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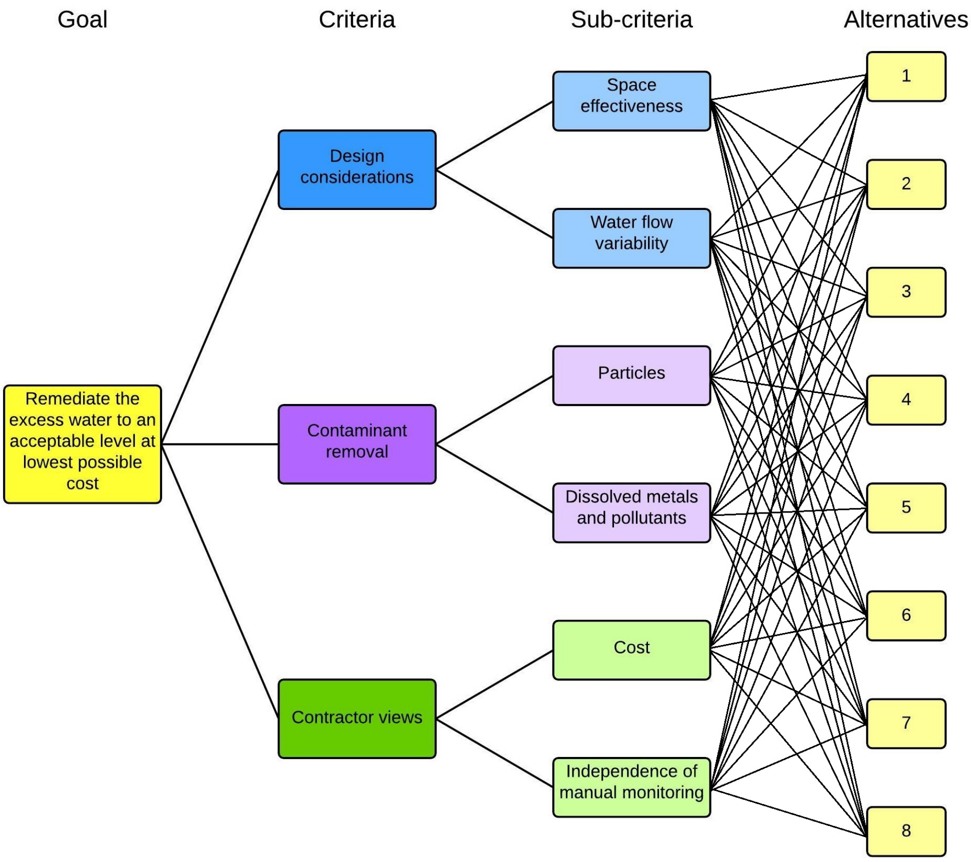

Remediation of Excess Water from Contaminated Sites

A Multi-Criteria Decision Analysis for Choosing Remediation Method

Master's thesis in the Master's Programme Industrial Ecology

AZUR BISCEVIC
INGRID OLOFSSON

Department of Civil and Environmental Engineering
Division of GeoEngineering
Engineering Geology Research Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
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AZUR BISCEVIC
INGRID OLOFSSON

Supervisor and Examiner: Jenny Norrman, Department of Civil and Environmental Engineering

Master's Thesis 2015:116
Department of Civil and Environmental Engineering
GeoEngineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Schematic model of the use of multi-criteria decision analysis on remediation of excess water contaminated by sediment.

Typeset in LaTeX
Printed by the Department of Civil and Environmental Engineering
Gothenburg, Sweden 2015

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Abstract

To be able to release excess water from excavations, the water has to be remediated to comply with the Environmental Administrations guidelines for water. Currently, there is no way of methodically choosing the appropriate remediation techniques for excess water.

