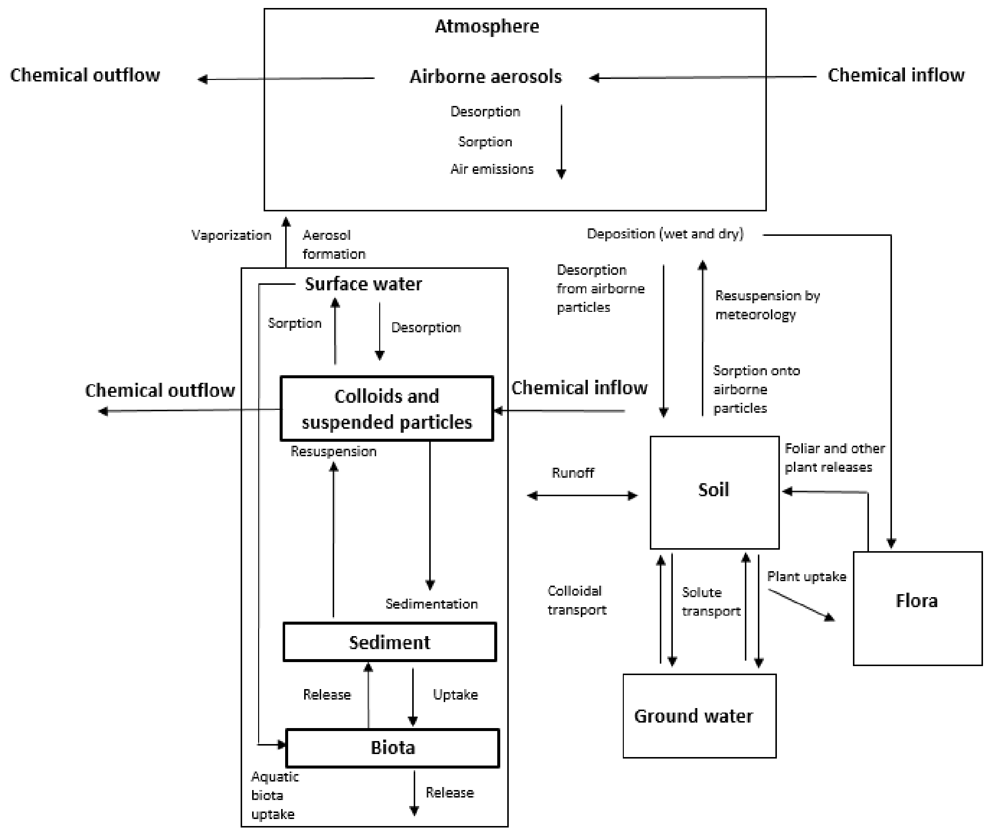

Figure 3.5: Example of a conceptual compartment model of chemical transport and fate. Adapted from Vallero (2004).

The different phases air, water and solid are here referred to as compartments; atmosphere, surface water and soil. Compartment models are commonly used to describe transport of material in biological systems and often, the different compartments are represented by boxes and the arrows between the boxes represent transport and fate processes (Blomøj et al. 2014). The advantages with a system approach is that it emphasises the relationships between forcing processes and the final spreading patterns which makes it possible to link observed spreading patterns of contaminants in soil to the most important processes (van der Perk 2014). Generally, the studies of environmental fate of a substance start by identifying natural and anthropogenic sources within the studied area, their magnitude and their spatial and temporal variability. The main purpose is then to evaluate fate and persistence of the substance and predict the chemical concentration as a function of space and/or time.

According to van der Perk (2014) there are five main applications of mathematical environmental modelling of contaminants.

1. To predict transport times of pollutants in rivers or groundwater when severe accidents occur.

2. To evaluate human exposure to contaminants

3. To forecast future effects of environmental change and assess management strategies.

4. To reduce the costs of environmental monitoring by replacing expensive measurement facilities with cheaper modelling prediction.

5. To increase the knowledge of fate of chemicals in the environment.

Similarly to mathematical models used for hydrological modelling, environmental models can be classified depending on their features and level of detail in a similar way as described for runoff models in section 3.5.1.

4 Method

In this chapter, the method used when conducting interviews with the different stakeholders are described. Moreover, the methods to estimate quality and quantity of excess water is presented.

4.1 Interviews

To deepen the understanding of the management of excess water in Gothenburg, interviews with relevant stakeholders in the Gothenburg area were conducted. The interviews were held in Swedish to avoid language barriers and misunderstandings. As a base for the interviews, which took place in face to face meetings, the same five questions were asked to all the interviewees. The questions were sent by mail to the interviewees before the meeting. It should however be mentioned that the discussions varied depending on the topics that came up during the meetings. The questions, here translated to English, are presented below.

- What are your experiences of management of excess water in soil excavations at construction sites?
- Have you encountered any problems when dealing with excess water management? (regarding for example decision-making, costs, remediation techniques, communication etc.) How would you describe these issues?
- How does it work with the monitoring of excess water? Who is responsible? Are flows and quality measured regularly?
- What is your opinion about the quality requirements for excess water in Gothenburg? Are they reasonable? Are "the right contaminants" monitored? Are they formulated in a good way?
- In your opinion, is there anything that could facilitate the management of excess water? For example a calculation tool, decision-making model, etc.

Four interviews, with totally six interviewees, were performed. Stakeholder representatives were three consultants from one consultancy firm, one environmental inspector at the Environmental Administration of Gothenburg and two providers of treatment technologies where one of them is a former consultant. The results from the interviews were derived by summarising the interviewees answers for each question, to pinpoint what the stakeholders opinions were.

4.2 Model Framework Description

The main method used to fulfil the purpose of this study is modelling. The resulting model framework consists of four parts; modelling of groundwater quantity, modelling of stormwater quantity, modelling of groundwater quality and modelling of stormwater quality. These four parts are compiled into one general model framework and to describe this further, a conceptual model and the model framework requirements are presented.

4.2.1 Conceptual Model

To identify relevant parameters for the quality and quantity of excess water, a conceptual model was constructed (Figure 4.1). The conceptual model describes the modelled system and its flows, pathways and potential fate processes.

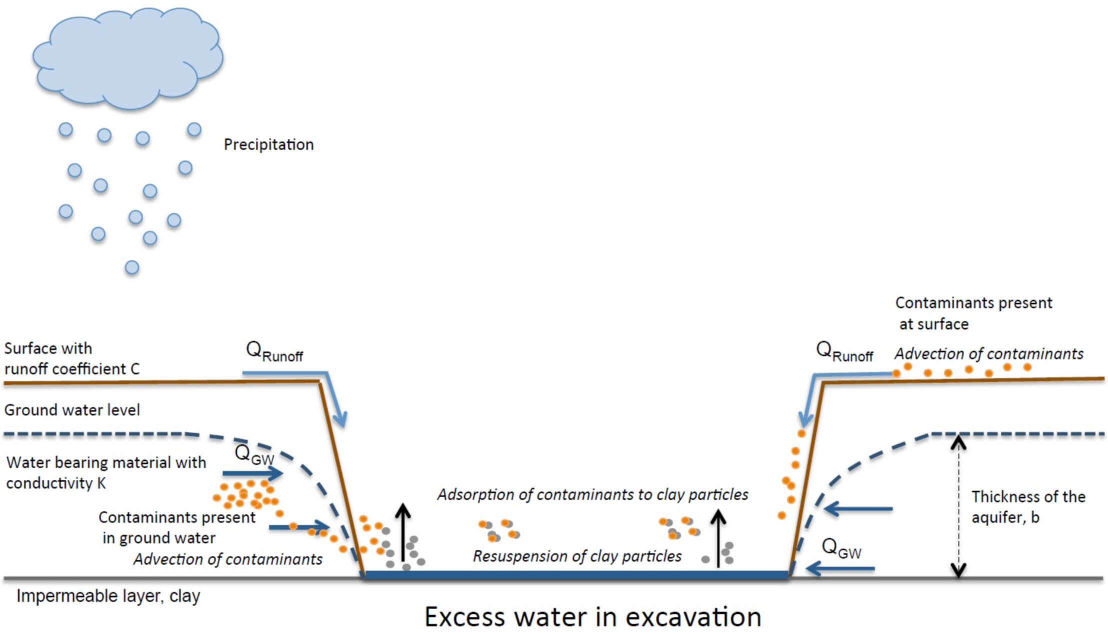

Figure 4.1: Conceptual model of model framework.

4.2.2 Model Framework Requirements

The model framework is based on available models which are combined and optimised to fit this use. To make sure that the model framework will fulfil its purpose, some requirements were formulated. The model framework should work as a tool for prediction of excess water quantity and quality in the early stages of a construction planning process and the requirements are presented in Table 4.1.

Table 4.1: Model framework requirements for different parameters.

Category	Parameter	Model requirement
Quantity	Groundwater	Calculate the flow generated by groundwater intrusion into the excavation
Quantity	Stormwater	Calculate the flow of stormwater runoff into the excavation
Quality	Groundwater	Evaluate the quality of the groundwater and relate the results to the EA guideline values*
Quality	Stormwater	Evaluate the quality of the stormwater runoff and relate the results to the EA guideline values*
Usability	Costs	Function without need of expensive software licences
Usability	Data availability	Function without need of much more than already existing data from investigations normally carried out in a project planning process e.g. geotechnical and environmental investigations
Usability	Knowledge	Function even if the user only has basic knowledge within the field of contaminated soil, hydrogeology and hydrology
Usability	Flexibility	Be standardised and function for different sites and situations

**Guideline values set by Environmental Administration in Gothenburg (Appendix A).*

4.3 Modelling of Groundwater Quantity

In section 3.4, different types of groundwater models were discussed. Finite difference method, FDM, was identified as commonly used within groundwater modelling. One limitation of FDM is however its need to use rectangular discretisation, which could be problematic when modelling complex geometries. The model requirements, (Table 4.1), however states that the model should be standardised, which implies that FDM could be a good fit for the model. The choice of numerical model therefore ended on a FDM model presented by Gustafsson (2012). Numerical models usually require an extensive number of calculation-iterations to provide accurate results and by setting up the model in a spreadsheet programme, for example Microsoft Excel, it is possible to make many iterations easily. This choice of model also fulfil the cost requirement, as expensive computer software licences are not needed.

4.3.1 Assumptions and Limitations

The following assumptions and limitations were used when creating the groundwater model. The assumptions and limitations are related to the model type used and the available information.

- The excavation is considered to function similar to a well.
- The modelled domain, and drawdown, is assumed to have reached a steady

state condition, where the drawdown at the excavation walls are as large as the aquifer thickness.

- The groundwater flow is considered to be two dimensional.
- The aquifer has homogeneous properties, and the transmissivity is calculated by T = K · b.
- The model is assumed to be at least as large as the radius of influence calculated by Sichardt's formula (equation 2.3).
- Recharge is not considered.
- The bottom of the aquifer is assumed to be where the clay layer begins, and the clay is assumed to be impermeable.

4.3.2 Model Set-up

The aquifer is built up in the model by a squared grid. The length of the sides of the square, Δ, needs to satisfy the following requirement (Gustafsson 2012)

$$\Delta << \sqrt{A} \tag{4.1}$$

A - Modelled area (m^2)
Δ - length of cell sides (m)

The level of the groundwater table, *h(x,y)*, at each cell is calculated in the middle of the cell, at the nodal point. Each cell is a controlled volume, the inflow is equal to the outflow (Figure 4.2). The level of the groundwater table at each nodal point is then calculated by equation 4.2

$$h(x,y) = \frac{h(x+\Delta x,y) + h(x-\Delta x,y) + h(x,y+\Delta y) + h(x,y-\Delta y) - Q/T}{4} \tag{4.2}$$

$h(x_i, y_i)$ - Level of groundwater table at point (x_i, y_i) (m)
Q - Flow from abstraction (m^3/s)
T - Transmissivity (m^2/s)

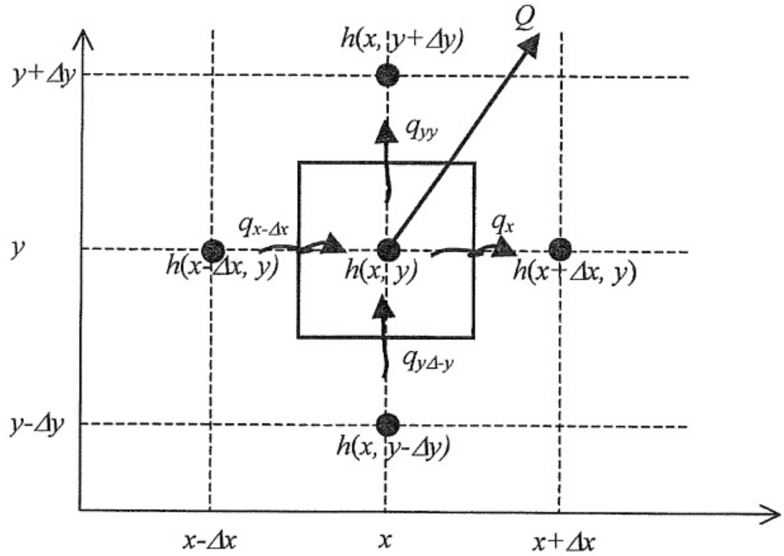

Figure 4.2: Flow in and out from each modelled cell (Gustafsson 2012).

The equation can be simplified by using local numbering, denoting the surrounding cells 1 to 4. For a cell without any water abstraction, the level of the groundwater table, here called h_0, is calculated with equation 4.3

$$h(0) = \frac{h_1 + h_2 + h_3 + h_4}{4} \tag{4.3}$$

$h(0)$ - Level of groundwater table in the cell (m)
h_i - Level of groundwater table in surrounding cell (m)

This equation is applied to each cell within the modelled area, except the boundaries and the excavation, marked in blue and light blue respectively, in the example shown in Figure 4.3.

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	=OM(E1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	-1	-1	-1	0	0	0	0	0
0	0	0	0	0	-1		-1	0	0	0	0	0
0	0	0	0	0	-1	-1	-1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.3: Example of model set up.

In Figure 4.4, the excavation is made up by 3 x 3 cells, illustrated by the light blue cells. The inflow to the excavation can be calculated by a sum of the inflow from each surrounding cell. The inflow from one cell is calculated with equation 4.4.

$$Q = K\Delta \frac{\sum(h_{out} - h_{in})}{\Delta} \tag{4.4}$$

K - Hydraulic conductivity (m/s)
h_{out} - Water table in outside cell (m)
h_{in} - Water table in inside cell (m)
Δ - Length of cell sides (m)

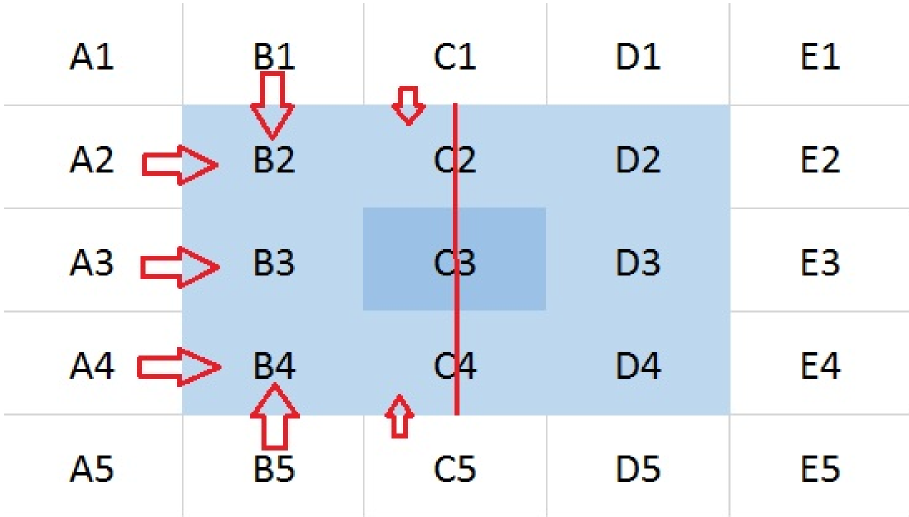

Figure 4.4: Inflow to excavation set up. The arrows illustrating the inflow of half the excavation, which then is doubled due to symmetry.

Using the example in Figure 4.4 the inflow is calculated according to equation 4.5.

$$Q = 2 \cdot K\Delta \frac{\frac{C_1 - C_2}{2} + (B_1 - B_2) + (A_2 - B_2) + (A_3 - B_3) + (A_4 - B_4) + (B_5 - B_4) + \frac{C_5 - C_4}{2}}{\Delta} \tag{4.5}$$

To be able to model different boundaries, the model also has the option to insert constant head boundaries, *Dirichlet*, or no flow boundaries, *Neumann*, if they occur within the modelled domain. Examples for this is e.g. a river or an impermeable rock formation respectively aligning to the aquifer. The results is also compared to results achieved by Thiem's well equation, 3.5, to validate the result of the model.

The number of iterations needed to achieve a stabilised result depends on the size of the model and the size of the Δ, and will need to be evaluated for each case. For this model set up, 1 meter was used for Δ, which could be made smaller to achieve a more accurate calculation.

4.3.3 Sensitivity and Scenario Analysis

To evaluate the model for which input parameters that are of most importance for the result, a sensitivity analysis was conducted using the method described in section 3.2. Two example excavations were used for the sensitivity analysis with the initial input shown in Table 4.2. In addition to evaluating the sensitivity of the input values, the effect of different boundaries and the distance to them from the excavation are analysed.

Table 4.2: Initial values for sensitivity analysis.

Initial input parameter	**Excavation 1**	**Excavation 2**
Hydraulic conductivity	0.0001 m/s	0.0001 m/s
Drawdown	2 m	3 m
Radius of influence	60 m	90 m
Length and width	2 m	10 m

4.4 Modelling of Stormwater Flows

As presented in section 3.5.1, runoff models can have different level of details depending on its features. Very detailed modelling requires large amounts of information and input data, which might not be available. One of the requirements of this study (Table 4.1), is that the model should function without need for expensive softwares. There are sophisticated stormwater modelling tools available that provides very detailed results, such as Civil Storm and Mike Urban, but they might require expensive licenses. Moreover, it would be preferable if the calculation of stormwater flow is integrated with the groundwater model. Therefore, the calculation of stormwater runoff is performed with the well established rational method, presented in section 3.5.2, in Microsoft Excel. The model is conceptually described in Figure 4.5

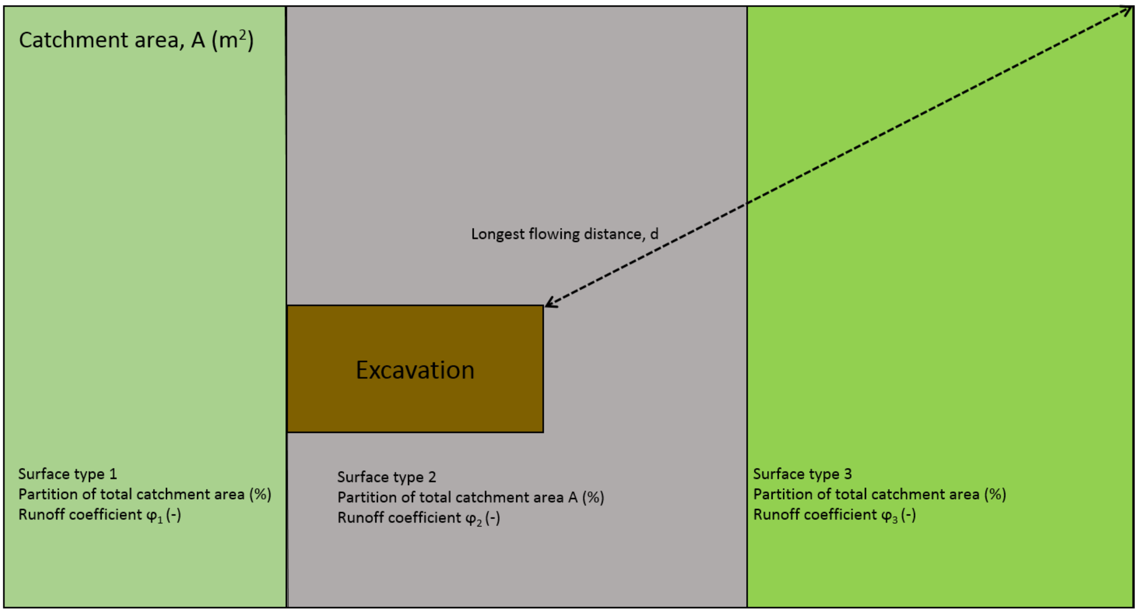

Figure 4.5: Conceptualisation of the stormwater quantity model.

4.4.1 Assumptions and Limitations

The following assumptions and limitations were used when creating the stormwater model. The assumptions and limitations are related to the model type used and the available information.

- The model is based on the Rational Method
- The model calculates the maximum flow during the chosen return period, Q_{max}.
- Maximum flow can be calculated for the return periods 0.5, 1,2 or 5 years.
- The model only has preprogrammed rain intensities for Gothenburg and Stockholm (tables presented in a Appendix B).
- The catchment area contributing with runoff to the excavation must be carefully approximated.
- Values for runoff coefficients are taken from the literature (Svenskt Vatten 2016). Type(s) of surfaces in the area must be approximated.
- The area is divided into maximum three parts to calculate the mean runoff coefficient. It is considered unlikely that a construction site has more than three different types of surfaces.
- The velocity of the water flowing to the excavation is assumed to $0.1 m/s$, referring to Svenskt vatten's suggestion of water flow velocity on ground.
- The rain duration is assumed to be equal to the time of concentration, $Tr = Tc$ (min).
- Due to the constraints of the tables for rain intensities, $Tc \leq 120$ min (i.e. there is no literature values for $Tc > 120$ min). Since Tc is dependent on the longest flowing distance, d, (see equation 3.8) $d \leq 720$ m.
- Kf, the climate factor is disregarded since excavations are no permanent structure, i. e. $Kf = 1$.

4.4.2 Model Set-up

The maximum contribution of stormwater into the excavation is calculated with equation 3.6, and is set up in Microsoft Excel.

4.4.3 Sensitivity Analysis

The sensitivity of the different parameters is analysed with equation 3.1. Evaluated parameters are Runoff Coefficient, C, catchment area A, flowing distance and return time.

4.5 Modelling of Excess Water Quality

To predict the quality of excess water, a framework model for quality assessment of excess water was developed (Figure 4.6). Equations and data are programmed in Microsoft Excel to make the model compatible with the quantity prediction model.

The framework model describes recommended procedure for the process to estimate the quality of excess water. Figure 4.6 shows the order in which each step should be conducted to predict the quality. Each step is further explained in this chapter.

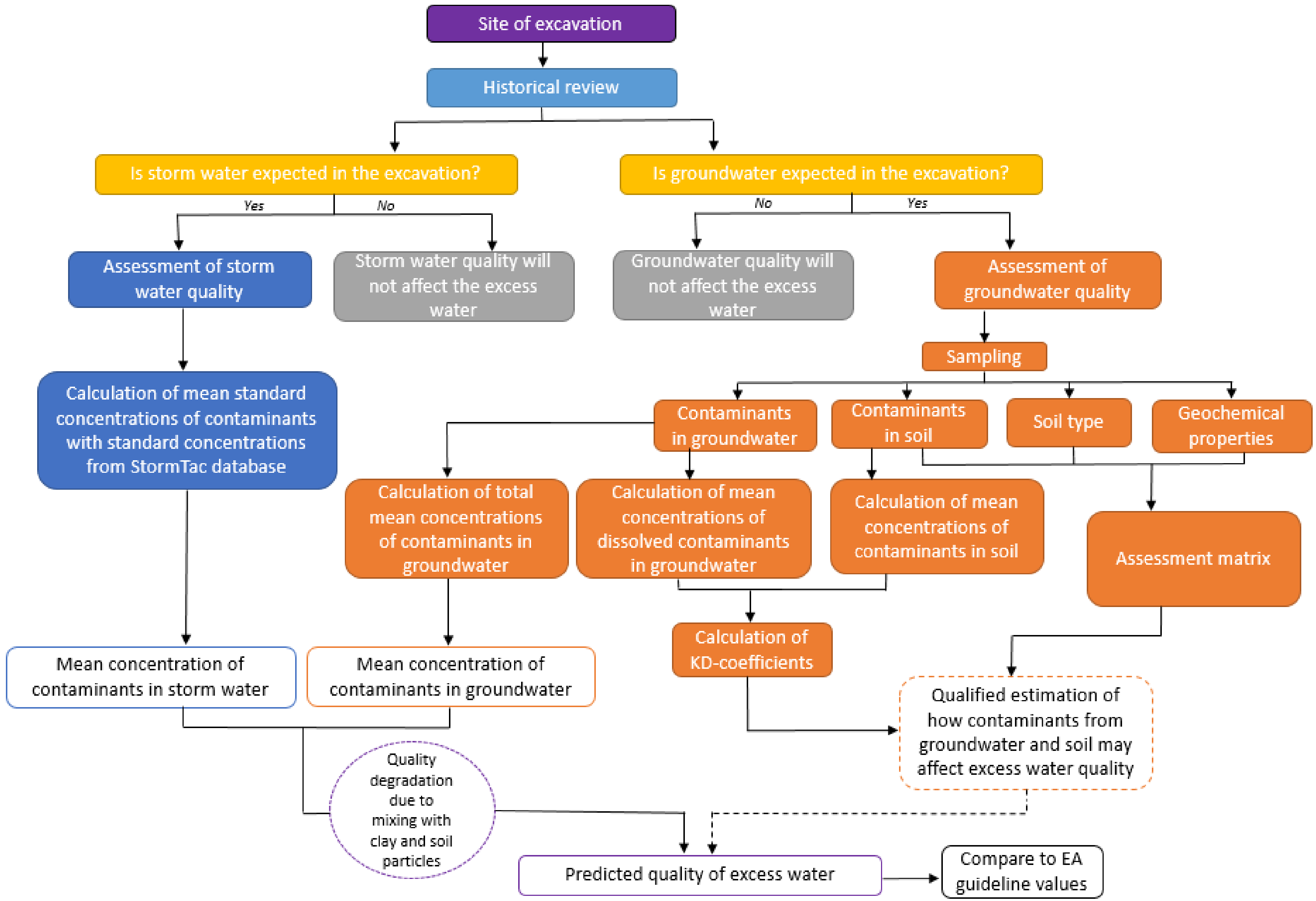

Figure 4.6: Illustration of framework model for quality assessment.

4.5.1 Historical Review

The first step when studying the site of an excavation is to investigate the previous land use and historical background of the site (Figure 4.6). Generally, if no industrial activities have been going on, there should be no reason to suspect industrial substances such as heavy metals and organic pollutants. This is an important step to get a first impression of the site and enable estimation on how much sampling that will be needed. If there is reason to believe that filling material was used when exploiting the area, there is a risk that these materials are contaminated, since contaminated filling were often used in the 60s and 70s i Sweden. However, due to lack of historic documentation, a historical review will not be enough to entirely exclude the risk of contamination.