This thesis was done in collaboration with the division of Environment, Risk and Safety at COWI AB in Gothenburg. The focus of the thesis was to create a model and a methodology for choosing an appropriate remediation technique. When choosing the method of remediation, several aspects need to be taken into account, such as available space, costs and fulfilling the environmental regulations. Based on criteria derived from these aspects and remediation techniques available, eight alternatives were evaluated by using a Multi-Criteria Decision Analysis model for finding the most appropriate alternative. The alternatives were scored based on the criteria found. Weights were assigned to the criteria by Malin Egardt at the Swedish Transport Administration, scores and weights were then combined in the java applet Web-HIPRE. Two flow rates of excess water were chosen and evaluated using the area of Marieholm in Gothenburg as a case study. The model gave the result that a lamella clarifier was the top ranked alternative.

The model was found useful to supply decision support when choosing a remediation alternative. Though, there are improvements to be made to the model. More precise data is needed for the different criteria and alternatives' scores, also an increased level of detail could be added by including more criteria; different types of case sites can be used for investigating how the result varies.

Keywords: construction, water, dewatering, sediment, particles, MCDA, decision analysis, remediation, Web-HIPRE, weighting, lamella, filter.

Efterbehandling av Schaktvatten från Förorenade Områden
En Multi-Kriterieanalys som Beslutsstöd vid Val av Behandlingsmetod
Examensarbete inom masterprogrammet Industrial Ecology
AZUR BISCEVIC
INGRID OLOFSSON
Institutionen för bygg- och miljöteknik
Avdelningen för geoteknik
Forskargrupp Teknisk geologi
Chalmers tekniska högskola

Sammanfattning

För att kunna släppa ut schaktvatten till recipienter måste vattnet uppfylla miljöförvaltningens riktlinjer för utsläpp av förorenat vatten. För tillfället finns det ingen särskild metod för att välja passande reningsteknik för en specifik plats.

Denna examensuppsats är gjord i samarbete med avdelningen Miljö, Risk och Säkerhet på COWI AB i Göteborg. Uppsatsen fokuserar på att ta fram en modell och metodik för att välja ett passande reningsalternativ för förorenat schaktvatten. När en specifik reningsmetod skall väljas finns flera faktorer som måste tas hänsyn till, till exempel tillgänglig yta, kostnader och uppfyllandet av miljökraven. Åtta olika alternativ har analyserats med avseende på kriterier baserade på dessa faktorer i en multi-kriterieanalys för att hitta det mest passande reningsalternativet. Alternativen blev poängsatta baserat på dessa kriterier. En viktning av de olika kriterierna gjordes av Malin Egardt på Trafikverket och sedan kombinerades viktningen med poängen som de olika alternativen fått i java-appleten Web-HIPRE. För att undersöka hur stor roll flödet från schaktet spelade, valdes två flöden ut för att studeras. Dessa flöden utvärderades i en fallstudie baserat på området Marieholm i Göteborg. Modellen visade att en lamellcontainer var det mest passande alternativet för båda fallen.

Modellen var möjlig att använda som beslutsstöd vid val av reningsalternativ. Dock har modellen förbättringspotential, som att använda mer specifik data för de olika kriterierna och vid poängsättningen av alternativen. Ytterligare kriterier kan läggas till för en högre detaljnivå och fallstudien kan utökas med fler områden för att se ifall detta har någon effekt på resultatet.

Nyckelord: konstruktion, vatten, avvattning, sediment, partiklar, multikriterieanalys, efterbehandling, Web-HIPRE, viktning, lamell, filter.

Acknowledgements

This master's thesis has been carried out at the Department of Civil and Environmental Engineering at Chalmers University of Technology in Gothenburg from January 2015 to June 2015. The work has been performed in collaboration with the consultancy firm COWI AB in Gothenburg.

We would like to thank our supervisor at Chalmers, Jenny Norrman, for all her help and valuable insights. We would also like to thank everyone at the division of Environment, Risk and Safety at COWI for their help and inputs to this thesis. A special thank you to our supervisor at COWI, Niklas Edvinsson, for always taking the time to answer our questions and for being very involved throughout the whole process. This thesis could not have been done without you.

We would also like to thank Johan Magnusson at NCC Teknik for his expertise and enthusiasm regarding the subject of this thesis, and Malin Egardt at Trafikverket for taking the time to help us with weighting the criteria.