4.5.2 Contributing Flows

The next step after the historical review is to consider if both stormwater and groundwater will contribute to the excess water (Figure 4.6). This can be assessed with the models described in section 4.3 and 4.4. If there is uncertainties, both stormwater and groundwater should be evaluated to avoid underestimating the risk of polluted water.

4.5.3 Groundwater Quality Prediction

Due to time constraints and lack of established methods to predict how groundwater affects the quality of excess water, the groundwater quality prediction in this model is qualitative rather than quantitative. The framework model includes sampling strategies, calculation of mean values of contaminants concentrations in soil and groundwater, calculations of K_D-coefficients, and an *assessment matrix for geochemical properties* that has been developed to facilitate qualified estimations of contaminant fate.

4.5.3.1 Sampling

To enable prediction of the excess water quality, sampling must be conducted (Figure 4.6). The recommendation is to test for specific substances of interest both in soil and groundwater since contaminants might be transported to the excavation both as dissolved in groundwater or sorbed onto soil particles. Preferably, sampling of groundwater and soil should be conducted close in time so more accurate comparisons can be made. The specific substances of interest in this study are the same as in the guideline provided by the Environmental Administration in Gothenburg.

Another important parameter to study is the soil type. It is of interest to know what soil type that is surrounding and covering the bottom of the excavation and usually, a geotechnical investigation is carried out. Two particular important soil types in the Gothenburg area are filling materials and clay. Filling materials usually have very inhomogeneous properties and may contain contaminants. Clay has the potential to attract contaminants and if the clay resuspends and mixes with the excess water in the excavation, the water becomes very turbid and difficult to remediate.

To enable a more comprehensive analysis of the groundwater quality, it is recommended to test geochemical parameters such as pH, turbidity and redox potential. These are of importance since they have the ability to affect the fate of contaminants and according to EPA (1999) it is essential to identify geochemical processes when predicting subsurface contaminant transport.

4.5.3.2 Calculation of Mean Concentrations and K_D-coefficients

To obtain an indication of whether the concentrations of contaminants in the excess water will exceed the EA guideline values, total mean values of the substances of interest from relevant groundwater monitoring wells should be calculated. Total mean values refers to unfiltered samples were both particulate phase and dissolved phase of a substance are included. Even if the results from the sampling have large variability, total mean values of contaminants in the groundwater may still give an indication of the excess water quality at the site. It is assumed that mean values represents the levels of contaminants. Furthermore, filtered samples from monitoring wells can be useful to evaluate the concentrations of contaminants only in solved phase. These can be used to calculate the K_d-coefficient and assess the properties of a contaminant. To enable calculation of K_d-coefficient, soil samples of the considered substances are needed as well.

If the sampling of groundwater and soil have been conducted at the same site and at the same time, it is possible to calculate the mean partition coefficient K_D for the different substances. If the results from the samples are very varied, mean values from different monitoring wells and spots might be considered as imprecise. Nevertheless, mean K_D-values can give an indication of whether the substance has a tendency to bind to soil particles or not. High K_D-values indicate that the contaminant is strongly bound to particles in soil whereas low K_D-values indicate high solubility in water. To calculate the K_d-coefficient, results from filtered samples of groundwater and soil samples are used.

4.5.3.3 Assessment Matrix for Geochemical Properties

The assessment matrix is a compilation of how the chemical soil properties affect the fate of different contaminants, developed specifically to evaluate excess water quality in this study. The assessment matrix consists of several geochemical quality parameters and how they affect different environmental contaminants. The matrix is limited to include the specific heavy metals and the organic pollutants that are included in the EA guideline values in Gothenburg. The information in the matrix is gathered from scientific reports and articles. The purpose of the matrix is to enable a general assessment of the excess water quality through an evaluation of the likely fate of the contaminants. The concept of the assessment matrix is explained in Table 4.3.

Table 4.3: Explanation of the assessment matrix.

	Group of contaminants	**Contaminant 1**	**Contaminant 2**	**Contaminant 3**
GCP1	How GCP1 generally affects this group	How GCP1 affects contaminant 1	How GCP1 affects contaminant 2	How GCP1 affects contaminant 3
GCP2	How GCP2 generally affects this group	How GCP2 affects contaminant 1	How GCP2 affects contaminant 2	How GCP1 affects contaminant 3
GCP3	How GCP3 generally affects this group	How GCP3 affects contaminant 1	How GCP3 affects contaminant 2	How GCP3 affects contaminant 3

GCP : Geochemical process

Worth noticing is that fate of metals and organic pollutants are complex to predict and geochemical processes such as pH and redox, do not only affects the fate of contaminants but also each other (Baoshan Xing 2011). The information in the assessment matrix origins from scientific articles and reports where laboratory tests have been conducted under controlled conditions and it is therefore likely that natural conditions might affect the contaminants differently. The assessment matrix should therefore be considered as an aiding tool to do qualified estimations. However, other relationships than those in the matrix might occur as well. The matrix is presented in Appendix F.

4.5.3.4 Assumptions and Limitations

The following assumptions and limitations were used when creating the groundwater quality model. The assumptions and limitations are related to the model type used and the available information.

- Only substances present in the EA guideline values are considered.
- Sampling of unfiltrated groundwater must be conducted. Mean values of the samples at the site are used to asses groundwater's contribution of contaminants to the excess water.
- Sampling of filtrated groundwater and soil must be conducted if the partition coefficient K_D are to be calculated. Mean values of these are used to calculate K_D and thus solubility can be assessed
- Quantitative assessment of contaminant fate due to geochemical properties is needed and no exact numbers of how the contaminants are affected is provided by the model.
- Quality degradation of the groundwater due to mixing of clay and soil particles in the excavation is not quantified but should be considered.

4.5.4 Stormwater Quality Prediction

The quality prediction of stormwater is conducted using the database from the model StormTac. StormTac is a modelling tool for water management in urban environment (StormTac 2017a). It performs both quantity and quality calculations for urban catchment areas and integrates processes of runoff, transport, treatment and flow detention. StormTac can be used as a forecast tool for water quality. Based on published data of pollutants concentration in stormwater, StormTac calculates yearly average pollutant concentrations and loads in the discharge points for more than 70 substances. Moreover, the largest pollutant sources and discharge locations to receiving waters can be identified.

StormTac uses a database which provides standard concentrations of different substances in stormwater for different type of land use such as parking, residential, forest, etc (Table 4.4). These concentrations are derived from scientific studies gathered by the StormTac team and are considered trustworthy. To verify the results, the StormTac values were compared to the American *National Stormwater Quality Database*, NSQD. NSQD is a database containing data regarding urban stormwater runoff characterisation from around USA (Appendix E). The two databases do not consider exactly the same land uses, but generally they have similar values.

Table 4.4: Concentrations of contaminants ($\mu g/l$) in stormwater runoff for different land uses (StormTac 2017b).

Substance	Parking area	Resident. area	Central area	Indust. area	Park ground	Forest land	Gravel
Lead	30	10	20	30	6	6	2.2
Copper	40	20	22	45	15	6.5	12
Zinc	140	80	140	270	25	15	33
Cadmium	0,45	0,5	1	1.5	0.3	0.2	0.11
Chromium	15	4	5	14	3	0.5	1
Nickel	4	6	8.5	16	2	0.5	0.85
Mercury	0.05	0.015	0.05	0.07	0.02	0.005	0.019
Susp. solids	140000	45000	100000	100000	49000	34000	9675
Bens(a)pyrene	0.06	0.05	0.1	0.15	0	0	0.01
Benzene	0.1	0.1	0.1	0.1	0.1	0.1	4
TBT	0.002	0.02	0.002	0.3	0.002	0.002	0.0016
Arsenic	2.4	3	2.4	4	4	4	2.4
PCB tot	0.1725	0.0825	0.0825	0.0825	0.0825	0.0799	0.0720

The mean concentration of contaminants in the contributing stormwater is calculated in Microsoft Excel with equation 4.6.

$$C_{mean} = (A_1C_1 + A_2C_2 + \ldots A_nC_n)/(A_1 + A_2 + \ldots + A_n) \tag{4.6}$$

C_{mean} - Mean concentration of contaminant in stormwater (μ/l)
A_1 - Area type 1 (ha)
A_2 - Area type 2 (ha)
A_n - Area type n (ha)
C_1 - Concentration of contaminant from subarea 1 (-)
C_2 - Concentration of contaminant from subarea 2 (-)
C_n - Concentration of contaminant from subarea n (-)

4.5.4.1 Assumptions and Limitations

The following assumptions and limitations were used when creating the stormwater quality prediction model. The assumptions and limitations are related to the model type used and the available information.

- Standard concentrations for different areas and substances from the StormTac database are used for calculation of stormwater quality.
- The partition of land use must be assumed.
- Only substances present both in the EA guideline values and the StormTac database are considered. These are Pb, Cu, Zn, Cd, Cr, Ni, Hg, As, Suspended solids, Bens(a)pyrene, Benzene, TBT and PCB.
- Quality degradation of the stormwater due to mixing of clay and soil particles in the excavation is not quantified but should be considered.

4.6 Application of Model

The developed model framework was applied to a case, an ongoing construction at the square in north of Gothenburg *Selma Lagerlöfs torg*. A more detailed description of the case study is presented in chapter 5.

5
Selma Lagerlöfs Torg

Selma Lagerlöfs torg is a square situated in Backa, on Hisingen, approximately five kilometers north of central Gothenburg (Figure 5.1). There are plans to develop residental housings in the area around the street *Litteraturgatan*, where the first stage is to rebuild Selma Lagerlöfs torg (Göteborgs Stad 2014). The plans include 800 new residences, as well as new business premises, with the goal to create an attractive meeting point in this part of Gothenburg.

Historically, large areas of Backa consisted of agricultural land, as it has some of the richest soils in Bohuslän region (HSB 2017). During the 60s and 70s the area was developed, and many residential houses was built along Litteraturgatan and Selma Lagerlöfs torg. The square was built 1971 and from then until 2003 a petrol station was located at the square (Göteborgs Stad 2016).

Figure 5.1: Location of Selma Lagerlöfs torg (Google, 2017).
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5.1 Geological Conditions

Through several soil samples collected using auger sampling, the stratigraphy at the site has been established (Atkins 2016). The investigation showed that the top layer at the site around Selma Lagerlöfs torg, under the impervious surfaces, consists of filling material, varying from around 1 to 3.5 meters in thickness and made up by sand, sandy clay or gravelly sand (Göteborgs Stad 2014). Beneath the filling material there is a clay layer with a varying thickness between 20 to 40 meters.

Constant Rate of Strain, CRS, tests conducted on clay samples show that the hydraulic conductivity of the clay is 10^6 m/s or smaller for all samples (Atkins 2016), indicating that the assumption that no groundwater percolates through the clay is valid. From site visits it was confirmed that the filling material is heterogeneous, materials visually determined as Styrofoam and other objects such as moldy wood and brick pieces are mixed together with the stoil at several places around the site (Göteborgs Stad 2016).

The groundwater level has been measured continuously at 15 points in the area, and water levels between 0.2 to 2 meters below ground surface has been registered (Göteborgs Stad 2016). Since there are no large topographical differences within the area, there is no large groundwater gradient.

5.2 Contamination at Site

Due to use of contaminated filling materials and previous activities at the site, the area is considered contaminated. There is also a known residue contamination, of 1 m^3, left from the gas station containing aliphatics (Göteborgs Stad 2016). The results from soil and water samples, presented in Appendix C, show that parts of the site are contaminated by aromatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and metals such as Pb and Hg (Göteborgs Stad 2016). These contaminants are mostly present in the filling materials. The groundwater samples show that there also are contaminants present in the groundwater, for example benzo(a)pyrene and metals, such as Pb, As, Cd, Cu and Hg.

5.3 Excess Water at Selma Lagerlöfs Torg

During construction at Selma Lagerlöfs torg there has been very various flows of excess water depending on the location of the excavations. Different remediation techniques has also been used, infiltration and sedimentation tanks, with unsatisfactory results as the guideline values have not been met at all times. The developed model is applied to the conditions at Selma Lagerlöfs torg, to evaluate if the results could have facilitated management of the excess water. Since the entire area is being redeveloped, many excavations are dug around the site. Therefore the model is applied more generally across the site, rather than using one specific excavation.

5.3.1 Input Groundwater Modelling

As mentioned, in many of the soil samples filling material was found. In a majority of the samples, the filling consists of sand or gravelly sand. The hydraulic conductivity of medium sand is between 10^{-2} and 10^-4 (Table 2.1). To verify the hydraulic conductivity at the site, two slug tests were performed at monitoring wells 16AT59 and 16AT64 (Figure 5.2). The tests were conducted by placing a pressure transducer in the monitoring well, which monitored the groundwater table change after 0.5 L water was added to the well. Only two tests were conducted due to time constraints. It is assumed that these tests represents the entire area, which is a simplification since slug tests only provide small scale estimations.

Figure 5.2: Location of monitoring wells 16AT64 and 16AT59 (Google, 2017). Published in accordance with Google copyright policy.

The results from the slug tests (Appendix D) showed that the hydraulic conductivity in 16AT64 was significantly lower than in 16AT59. This result, together with analysis of the soil samples at the sites (Appendix C), leads to the conclusion that the filter in 16AT64 was completely placed in clay, whereas 16AT59 was partly placed in the filling material. Therefore 16AT64 was used to evaluate the hydraulic conductivity of the clay layers, and 16AT59 to estimate the hydraulic conductivity of the filling materials. The conductivity of the filling material is estimated to between 10^{-5} and 10^{-4} m/s whilst the conductivity of the clay is smaller than 10^{-7} m/s, confirming that percolation from this layer would be very small. The results and calculations from the slug tests are presented in Appendix D.

5.3.2 Application of Groundwater Model

When modelling groundwater quantity at Selma Lagerlöfs torg, the groundwater level is assumed to be at 0.5 m below ground surface, as observed at the site. Due to the uncertainty of parameters and variations at the site, four different scenarios were modelled (Table 5.1). One best and worst case scenario using the estimated hydraulic conductivity based on the slug tests, and one best and worst case scenario based on the table values for medium sand. The thickness of the filling material is assumed to vary between 1 to 1.5 meters between best and worst case, as this is what is generally observed in the geotechnical report (Atkins 2016). As many different sizes of excavations has been conducted at Selma, an example of 3 x 3 m is evaluated.

Table 5.1: Input groundwater model parameters for the different scenarios.

	Scenarios			
	Slug test		**Table values**	
Parameter	*Best case*	*Worst case*	*Best case*	*Worst case*
K [m/s]	10^{-5}	10^{-4}	10^{-4}	10^{-2}
d [m]	0,5	1	0,5	1
R_0 [m]	30*	30	30*	300
Boundaries	1 Impermeable	Open	1 Impermeable	Open

**Minimum value for R_0 used as calculated falls below this*

5.3.3 Input Stormwater Modelling

To estimate the water flow caused by precipitation two different locations were evaluated (Figure 5.3). Since excavations were conducted at several different locations around the site, two locations exhibiting different types of land use and catchment areas were chosen. The first location, A, is placed on a grass field, and the second, B, on a paved parking lot. The excavation is assumed to form a low point of the area, the water flow is directed towards the excavation.

Figure 5.3: Catchment area for location A and B (Google, 2017).
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For location A, the contributing catchment area was assumed to be the grass field between the crossing roads in the north and the south, and the road *Litteraturgatan*. There is a submerged walking and bike path east of *Litteraturgatan* restricting any further flow from this way, and from the west the residential area was assumed to be dewatered by existing stormwater facilities. The green area is estimated to approximately 10 0000 m^2 and the road to 5000 m^2.

For location B, the parking area was considered to be the contributing area. Roofs adjacent to the parking lot are assumed to be dewatered into existing facilities, and not lead to the parking area. There are a few storm drains on the edge of the parking lot which are assumed to drain any water approaching from the surrounding areas. The size of the parking lot is estimated to 11 000 m^2.

Since excavations were located at several places at both locations, a worst case scenario and a best case scenario were modelled. In the worst case, the excavation is located in the centre of the catchment area which gives a shorter longest flowing distance and in the best case, the excavation is located close to the edge of the catchment area (Figure 5.4) The longest flowing distance for area A is estimated to 175 m in the worst case and 350 m in the best case. For area B, the longest flowing distances were estimated to 135 m in the worst case and 190 m in the best case.

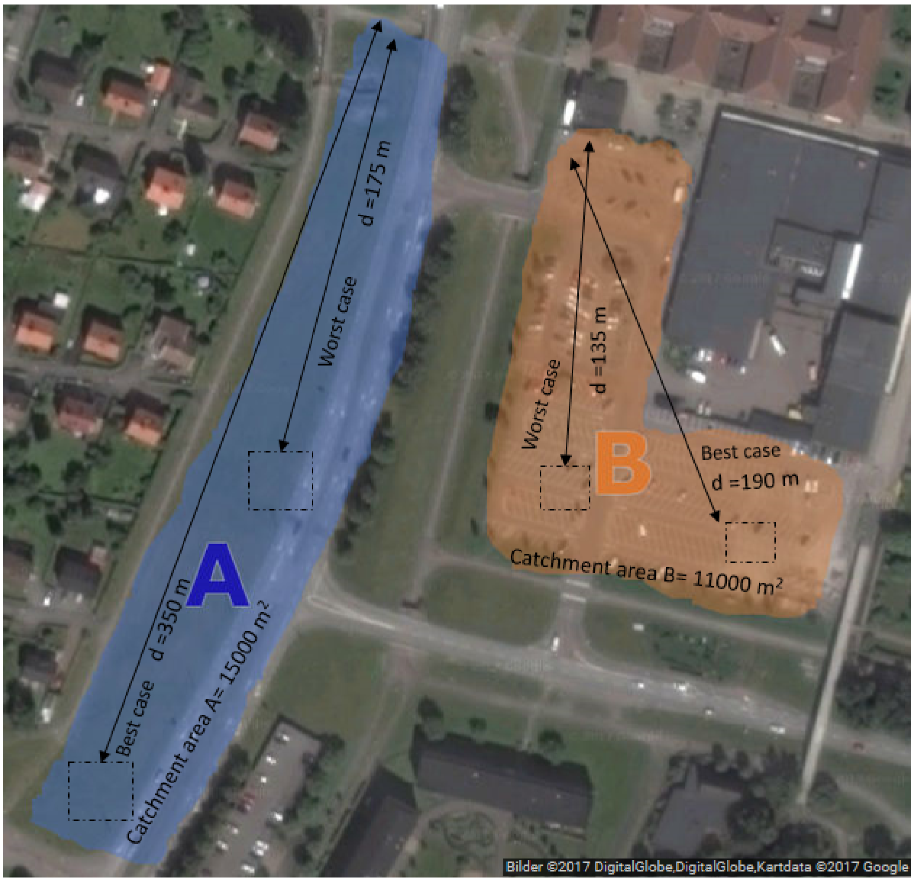

Figure 5.4: Worst and best case excavations, longest flowing distance d marked (Google, 2017). Published in accordance with Google copyright policy.

Regarding return periods, there is no standard praxis for what should be used for these type of non-permanent structures. According to discussions with involved consultants, 2-years return period has been used for excavations that will be open for a long time. Since some excavations are open for only a short period of time, 0.5 years return period is used as a comparison.

5.3.4 Application of Stormwater Model

Flows for the two catchment areas are calculated with the developed stormwater model by using the input from Table 5.2.

Table 5.2: Input stormwater model for the different scenarios.

Parameter	Area A	Area B
Location	Gothenburg	Gothenburg
Catchment area	15000 m^2	11000 m^2
Surface type 1	Green area, $\varphi = 0.1$, partition 0,67	Asphalt $\varphi = 0.8$, partition 1.0
Surface type 2	Asphalt $\varphi = 0.8$, partition 0,33	-
Average Runoff coefficient	0.331	0.8
Longest flowing distance		
Worst Case	175 m	135 m
Best Case	350 m	190 m

5.3.5 Input Stormwater Quality Model

To evaluate the quality of the stormwater in the excavations at Selma Lagerlöfs torg, standard values from StormTac data base are used, see section 4.5.4. The stormwater quality is calculated for the same catchment areas as the stormwater flow presented in section 5.3.3.

For location A, approximately 67 % consists of park ground and 33 % of road, which in the model is characterised as parking area. For location B, the catchment area consists entirely of parking area. The concentrations of contaminants at Selma Lagerlöfs torg are calculated with equation 4.6.

6
Results

6.1 Results from interviews

In this section, the results from the interviews are presented. The results are divided into three categories: *identified issues*, *suggestions for improvement* and *identified needs*.

The main identified issues regarding the management of excess water in Gothenburg were:

- There is a lack of suitable remediation technologies for excess water.
- The implementation and control of quality requirements are not stringent. Sometimes exceptions are given and sometimes not.
- It is difficult to determine reasonable costs for remediation of excess water in relation to the environmental damage.
- There is a lack of incentives to invest in well-functioning treatment facilities, partly because of inadequate control and monitoring but also due to large differences in costs between sedimentation tanks and more sophisticated alternatives.
- The regulations for stormwater are not nationally coordinated, which leads to different prerequisites and approaches to management of excess water in different and even neighbouring municipalities. Most municipalities do not have regulations at all, and the existing regulations in Gothenburg and Stockholm differs in several ways.
- The consequences for the operator of exceeded guideline values are unclear.
- There is a lack of consensus in how often excess water should be monitored. Moreover, there are differences between different regions weather it is momentary values or mean values that should be measured.
- Projects are rarely followed up and evaluated after they are finished, hence it is difficult to know if (eventual) conducted predictions were accurate.
- There is no praxis for how treatment facilities should be dimensioned.
- There is a general knowledge gap regarding excess water management within the business.

Moreover, the interviews generated some suggestions for improvement and needs:

- It is preferable to discuss the remediation and management of excess water at an early stage of the project investigation, and then decide if a sedimentation tank is sufficient.
- The guideline values could be adjusted depending on the sensitivity of the receiving waters to avoid long and time-consuming negations about exceptions.
- More resources to enable improved monitoring and control of treatment facilities would increase the incentives to follow the regulations.
- It is preferable to have a standard framework for design of treatment facilities for excess water.
- To increase the monitoring of excess water in general, it would be valuable to complement sporadic sampling of environmental contaminants with continuous sampling of turbidity and flow.
- There is a need for some kind of educational tool that explains different remediation technologies and their limitations.
- There is need for a tool, or model, to predict the flows of excess water and how they may vary over the year.

6.2 Sensitivity Analysis of Flow Models

To evaluate how the model output change due to a changes in one of the input parameters, a sensitivity analysis was conducted. Sensitivity analyses were conducted for the groundwater quantity model and the stormquantity water model. The sensitivity analysis was carried out using the equation for sensitivity, equation 3.1.

6.2.1 Groundwater model

In this section, the sensitivity of parameters determining the result for the groundwater quantity prediction model is evaluated. This was done by evaluating two excavations with different input data (Table 4.2).

6.2.1.1 Hydraulic Conductivity, K

The hydraulic conductivity, K, was evaluated by changing the initial K +/- 50 % (Table 6.1). Since the sensitivity is 1 this means when the conductivity is changed, the results are proportional to this change. However, since the radius of influence is determined with Sichardth's equation, 2.2, R_0 will also change if the hydraulic conductivity changes, which will be evaluated further down in the analysis.

Table 6.1: Sensitivity, s_p, for hydraulic conductivity.

Hydraulic conductivity	Δ **P**	**Excavation 1** s_p	**Excavation 2** s_p
0.0001			
0.00015	+50%	1	1
0.00005	−50%	1	1

6.2.1.2 Radius of Influence, R_0

The sensitivity of the radius of influence was evaluated by changing R_0 +/- 50 % as well as +/- 10 m (Table 6.2). For excavation 1, the results are less sensitive when the model is made larger than the initial radius of influence. If made smaller however, the results change proportionally to this change. For excavation 2, the results show low sensitivity to all changes.

Table 6.2: Sensitivity for radius of influence, R_0.

Δ **P**	**Excavation 1** s_p	**Excavation 2** s_p
+50%	-0.020	-0.028
−50%	1	-0.33
$+10m$	-0.04	0.072
$-10m$	1	-0.12

As it is assumed that R_0 is decided based on hydraulic conductivity, the effect when R_0 changes with K was done (Table 6.3). This shows the result still is close to proportional to change in K.

Table 6.3: Sensitivity for hydraulic conductivity with changing R_0.

Δ **P**	Δ R_0	**Excavation 1** s_p	**Excavation 2** s_p
+50%	+22%	0.97	0.96
−50%	−30%	0.95	0.94

6.2.1.3 Excavation Depth, b

The model's sensitivity for the thickness of the water-bearing layer of the excavation, i.e. the groundwater level to the impermeable clay layer, is presented in Table 6.4. The results show a generally high sensitivity for the change in depth.

Table 6.4: Sensitivity of aquifer thickness.

Δ P	Excavation 1 s_p	Excavation 2 s_p
+50%	2.38	0.73
−50%	1.46	1.44
+10%	2.01	1.97
−10%	1.83	1.26

6.2.1.4 Boundary Conditions

To analyse the influence of impermeable boundaries, the effect of changing the boundaries was observed, as well as the effect if the impermeable boundary was moved closer to the excavation than the radius of influence. The results (Figure 6.1, Figure 6.2), show that 1 impermeable boundary decrease the flow by approximately 10 % if located 50 % closer to the excavation than the radius of influence in both simulated excavations.

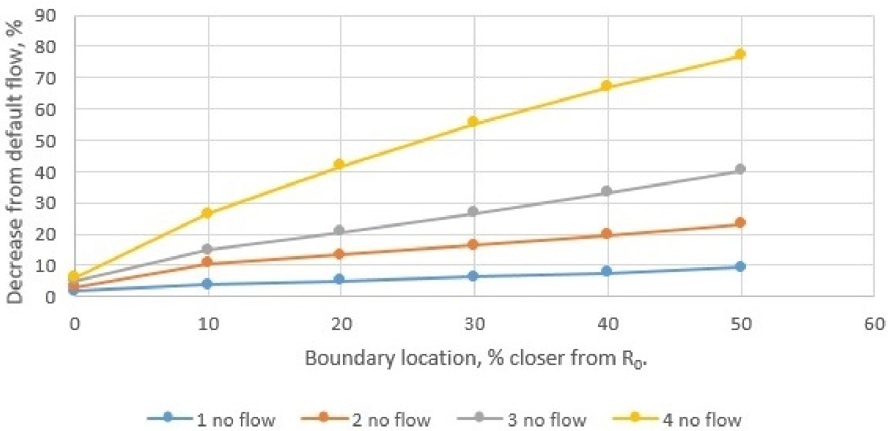

Figure 6.1: Effect of 1 to 4 no flow boundaries applied to excavation 1, with different distances from the excavation.

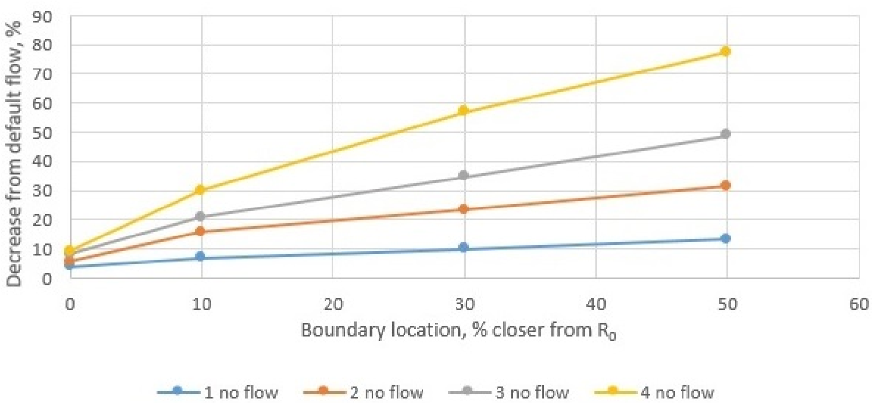

Figure 6.2: Effect of 1 to 4 no flow boundaries applied to excavation 2, with different distances from the excavations.

To simulate the influence of e.g. a river, the effect of a constant head boundary closer to the excavation was investigated. Figure 6.3 shows that the flow increases by less than 5 % if the constant head boundary is located at half the distance of the radius of influence.

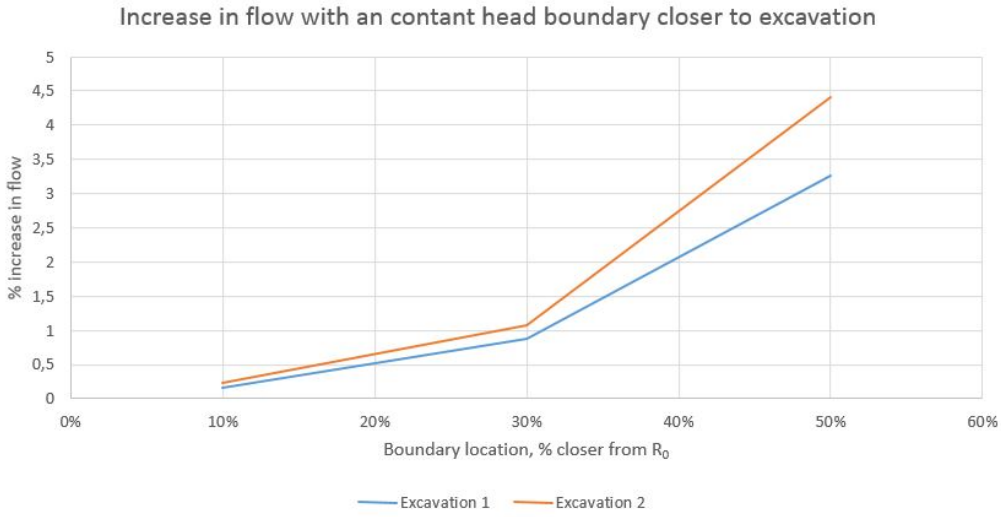

Figure 6.3: Effect of flow into excavation by nearby river.

6.2.2 Stormwater Model

The sensitivity of parameters used in the stormwater quantity prediction model *The Rational Method* were evaluated using equation 3.1.

6.2.2.1 Catchment Area, A

The sensitivity of the catchment area was tested by varying the contributing area +/- 50 % and +/- 10 % (Table 6.5).

Table 6.5: Sensitivity of catchment area, A.

Δ **P**	s_p
+50%	1
−50%	1
+10%	1
−10%	1

The result show that the sensitivity of the catchment area is equal to 1 in all cases, i. e. the change in size of the catchment area is proportional to the change of the maximum flow.

6.2.2.2 Runoff Coefficient, φ

The sensitivity of the runoff coefficient was tested by varying the coefficient +/- 50 % and +/- 10 % (Table 6.6).

Table 6.6: Sensitivity of runoff coefficient, φ.

Δ P	s_p
$+50\%$	1
-50%	1
$+10\%$	1
-10%	1

The sensitivity of the runoff coefficient is equal to 1 in all cases, i. e. the change in runoff coefficient is proportional to the change of the maximum flow.

6.2.2.3 Longest Flowing Distance, d

The sensitivity of the longest flowing distance d was tested by varying d +/- 50 and +/- 10 %. The sensitivity was tested for four different d_0 to evaluate if the result varied depending on length of d (Table 6.7).

Table 6.7: Sensitivity of longest flowing distance, d.

Δ P	s_p $d_0 = 10$	s_p $d_0 = 50$	s_p $d_0 = 100$	s_p $d_0 = 400$
$+50\%$	0	-0,4	-0,7	-0,5
-50%	0	-0,8	-0,5	-1,4
$+10\%$	0	0	-1,4	0
-10%	0	0	0	0

The longest flowing path determines the time of concentration, T_c, which in turn determines the rain duration, T_r and the rain intensity i according to tabulated values. Due to the fact that the calculation uses tabulated values, the results are given in certain intervals, which make the sensitivity varies. The result is the same for certain intervals of d-values and then the sensitivity is 0. When the result skip one step in the table, flowing distance d becomes sensitive to the changes.

6.2.2.4 Return Time

When testing the sensitivity of the return time, the available input values are limited to 0.5, 1,2 and 5 years. The sensitivity of the return time was hence evaluated using equation 3.1 an increase of 100% and 500 % (Table 6.8).

Table 6.8: Sensitivity of return time, Tr.

Δ P	s_p
$+100\%$	0.3
$+500\%$	0.3

The result indicates that the return time not is a sensitive parameter. The changes in output are small compared to the changes in input. However, due to that the available alternatives are limited and there is large differences (e.g. 100%) between the alternatives, return period should still be thoroughly considered.

6.2.3 Results Case Study

In this section, the results of the model framework applied on Selma Lagerlöfs torg is presented.

6.2.3.1 Groundwater Quantity

Calculated groundwater flows from the four scenarios used at Selma Lagerlöf's torg are presented in Table 6.9.

Table 6.9: Result from groundwater model, numerical and analytical.

	Scenarios			
	Slug test		**Table values**	
Flow	*Best case*	*Worst case*	*Best case*	*Worst case*
Model (m^3/h)	0.020	0.87	0.23	61
Thiem's (m^3/h)	0.019	0.75	0.22	43

6.2.3.2 Stormwater Quantity

Stormwater flows were calculated at two locations at Selma Lagerlöfs torg, presented in Table 6.10.

Table 6.10: Result of stormwater model.

	Area A	**Area B**
Scenario 1: Worst Case		
Flow Q_{max} (m^3/h), Return time 0.5 year	81	250
Flow Q_{max} (m^3/h), Return time 2 years	130	420
Scenario 2: Best Case		
Flow Q_{max} (m^3/h), Return time 0.5 year	51	200
Flow Q_{max} (m^3/h), Return time 2 years	77	310

6.2.3.3 Groundwater Quality

In Table 6.11, mean values for soil and dissolved contaminants in groundwater are presented. These were the values used to calculate the site specific Kd values. The mean soil values origins from samples taken at several sites at Selma Lagerlöfs torg 2016-02-09 (Göteborgs Stad 2016). The data for the mean dissolved concentrations of in the groundwater were from filtered groundwater samples taken 2016-02-22. Table 6.12 shows the mean total values of contaminants in the groundwater compared to the municipal values. These values were calculated from unfiltered samples taken 2015-11-02. All sampled values are presented in Appendix C.

Table 6.11: Mean concentrations of pollutants in soil and groundwater. Bold text represents results exceeding the guideline values.

Metal	**Soil** (mg/kg)	**Groundwater (dissolved phase)** ($\mu g/l$)
Arsenic	2.03	2.33
Chromium	9.45	0.5
Cadmium	0.16	0.05
Lead	23.23	0.28
Copper	12.52	5.48
Zinc	69.48	11.5
Nickel	6.53	3.6
Mercury	0.35	0.02

Table 6.12: Mean concentrations of total pollutants in groundwater compared to Gothenburg guideline values.

Metal	**Groundwater (total)** ($\mu g/l$)	**Range samples**	**GBG guideline value** ($\mu g/l$)
Arsenic	4.41	<1 - 4.42	15
Chromium	4.91	1.1 - 11.3	15
Cadmium	0.13	<0.05 - 0.5	0.4
Lead	**19.59**	0.8 - 85	14
Copper	**25.15**	2.9 - 97	10
Zinc	**45.98**	4.9 - 150	30
Nickel	9.07	7 - 15	40
Mercury	**0.11**	<0.02 - 0.5	0.05

Estimated Kd values and mean Kd values from the literature (Sauvé et al. 2000) are presented in Table 6.13. The calculations are based on the mean pollutant concentrations found at the site in the soil and the filtered groundwater samples taken 2016-02-22 and 2016-02-09 respectively (Appendix C). Due to data limitations, only Kd values for metals are calculated.

Table 6.13: Calculated and literature Kd values for heavy metals .

Metal	**Calculated Kd**	**Literature mean value**	**Range literature value**
Arsenic	871	13 119	1.6 - 530 000
Chromium	18 908	14 920	125 - 65 609
Cadmium	2 898	2 869	0.44 - 192 000
Lead	83 891	171 241	60.6 - 2 304 762
Copper	2 283	4 799	6.8 - 82 850
Zinc	6 037	11 615	1.4 - 320 000
Nickel	1 815	16 761	8.9 - 256 842
Mercury	17	8946	4 286 - 16 500

6.2.3.4 Assessment matrix of geochemical properties

Due to lack of data regarding geochemical properties, the assessment matrix has not been applied in the case of Selma Lagerlöfs torg.

6.2.3.5 Stormwater Quality

The result of predicted concentrations of contaminants in stormwater in excavations at Selma Lagerlöfs Torg are presented in Table 6.14.

Table 6.14: Result of stormwater quantity prediction. Bold text represents results exceeding the guideline values.

Concentration of contaminant (μ/l)	Area A	Area B	GBG Guideline values
Arsenic	3.5	2.4	15
Chromium	7	15	15
Cadmium	**0.4**	**0.5**	0.4
Lead	**14**	**30**	14
Copper	**23**	**40**	10
Zinc	**63**	**140**	30
Nickel	3	4	40
Mercury	0.03	0.05	0.05
PCB tot	**0.11**	**0.17**	0.014
TBT	**0.002**	**0.002**	0.001
Benzo(a)pyrene	0.0192	**0.006**	0.050
Benzene	0.1	0.1	10
Suspended solids	**79030**	**140000**	25000

6.3 Summarising Result Case Study

The results of conducted groundwater quantity modelling, showed that the flows of groundwater into excavations at Selma Lagerlöfs were strongly dependent on the hydraulic conductivity at the site. To enable more precise modelling results, more thorough investigations of the hydraulic conductivity are needed. Regarding the stormwater quantity, the result varied depending on where in the catchment area the excavation is located, what runoff coefficient the catchment area has and what return-times that are used when performing the calculations. Since the quantity is calculated with the rational method, the calculated stormwater flow is the maximum flow.

The predicted stormwater quality, indicates that the stormwater will exceed several of the quality parameters in the Gothenburg guideline values, especially if the excavation receives water from a parking area. Moreover, the groundwater at Selma Lagerlöfs torg is contaminated with metals and organic pollutants and the total mean concentrations of contaminants in the groundwater does also indicate exceedance of the guideline values.

As excavations are made, oxygen levels in the soil increases, which changes redox conditions. Oxidising environment increases metals tendency to attach to clay particles in the excavation. According to literature values and calculated K_d-coefficients, the metals with highest tendency to bind to particles are lead and chromium. When the water mixes with clay, the amount of suspended solids will rise.

According to the results from the quality assessment, the excess water in excavations at Selma Lagerlöfs torg will exceed the Gothenburg guideline values.

7
Discussion

7.1 Interviews

7.1.1 Method

The interviews were conducted to obtain an overview of how different stakeholders experience of the problems associated with excess water management. The interviewees were chosen based on their experience of the topic. Since the interviews were not the main focus of this study, only four interviews were held. To get a more complete view of the situation, more interviews should be conducted and with more diverse stakeholders, e.g. developers and contractors or stakeholders from other locations in Sweden. However, many issues and opinions were discussed.

7.1.2 Costs, Responsibility and Monitoring

One of the identified issues was the difficulty to determine what are reasonable costs for remediation of excess water. According to the Environmental law (*Miljöbalken*), costs of protective measures should be considered in relation to the environmental benefit. With this background, it is difficult for authorities and other stakeholders to determine how much is reasonable to spend on advanced treatment facilities. One major problem is that the more effective alternatives including precipitation and flocculation are considerably more expensive and require a wider competence that might not be possessed. During the procurement, there are many items that should be priced by the contractor. The consultants have experienced that if it is possible to set a low price for the remediation of excess water, the contractor is likely to do so to increase the chances to win the contract. There is a need for the issue to be better understood by the contractor, so that the remediation cost is not underestimated.

During a general agreement, the responsibility for the excess water lies on the developer and therefore, the whole issue depends on the developer's interest in the question. Sometimes, developers are very eager to fulfil all environmental requirements and prioritise management of excess water and in those cases, it is more likely that more sophisticated treatment solutions are installed. Unfortunately, it seems as if the results are rarely followed up, which leads to decreased motivation to make such investments, since the developer or contractor might not see the benefits.

Since it is the developers', or contractors', responsibility, depending on what type of contract, to report to the Environmental Administration if the guidelines values are exceeded when excavating, honesty and responsibility are put on them. If the developer is not engaged or honest, there is a risk that exceeded values will never be discovered. There seems to be a lack of incentives to invest in well functioning treatment facilities and some of the interviewees experience that enforcement of the guidelines is rather sporadic.

7.1.3 Guideline Values and Sampling Strategies

There are many opinions regarding the guideline values for excess water and how they are developed. One issue is that there is a lack of national coordination, leading to different approaches and possibilities regarding excess water management across the country. A comparison between Stockholm and Gothenburg shows that the regulations in Gothenburg are stricter, but unfortunately this was not further discussed with the interviewed stakeholders. It could however be interesting to make similar investigations in Stockholm for further research within the topic.

It could be useful to coordinate the guideline values, and make the regulations more similar on a national level. Consultants and entrepreneurs often work in many different municipalities, but currently the treatment of stormwater and excess water depends on in which municipality a particular project is carried out. Although, it seems like smaller municipalities are usually using the existing guideline values from Gothenburg or Stockholm as reference when making decisions about stormwater.

In Gothenburg, consultants and providers of treatment technologies experience the guideline values as very strict due to the low concentrations of different substances that is allowed in the water. The reason for them being strict, according to the Environmental Administration, is that they should be applicable for all receiving waters in the municipality. To ensure that the guideline values are achieved, rigorous treatment and sampling might be needed. However, consultants experience that it is unclear what the consequences are if the values are exceeded. Lack of monitoring and consequences when exceeding the values lead to difficulties to motivate developers and entrepreneurs to invest in sufficient treatment solutions. However, there is usually a dialogue between the Environmental Administration and the consultants and sometimes, exceptions from the guideline values are made. The Environmental Administration have the ambition to be flexible and make exceptions if the cost for remediation will be unreasonable, but the problem seems to be that these processes can be time consuming and sometimes there is not enough time to go through this process. This leads to consultants sometimes experience the Environmental Agency unnecessarily strict instead. It might therefore be better if the rules where coherent and exceptions were made more seldom.

It could also be discussed if the guideline values are relevant, or if they are too strict and too difficult to meet within reasonable costs. There is an opinion that the guidelines should be adapted to the sensitivity of the receiving waters, which is considered in the Stockholm guidelines. This would most likely benefit the management of excess water, as it might create a better understanding why the guidelines are implemented and not require expensive remediation where it might not be needed. Since March 2017, there is an additional PM that considers the sensitivity of receiving waters recently released by the Gothenburg municipality (Göteborgs stad 2017).

In this document, the receiving waters in the region are divided into three categories; very sensitive, sensitive and less sensitive. Only receiving waters in the class very sensitive will need to follow the guidelines from the Environmental Agency. Since the document is very new, it was not possible to evaluate the effects of such classification within this study.

In Stockholm, the guideline values are treated as annual mean concentration, and it is advised against using random grab samples to evaluate the water quality, instead flow proportional sampling is encouraged. The Gothenburg guidelines only states that flow proportional sampling is necessary in some cases. The impression from several of the interviewees is that random sampling with varied frequency is praxis, even though this only gives momentarily values which are not representative of the entire contamination situation. Most often pollution peaks correlate with heavy rain events and if only one sample per month is collected, the time of sampling crucial for the outcome. There is a need for an established praxis on how sampling should be conducted, and how the results should be interpreted . It does seem more beneficial to evaluate the effect on the total load of the contamination released to the recipient, rather than just a few measurements of concentration, by continuously measuring flow and contaminants.

7.1.4 Design of Treatment Facilities

Regarding quantities of water, there is no praxis for how to design treatment facilities. Generally, previous experiences from other project are used as a basis and adjustments are done if needed. The issue with design is nevertheless important and the interview discussions indicate that a standard framework for designing would facilitate selection of sufficient treatment alternatives. Moreover, it would be useful to follow up and evaluate how well previously conducted projects functioned and investigate if the predictions were accurate.

7.1.5 Identified Strategies for Improvement

Several suggestions for how to improve the work associated with excess water in excavations have been identified.

- One key factor is to discuss the remediation and management of excess water at an early stage of a project investigation, where it is important to identify whether a sedimentation tank will be sufficient or if more advanced solutions are required. To facilitate these discussions, a tool, or model, to predict the water flows and how it varies over the year would be helpful.
- There is a knowledge gap about this issue. Therefore, some kind of educational tool that explains different remediation technologies and their limitations would help to avoid misunderstandings and wrong decisions.
- Regarding the guideline values, it would be beneficial to make them more flexible, by adjusting them depending on the sensitivity of the receiving waters. If sporadic sampling of contaminants is combined with continuous sampling of

turbidity and flow, the total load of contamination could be evaluated rather than a few random momentary values, which would give better overview of contaminants released to the receiving waters.

- More resources to enable regular monitoring by the Environmental Administration would increase the incentives to actually meet the requirements.
- The use of retaining reservoirs that can delay and reduce flows should be investigated. That could possibly enable smaller treatment facilities and reduced costs.

7.2 Groundwater Quantity Prediction Model

The groundwater model was developed by assuming excavations to have similar properties as wells, and existing modelling methods for determining radial flow into wells was applied. This assumption is supported by the fact that excavations and wells would behave in the same matter, and the chosen methods, both analytical and numerical, has already been applied to e.g. tunnelling in rocks. There are probably other, and more advanced, ways to calculate the groundwater inflow into excavations, but based on the requirements set up for the model (Table 4.1), this was considered as the most appropriate approach.

7.2.1 Hydraulic Conductivity

Both the sensitivity analysis and the case study show that the resulting flow depends greatly on the assumptions made in the model. The tested scenarios at Selma Lagerlöfs torg show that the hydraulic conductivity greatly affects the results. Therefore, it seems vital to narrow down the range of the filling material's potential hydraulic conductivity. By using the table values for sand (Table 2.1), which most likely is an inaccurate assumption since the filling material is very heterogeneous, the hydraulic conductivity changes with 100-fold and therewith the resulting groundwater flow. The slug test was conducted with the hope of pinpointing a more plausible hydraulic conductivity.

The slug test gave a sense of the magnitude of the hydraulic conductivity, but the result is however uncertain. Due to time constraints, only a limited number of tests were performed and only a simple analysis of the data was carried out. More slug tests would give a better view of how much the transmissivity changes over the area. Since filling material can be very heterogeneous, further investigations are probably needed if more specific predictions are required as it is unsure how representative the results from well 16AT59 is for the larger area. There were however only few wells where the filter was present in the filling material, as most of them had 2 or more meters of pipe before the filter media started, whereas the geotechnical investigation indicates that the filling material was only 1 m deep. It has also been suggested that repeated testing of the same monitoring wells, or other techniques, e.g. withdrawing water or using a more solid slug, would have given more accurate results of the hydraulic conductivity.

The method used to calculate the hydraulic conductivity is also a simplified method, for a more precise calculation more sophisticated equations or software should be used. This was not possible for the current study due to both restriction in data availability and time constraints. The rough estimate however is considered sufficient for this purpose to show that testing of the hydraulic conductivity is helpful.

7.2.2 Numerical and Analytical solutions

The results show that both the numerical and analytic solution give similar groundwater quantity results, which is positive as it shows that the numerical solution is performing as expected. The advantage of using the numerical solution is that different types of boundaries could be considered. However, as shown in the sensitivity analysis, if using only one impermeable boundary, the change in flow is less than 5%. In addition, since other parameters, such as hydraulic conductivity, has a large impact on the results, the numerical solution might not give a better estimation of the groundwater flow than the analytical solution.

7.2.3 Assumptions

The assumption to calculate the radius of influence by using equation (2.2) might also be considered as approximate. The empirical relationship, which calculates the maximum radius of influence, was used as it was a simple equation that do not need data that were not already used in the model. There are several other equations available to estimate R_0, but they generally need information not available or applicable for this modelling case. However, the equation seems for the cases in this study, to give rather small radiuses. It could therefore be the case that the maximum radius of influence are underestimated. The sensitivity analysis however showed that, if made larger, the results were not largely impacted by the magnitude of R_0.

The model also assumes steady state conditions, the flow is calculated from when the drawdown at the excavation has reached the edge between the filling material and the clay layer. This means that the resulting flow are the flow that would flow after the excavation has been open for a while, possibly a few days, and not the flow that occurs instantly when the excavation is dug. To estimate instant flow, another type of model are needed. The instant flow would potentially be larger than the ones calculated from the model. Moreover, no recharge is included in the model, which also might underestimate the groundwater flow into the excavation.

Another assumption made is that the clay is considered impermeable, which is a simplification as some water might percolate through it, especially of the clay is mixed with other fractions. Although, this possible extra flow is estimated to be small enough to be disregarded.

7.3 Stormwater Quantity Prediction Model

The contributing stormwater quantity was calculated using the rational method, a method commonly used to design stormwater structures. The method calculates the maximum flow occurring during a certain time period e.g. 1, 2 or 5 years. Advantages with this method is that is a well-established method and the runoff flows will not be underestimated since the model calculates the maximum flow. If the rational method is used to calculate the contributing flows, it is unlikely that the flows will be exceeded unless the excavation is opened longer than the chosen return period of the rain event. One problem with calculating maximum flow is that the remediation facility might be unnecessary large and expensive if designed for a rain event that occur only a few times a year. In that sense it might be better to design for a mean flow, but then the risk for exceeding the capacity would increase and the quality of the effluent might not meet the requirements. To avoid the release of contaminated water, it is better to design for maximum flows. It should be noticed that the flow calculations are based on statistics and even if no major storm events are predicted, it is never guaranteed that they will not occur during the life-time of the excavation.

Even though Magnusson and Norin (2013) mention that the requirement of designing for 2-years or 5-years return period sometimes exists, it is identified from the interviews that clearer praxis for designing of treatment facilities are needed. It is however reasonable to relate the return period to the time that the excavation is open and then consider how often it is acceptable to have larger flows and release untreated water.

7.3.1 Assumptions

The stormwater model requires several assumptions and if not carefully considered, these assumptions can become sources of errors in the model outcome. Both the catchment area and the proportion of runoff coefficients must be assumed by the user. Since both parameters are proportional to the resulting flow, they must be correctly assumed, or the result will be misleading. The model is limited to only divide the catchment area into three different subareas, this because a construction sites generally do not consist of more than three different surfaces covers. However, more alternatives could increase the accuracy of the model.

Other sources of errors are the tabulated values for runoff coefficients. These may vary, and even though more exact values that consider slope and more exact descriptions of the surfaces are available, the number of alternatives in the model is narrowed down to increase its usability of the model.

The longest flowing path, d, highly affects the result and can be difficult to estimate. d determines the time of concentration which in turn determines the rain intensity. Since the calculated Tc must be rounded off to the closest tabulated value, the model gives the same result for intervals of d. d should therefore be carefully assumed to avoid errors.

One advantage with the rational method is however that it is well established and people within the field will probably not find it difficult to interpret the results from this method.

7.3.2 Results from Case Study

The strongest observation made when the model is applied on the case study *Selma Lagerlöfs torg* is that the stormwater flows appears to be very high, which is an expected result of the model as it calculated the maximum flow for a given return period.

It could be questioned whether the whole catchment area actually contribute to water in the excavation. The excavation is assumed to form the lowest point of the catchment area, which is an assumption that might not always be true. One alternative could be to only consider the area closest to the excavation, but then it is truly difficult to determine how large that contributing area should be, as site visits and maps show that the considered areas are generally flat.

To compare the two modelled locations A and B, the volumes are, as expected, much larger at surface B due to the higher runoff coefficient. Moreover, from the two tested scenarios (Table 6.10) tested it can be concluded that the results also vary considerably more at location B, which further emphasises the importance of correctly assumed catchment areas and surface types. Regarding the return times, 6 months is probably the most applicable alternative for short-term excavations like the ones at Selma Lagerlöfs torg, but the safety margin to handle unexpected heavy rain storms causing severe pollution of the receiving waters are then limited. Even if 2-years rain should occur every second year, it is no guarantee that they will occur during the time the excavation is open. To facilitate for consultants and entrepreneurs, it would be beneficial if the Environmental Agency, or other authority, decide on the minimum design return period.

Conclusively, this model can function to highlight plausible stormwater flows and hence facilitate the planning of the excess water management. Even if maximum flows are unsuitable to use when designing temporary structures due to high costs, it is definitely effective in order to avoid flooding and under-dimensioned treatment facilities. As long as price are not prioritised over environment, this method should be applicable to fulfil its purpose.

7.4 Quality Assessment Framework Model

To enable prediction of excess water quality, consideration of both groundwater and stormwater was needed. Due to the already existing database from StormTac, it is possible to perform estimations of the stormwater quality without sampling even though the result is standardised and not very precise. This however, was not possible for groundwater. If there is no obvious source of contaminations, groundwater should not contribute with contaminants to the excess water. Unfortunately, hidden sources of contaminants and lack of historic documentations can cause surprisingly contaminated groundwater, and it is a high risk that the groundwater quality will contribute with contaminants. At Selma Lagerlöfs torg, a residual contamination from a petrol station was known, and the groundwater was sampled. Here, the concentrations of heavy metals and organic pollutants were surprisingly high and all the substances could not be derived from the old petrol station. It is believed that this is a quite common scenario occurring in urban environments and it is therefore concluded that it is difficult to predict the groundwater quality without aid from sampling. It can be recommended that if working in urban environment, it should always be assumed that the site is contaminated and sampling is necessary.

The fact that our urban environments and groundwater are as contaminated as they are, is worth a deeper reflection. As groundwater is transported over relatively large areas, contaminated groundwater has potential to spread contaminants to sensitive areas where serious damage can be caused. It should hence be noticed that the consequences of contaminated soil and groundwater to large extent are a lot more severe than the potential contamination of excess water in excavations, even though that is not further addressed in this study.

7.4.1 Sampling

In the quality assessment framework model, the groundwater quality is estimated using mean values from sampling. Sampling is generally a good, and maybe the only way, to assess groundwater quality when no sources of contaminants are documented. There are however several problems prevailing also with this methodology.

First, to do valid analyses of sampled results, quite many samples are needed. One sample is seldom enough to represent a certain monitoring well or soil location. Samples are required at many locations and many times to get an accurate picture of the contamination situation. However, sampling is very time consuming and expensive so it is understandable that documented samples from the case study varies both spatially and timewise. Due to inadequate sampling, there is a risk to both underestimate or overestimate the contamination situation and therefore mean values are used in this study. This is certainly not the best methodology and there is a high risk that wrong decisions are made. However, as precise information about where and when excavations have been opened is lacking, and the values varies considerably both spatially and timewise, it is still believed to be better than the usage of e.g. maximum values.

To increase the accuracy of the model, samples for groundwater and soil shall be taken adjacent to the location of the excavation. Moreover, they should be taken close in time to enable accurate calculations of K_d-coefficients. This probably facilitates the prediction of the excess water greatly.

It should however be noticed that these K_d-coefficient calculations only should be considered as an indicator for how the solubility of the metals might be. Literature suggest that even if equation 2.4 is commonly used, it does not always give reliable results. This since K_d can vary greatly depending on pH, organic content and other parameters. There are more complex relations derived including some of these parameters, but to use them there is need for more detailed analyses of the soil which generally not is done during an investigation. And there is still no guarantee that these estimations are better than the more simple method used here. The method of comparing soil samples to filtered groundwater samples also has extra uncertainties, especially the ones used in the case study, as the sampling locations and times might not be the same for the samples. If more accurate estimations are of interest for a certain site or contaminant, it would be advised to perform a leaching test to obtain a more precise K_d-coefficient for that specific site.

Another important factor to consider is that results from sampling not always are reliable. Sampling methodology is a very discussed subject and mistakes made during the time of sampling or inadequate results from the laboratory may affect the results of samples and the predicted quality.

7.4.2 The Quality Assessment Matrix

To facilitate evaluation of the excess water, a *Quality assessment matrix* was developed. The quality assessment matrix describes how different contaminants are affected by geochemical properties. It is assumed that the matrix has good potential but currently, far from all relevant information is gathered and compiled in the matrix. Due to time constraints and limited research on the subject, the matrix lacks some information. Although, it is still possible to use it as a “mini-encyclopedia” to get an overview of which geochemical properties that are of importance for which contaminants. To make the matrix useful, these geochemical properties must be increasingly monitored. Contaminant fate are of great importance when studying excess water quality and it could therefore be good to introduce a more frequal measuring of these parameters. It should however be emphasised that the matrix are not complete and additional work with it are required to increase it’s usability.

7.4.3 Prediction of Stormwater Quality

The quality of the stormwater is estimated using standard values from the StormTac database. Generally, StormTac is a trustworthy source of information as the standard values are derived from scientific articles. However, the research on contaminants in stormwater sometimes are limited and for some substances, only one or a few studies are used as basis for the standard value. Moreover, the studies originates from different countries, times and contexts, which also might affect the standard values and make them less reliable.

To evaluate if the StormTac standard values are useful to predict excess water quality, it would be valuable to measure concentrations of metals and organic pollutants in the excess water recently after heavy rain events to see if the estimations are within the right spectras.

According to the calculations with StormTac standard values, the concentrations of contaminants in the stormwater at Selma Lagerlöfs square will exceed the municipal guideline values, especially the values for suspended solids are greatly exceeded. Considering that the parking lot at the square are heavily trafficked and the filling material at the site are contaminated, that estimation seems valid. How well the calculated concentrations correspond with reality is although difficult to know if no sampling of the rain water in the excavation is performed.

To enable evaluation of the modelled predictions and to better understand determining factors for excess water quality, improved monitoring of excess water at construction sites is needed.

7.4.4 Excess Water as Environmental Issue

This project focuses on quality of excess water and which measures that are needed to fulfill the requirements set by the environmental administration. However, the environmental issues connected with excess water should also be considered from larger perspectives. The main driver to treat excess water today seems to be to fulfill the regulations set by an authority but it should be remembered that the overall reason to perform responsible management of excess water is to limit the release of environmental pollutants and improve the ecological status of our water courses. The consequences of the release of untreated, polluted and turbid excess water to receiving waters are difficult to evaluate since several sources of pollution cumulatively lowers the water quality and affects the living habitats of water living organisms. In perspective to other sources of pollutants, this could be seen as less important but that is very difficult to determine. It is however important to limit all sources, and even if treatment of excess water might be costly, these investments can be seen as reasonable to prioritise considering that freshwater is one of our most valuable natural resources.

7.5 Work Procedure

During the study, much effort was put into developing and optimising the numerical model for the groundwater inflow prediction. In the end, the results however show that since many of the input parameters, such as the hydraulic conductivity, was very uncertain, it might not give a more precise estimation than the analytical model. It might have been of more use to spend more effort on investigating the hydraulic conductivity at the site, both to get a better estimation of the actual conductivity and to obtain a better insight in how the hydraulic conductivity in filling materials might vary, as there currently is very limited data on this. Another idea would be to make Monte-Carlo simulations of the analytical model to obtain probability density functions for the predicted volume.

Regarding the stormwater assessment, the choice to use the rational method and the data from StormTac was both appropriate choices, as these are is the established methods for stormwater predictions. Although, there might be need of predictions that considers yearly variation of precipitation as well as usage of retaining reservoirs, which are suggestions for further investigations within the subject.

When it comes to the groundwater quality, much more is left to explore. Since there are many factors that influence the mobility of contaminants in the soil, further research within this subject are needed. There is a need to continue to develop more understanding of these processes to enable, in the future, a tool or model that can quantify the quality of the groundwater percolation into excavations. This was however too complex to manage during this study. It would also have been interesting to further study the impact excavating has on the quality of the excess water or the groundwater surrounding the excavation, by affecting the geochemical processes. There was however few studies found on this, which indicate the more than a literature review would be needed to fully understand these effects. Moreover, it would be interesting to make an ecological risk assessment, to further analyse the magnitude of the environmental effects caused by contaminated excess water.

This study has covered many aspects around excess water management, from stakeholders views, to modelling of groundwater and stormwater inflow and assessment of water contamination. This has lead to a study that touches on all subjects, but due to time constraints, all subjects has not been studied as thoroughly as wished, which might be needed to receive reliable results. It is therefore a risk that the results are rather approximate and far from the truth. Despite this, the study still provides a usable tool, which also can be used as basis for further studies to develop from.

7.6 Research value

The interest for excess water management in Gothenburg has increased since the Environmental Administration published their guideline values, which can be seen as several publications has been published since this time. The report published by Magnusson and Norin (2013) presents different techniques for excess water remediation, as well as cost estimations, to aid contractors and developers in finding the most suitable technique. To further help in finding the best remediation technique the master thesis by Biscevic and Olofsson (2015) presented a multi-criteria decision analysis to compare different techniques. This thesis function to facilitate decision-making within the field of excess water management and contributes with improved knowledge and understanding of excess water and its complexities.

8

Conclusions

The main conclusions and recommendations from this study are:

- Stakeholders within this field experience issues regarding excess water management and there is a need to restructure, clarify and coordinate the existing guideline values provided by the Environmental Administration.
- Estimations of excess water quantity and quality have potential to facilitate the process of assessing alternatives for remediation of excess water.
- Groundwater intrusion from filling materials to an excavation can be estimated using the Finite difference method or Thiem's well equation. To improve the accuracy of the estimations, the hydraulic conductivity at the site needs to be properly investigated.
- Inflow of stormwater to excavations can be calculated using the rational method. Although, it is important to consider that the rational method gives the designing *maximum flow*. To improve this methodology, standard recommendations for return times and investigation of the potential usage of retaining reservoirs are needed.
- The quality of stormwater contributing to the excess water can be calculated using standard concentrations of contaminants from the StormTac database. StormTac suggests relatively high standard values, especially for suspended solids. If using this methodology, the result will likely be that more complex treatment than a sedimentation tank is needed.
- The quality of groundwater can not be accurately estimated without sampling. To make as reliable predictions as possible, contaminants in soil, unfiltered groundwater and filtered groundwater should be measured. Samples of groundwater and soil shall be taken adjacent to the location of the excavation and at the same time. To facilitate qualitative assessment of how groundwater affects excess water quality, K_D-coefficients can be calculated and geochemical properties of the soil should be measured.
- It is difficult to determine reasonable cost for excess water management. However, considering that excess water has potential to cause damage to receiving waters, it should generally be prioritised.
- To enable improved predictions of excess water quantity and quality, further research, monitoring and documentation of excess water are required.

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A

Guideline values

Table A.1: Guideline values for discharge of water (Carlsrud and Mossdal 2013).

Substance or Parameter	**Guidance values at the discharge point**
Arsenic (As)	15 μg/l
Chromium (Cr)	15 μg/l
Cadmium (Cd)	0.4 μg/l
Lead (Pb)	14 μg/l
Copper (Cu)	10 μg/l
Zinc (Zn)	30 μg/l
Nickel (Ni)	40 μg/l
Mercury (Hg)	0.05 μg/l
PCB	0.014 μg/l
TBT	0.001 μg/l
Oil index	1000 μg/l
Benzopyrene	0.05 μg/l
MTBE	500 μg/l
Benzene	10 μg/l
pH	6-9
Total phosphorus	50 μg/l
Total nitrogen	1250 μg/l
TOC	12 mg/l
Suspended material	25 mg/l
Particles	Requirement of at least 90 % separation of particles > 0.1 mm if the particles originates from washing processes or similar
Flow	The quantity of discharge can be maximum 1/10 of the recipient's flow rate at the discharge point in the recipient

B

Rain intensities

Table B.1: Rain intensities (l/s ha) for Stockholm (Svenskt Vatten 2016).

Return time (years)	**Rainduration (min)**									
	5	**10**	**15**	**20**	**30**	**40**	**50**	**60**	**90**	**120**
0.5	126.4	88.4	69.6	58.8	45.4	37.3	32.3	28.8	22.1	18.6
1	159.8	113.2	89.3	75.9	58.0	47.0	40.3	35.5	26.9	22.4
2	197.8	142.1	112.6	96.3	72.8	58.3	49.4	43.1	32.4	26.7
5	257.4	188.7	150.0	129.5	96.8	76.4	63.7	54.9	40.8	33.1
10	311.0	231.8	184.6	160.6	119.1	93.1	76.7	64.6	48.2	38.8

Table B.2: Rain intensities (l/s ha) for Gothenburg (Svenskt Vatten 2016).

Return time (years)	**Rainduration (min)**									
	5	**10**	**15**	**20**	**30**	**40**	**50**	**60**	**90**	**120**
0.5	103	76.1	60.6	50.7	38.4	31.8	27.6	24.6	18.8	15.5
1	135.8	101.3	81.0	68.1	51.9	42.6	36.8	32.6	24.7	20.3
2	174.7	132.3	106.5	90.1	69.3	56.7	48.7	43.0	32.4	26.4
5	239.6	184.7	150.2	128.8	100.8	82.1	70.0	61.6	46.1	37.3
10	301.1	235.5	193.1	167.4	133.2	108.2	91.9	80.6	60.1	48.4

C

Soil and water samples

Geotechnical soil samples taken at Selma Lagerlöfs torg, close to where the two slug tests where conducted.

Table C.1: Soil sample, 16AT59 (Atkins 2016).

Meter below ground	Soil type
0 - 0.5	Filling material, coarse sand
0.5 - 1.0	Dry crust clay
1.0 - 2.0	Clay (top dm dry crust)

Table C.2: Soil sample, 15AT14 (Atkins 2016).

Meter below ground	Soil type
0 - 0.2	Humus soil
0.2 - 1.0	Dry crust clay
1.0 - 3.0	Clay

Table C.3: Soil sample, 15AT20 (Atkins 2016).

Meter below ground	Soil type
0 - 0.5	Sand
0.5 - 1.0	Silt
1.0 - 1.5	Sandy clay
1.5 - 2.0	Clay
2.0 -3.0	Clay with streaks of gravel and sand
3.0 -5.0	Clay

Table C.4: Soil sample, 16AT60 (Atkins 2016).

Meter below ground	Soil type
0 - 1.2	Filling material / Humus soil
1.2 - 2.0	Clay

Total concentrations of contaminants in groundwater, unfiltrated samples taken 2015-11-17 (table C.11).

Table C.5: Soil sample, 16AT79 (Atkins 2016).

Meter below ground	Soil type
0 - 0.1	Asphalt
0.1 - 1.4	Filling material /Gravelly, stony, sandy
1.4 - 2.0	Clay

Table C.6: Soil sample, 16AT64 (Atkins 2016).

Meter below ground	Soil type
0 - 0.5	Filling material / Humus soil
0.5 - 1.0	Filling material / Dry crust clay
1.0 - 2.0	Filling / Clay
2.0 - 3.0	Clay

Table C.7: Soil sample, 16AT61 (Atkins 2016).

Meter below ground	Soil type
0 - 0.6	Filling material / Humus soil, sandy, clayey
0.6 - 1.0	Dry crust clay
1.0 - 2.0	Clay

Table C.8: Soil sample, 16AT65 (Atkins 2016).

Meter below ground	Soil type
0 - 0.8	Filling material / silty, sandy
0.8 - 1.0	Silty clay
1.0 - 2.0	Silty Clay

Table C.9: Soil sample, 15AT22 (Atkins 2016).

Meter below ground	Soil type
0 - 0.4	Humus soil
0.4 - 1.2	Humus rich fine sand
1.2 - 3.0	Dry crust clay

Table C.10: Soil sample, 15AT17 (Atkins 2016).

Meter below ground	Soil type
0 - 1	Filling material, gravelly sand
1.0 - 3.0	Dry crust clay

Concentration of contaminants in soil samples, collected at 2016-02-22 (Table C.12). Concentration of contaminants in filtered groundwater samples, 2016-02-09 (Table C.13 and C.14)

Table C.11: Unfiltrated groundwater samples, 2015-11-17 (Göteborgs Stad 2016).

($\mu g/l$)	15AT05	15AT14	15AT22	15AT37	15AT40	15AT47	Mean	GBG GV
As	9.6	<8	<2	<1	4.7	1.2	4.42	15
Cr	9.3	1.2	2.16	4.42	11.3	1.1	4.91	15
Cd	0.5	<0.05	0.05	<0.05	0.1	<0.05	0.13	0.4
Pb	85	0.8	8.4	6.92	13.2	3.2	19.59	14
Cu	97	2.9	16	12	15	8	25.15	10
Zn	150	4.9	31	19	51	20	45.98	30
Ni	15	4.2	7	10	10	8.2	9.07	40
Hg	0.5	<0.02	0.04	0.04	<0.02	<0.02	0.11	0.05

Table C.12: Soil samples, 2016-02-22 (mg/kg). (Göteborgs Stad 2016).

Metal	**16 AT50**	**16 AT51**	**16 AT52**	**16 AT52**	**16 AT53**	**16 AT54**	**16 AT54**	**16 AT55**
As	2.05	<0.5	0.601	2.9	1.56	2.43	2.65	<0,5
Cr	5.83	6.37	18.7	15.1	7.36	7.85	11.7	2.72
Cd	0.114	0.181	<0.1	<0.1	<0.1	0.23	0.117	<0.1
Pb	35.6	24.6	5.68	10.9	10.3	72.6	20.8	5.37
Cu	1.9	2.06	9.78	7.22	19.8	36.1	16.2	7.13
Zn	64.9	124	57.7	60	43	120	58.1	28.1
Ni	3.63	3.98	12.1	11.1	5.36	4.8	8.99	2.31
Hg	0.322	<0.2	<0.2	<0.2	<0.2	0.373	<0.2	<0.2

Table C.13: Filtered groundwater samples, 2016-02-09 ($\mu g/l$) (Göteborgs Stad 2016).

Metal	**16AT22**	**15AT37**	**15AT40**	**15AT47**	**15AT05**	**16AT77**	**16AT64**
As	<1	<1	<2	1.6	<1	<1	1
Cr	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	0.1
Pb	<0.2	0.7	<0.2	<0.2	<0.2	<0.2	<0.2
Cu	14.6	4.7	2.3	3.7	8.5	9.3	6.8
Zn	36.1	5.4	9.7	2.8	11.6	26	13
Ni	3.7	4.1	1.4	1.8	2.1	12.4	7.8
Hg	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table C.14: Filtered groundwater samples, 2016-02-09 ($\mu g/l$) (Göteborgs Stad 2016) .

Metal	**16AT61**	**16AT68**	**16AT79**	**16AT51**	**16AT59**	**16AT75**
As	1.74	4.4	3.6	<3	<8	<2
Cr	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Pb	<0.2	<0.2	<0.2	<0.2	0.2	0.7
Cu	2.2	2.8	3.4	3.4	3.5	6.1
Zn	5.9	<2	2.9	4.9	3.3	26
Ni	2.6	1.9	3.5	1.5	1.4	2.6
Hg	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

D

Slug test results and calculations

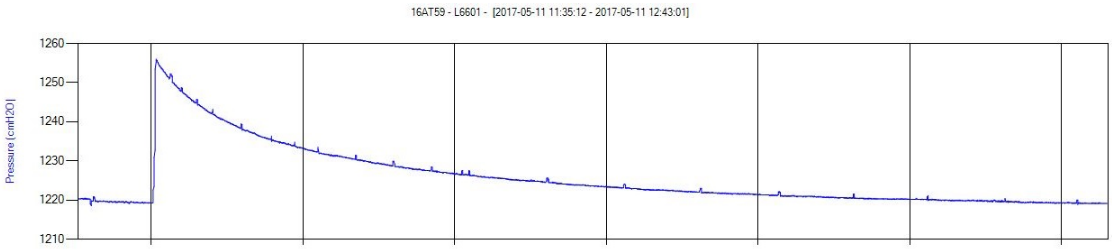

Figure D.1: Result from slug test in monitoring well 16AT59.

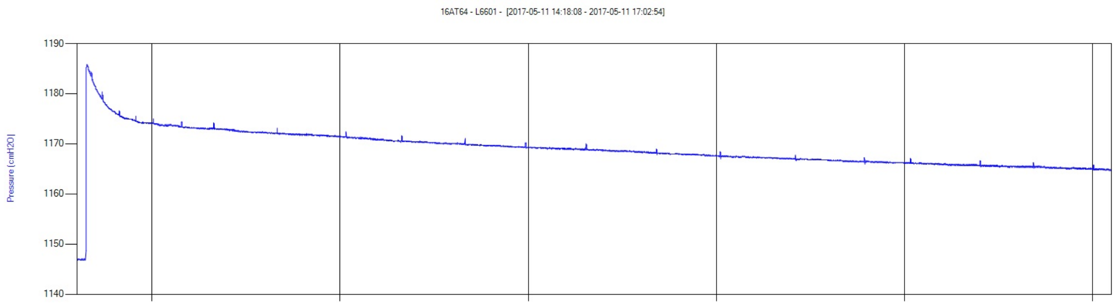

Figure D.2: Result from slug test in monitoring well 16AT65.

Hydraulic conductivity estimated using equation D.1.

$$T = \frac{4r^2}{2t_{50\%}} \tag{D.1}$$

T - Transmissivity (m^2/s)
r - Radius of well (m)
$t_{50\%}$ - Time when 50 % of recovery (s)
From this the hydraulic conductivity is calculated by D.2

$$K = \frac{T}{b} \tag{D.2}$$

16AT59

The geotechnical sampling from the site shows filling and dry crust clay the first meter, and then clay below this. The installed monitoring well consists of 1 meter plastic pipe followed by 3 meters filter material, with an inner radius of 40 mm. The water within the filling material and cry crust is assumed to contribute mostly to the test, entering the well at the top of the filter. The groundwater table before the test is measured to be 0,5 meters below ground level, giving a thickness of the aquifer to 0,5 meters. From the test $t_{50\%}$ is estimated to around 350 seconds.

$T = \frac{4 \cdot (0{,}04)^2}{2 \cdot 350} = 9,14 * 10^{-6} m^2/s$

Depending on the assumption if the entire filling layer contributes or only the lowest decimeter in connection to the well the hydraulic conductivity is estimated.

$K = \frac{9{,}410^{-6}}{0{,}5} = 210^{-5} \approx 10^{-5}$ or $K = \frac{9{,}410^{-6}}{0{,}1} = 9,4 * 10^{-5} \approx 10^{-4}$

16AT64

The monitoring well 16AT64 consists of 2 meters plastic pipe, followed by 3 meters filter, supporting the assumption that the slug test at this site evaluated the hydraulic conductivity of the clay, and not the filling material. The slug test at this site could not be finished, as only part of the recovery had taken place after 2,5 h after the test was initiated.
From analysing the results $t_{50\%}$ is estimated to be at least 10 000 seconds.

$T = \frac{4 \cdot (0{,}04)^2}{2 \cdot 10000} = 3,2 * 10^{-7} m^2/s$

$K = \frac{3{,}210^{-7}}{3} = 1 * 10^{-7}$

E

Data from The National Stormwater Quality Database

Average and median concentrations for different land uses found from the National Stormwater Quality database. The land uses categories are as followed: ID - Industrial, FW - Free way, RE - Residential, CO - Commercial, IS - Institutional and OP - Open space

Table E.1: Average concentrations of contaminants in stormwater runoff for different land uses ($\mu g/l$).

Substance	**ID**	**FW**	**RE**	**CO**	**IS**	**OS**
Ar	9	3	6	6	6	14
Pb	56	65	22	37	9	22
Cu	40	73	30	33	11	21
Zn	247	227	136	217	103	78
Cd	5	4	2	4	1	14
Cr	20	10	8	10	7	20
Ni	25	13	10	11	10	33
Hg	1	0	4	0	1	3
TSS	152000	140000	126000	119000	144000	261000

Table E.2: Median concentrations of contaminants in stormwater runoff for different land uses ($\mu g/l$).

Substance	**ID**	**FW**	**RE**	**CO**	**IS**	**OS**
Ar	4	2	3	2.8	6	4
Pb	19	33	10	17	2	9
Cu	20	25	15	18	6	10
Zn	155	136	77	130	65	50
Cd	2	1	0.74	1	1	0
Cr	12	8	5	6	6	8
Ni	14	9	6	7	7	14
Hg	0.2	0	0.2	0.2	1	1
TSS	72000	75000	57000	52000	66000	44000

F

Assessment Matrix

The assessment matrix is intended to work as an aiding tool when predicting excess water quality. The matrix contains information about selected metals and organic pollutants and the sources of information are listed below the two parts of the matrix respectively.

Metal	pH	Redox potential	Organic content	Complex formation
Generally	Solubility increase with decreasing pH, drastically at low pH levels (around 3) [2]. pH if the factor with the greatest influence on heavy metal solubility [4]. pH dependency of Kd values is in the order of Cu < Pb < Cd < Zn < Ni 7.	Solubility increase as redox potential decrease [2]	Higher concentration of Organic matter may increase the colloid concentration [5].	Metal cations can form complexes with inorganic and organic ligands, which will have a smaller positive charge than the free ion [6]. This generally reduces the adsorption of the metal to negatively charged surfaces like clay particles. This might increase the mobility of the metal in soil. DOM (dissolved organic matter) is an important factor, as a majority of the dissolved metals form complexes with DOM[7]. So if a factor influences DOM solubility it will also affect the metal solubility. SOM is an significant contributor for Cd, Cu and Ni, not Pb or Zi.
As	The adsorption of As is strongly connected to pH [6].	As is precipitating together with Fe and Mn in oxidising environemnt[3]. At high redox levels As(V) predominats, which is the less soluble form of As, and mobility is decreased.		
Cr	Soil acidification can drastically increase the in general low solubility of Cr [4].			

Metal	pH	Redox potential	Organic content	Complex formation
Cd	Soil pH is the main factor influencing the sorption to soil for Cadmium [4]. At acidic conditions very little adsorption by soil colloids and organic matter happens and the solubility increases [6]	Increased solubility with decreasing E_H (reducing conditions) [1]		Forms soluble complexes with organic and inorganic ligands, which might increase the mobility in soil [6].
Pb	Over pH 6, Pb is is either adsorbed to clay or forms lead carbonates. In many studies, lead is the metal that is retained best in the soil 6			Forms soluble complexes with organic and inorganic ligands, which might increase the mobility in soil [6].
Cu	Cu is largely affected by pH, with higher solubility at low pH. However compared to other metals, pH has smaller influence on Cu, as Cu is complexed with dissolved organic matter if present in the liquid phase. [4]		Copper binds well to organic matter, and is largely responsible for retention of Cu in soil. Therefore Cu has larger solubility if the organic content is low [4].	
Zn	pH is the dominant factor when it comes to the solid-liquid distribution for Zn [4].			

Metal	pH	Redox potential	Organic content	Complex formation
Ni	Ni has in general low solubility, and the solubility strongly depends on the pH [4].			Forms soluble complexes with organic and inorganic ligands, which might increase the mobility in soil [6].
Hg	Like many metals adsorption of Hg is pH dependant [6].	The redox potential decides which oxidation state Hg occurs in [4]. Under mildly reducing conditions Hg can be transformed into the most toxic forms of Hg, which also are soluble [6].		

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Pollutant	pH	Redox potential	Organic content	Suspended solids	Specific surface area (SA) of clay particles	Particle size
Generally			The K_D-value are assumed to be directly proportional to the OC in the soil[13]. Natural Organic Matter (NOM) is a major sorbent for organic pollutants in soils and sediments[9]			
PCB			Hydrophobic compounds binds stronger to soil if OC is high13. Desorption of depends on the degree of hydrophobicity of the PCBs[10]	Concentrations of PCBs closely follows the concentrations of suspended particulate matter. [10]		Higher amounts in large particles with high organic matter content and in the finest fractions. Enrichment of PCBs of the clay-sized fractions after resuspension.[10]
TBT	Highest K_d values existing at around neutral pH[11]		K_d is positively correlated with total organic material, humic substances, and a high silt content.[11]	Tributyltin (TBT) has a low aqueous solubility and relatively high affinity for particulate matter[11]		

Pollutant	pH	Redox potential	Organic content	Suspended solids	Specific surface area (SA) of clay particles	Particle size
Benzo(a)pyrene			Hydrophobic compounds binds stronger to soil if OC is high[13]. The sorption coefficient increases increase with the organic carbon content12		Stronger bonding with clay particles with higher SA may occur[8].	The sorption coefficient was found to increase with the specific surface area of sediment particles[12]
Benzene			Hydrophobic compounds binds stronger to soil if OC is high[13].		Stronger bonding with clay particles with higher SA may occur[8]	

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