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

Gothenburg, June 2015
Azur Biscevic
Ingrid Olofsson

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1

Introduction

One of the many challenges during a construction project is meeting different environmental standards for the release of wastewater. Often the wastewater comes from excavations, where both the water flow from groundwater and surface water from rain events can end up. The responsibility for dealing with this water is put on the contractor, who will have to remediate it. Currently, there is no method for choosing the best available technology (BAT) and the selection of remediation techniques is done rather haphazardly.

1.1 Background

The European Union has set an overall goal of improving the water quality in its member states (European Commission 2015). An approach to reach this goal is the joint implementation strategy, where member states adapt their regional and national laws to the Water Directive. The Swedish implementation of this can be seen nationally in the Environmental Code, and in the Gothenburg region as the guideline values from the Environmental Administration.

The Environmental Administration in Gothenburg have derived their guideline values from EU directive 2013/39/EU in combination with the Swedish Environmental Code as well as local, regional and national environmental goals (Carlsrud and Mossdal 2013). For a deeper introduction to these guideline values and the Water Directive, see Appendix A. The guidelines focus on the most commonly occurring substances in wastewater from processes and activities, such as heavy metals, oils and several other substances. The guideline document also restricts the concentration of suspended material in the water and demands a reduction of particles before release into different waterbodies and streams.

The responsibility for meeting the guideline values is put on the practitioners (Carlsrud and Mossdal 2013). If there is an activity going on which produces contaminated wastewater, they are responsible for reporting the activity to the Environmental Administration, to minimize the effect on the environment and to use the best available technique.

The guideline values are valid for both permanent and temporary activities, and the benchmarks should be achieved at the place where the water is released into the recipient (Carlsrud and Mossdal 2013). In some cases, the guideline values for the excess water from excavations can be lowered, for example in case of heavy rain periods, during snow melting and other rare cases.

Particles are identified as carriers of different pollutants, and are therefore important to remove. Particles have been found to affect the life of the bottom fauna, by clogging respiration canals and reducing the density of prey items (Wood and Armitage 1997). The particles can cloud the water as well as destroy the important places where fish spawn after settling.

During construction work and more specifically excavations, a problem with excess water in the shafts and excavations can occur. The excess water comes from surface runoff and groundwater that flows into the excavation pit (Magnusson and Norin 2013). To be able to continue working, the excess water has to be handled and a common solution to the problem is to pump the water into either a recipient nearby or into the storm water system. Some general characteristics for the excess water is turbidity and particulates, and pollutants such as heavy metals and oil. To be allowed to release the water into these systems, the excess water needs to fulfill demands and benchmarks of water quality set by the Environmental Administration in the city of Gothenburg. These guideline values were set to protect the water quality in the waterbodies, human health and the environment. The Transport Administration can set a demand on the surface loading that a water treatment option must be dimensioned to.

The Swedish Transport Administration has an on-going project in the district of Marieholm in Gothenburg, where they are excavating for a tunnel under the Göta Älv River. The soil in this area is contaminated, due to previous industrial activities. As a result, the excess water that is created contains contaminants, such as heavy metals and organic compounds. To be able to release the excess water from this project, some treatment of the excess water is needed.

The methods used for choosing the different remediation techniques for the excess water are vague and done rather haphazardly, and the remediation techniques available are suitable for different conditions. The quality of the excess water depends on site specific conditions such as contaminants in the soil where the excavation takes place, and the type of soil present. Some soils consisting of finer grains can give a higher amount of particles in the water as well.

1.2 Aim

The overall aim of this thesis is to generate a general model for deciding upon which remediation alternative to use in excavation projects. The thesis aims to evaluate the use of multi-criteria decision analysis to compare available remediation techniques for excess water while using the Marieholm area as a case study. A secondary objective is to provide guidance for selection of remediation techniques for excess water for areas with similar conditions as the Marieholm area.

1.3 Scope

This thesis will carry out a multi-criteria decision analysis for evaluation of different remediation techniques for contaminated excess water. The Marieholm construction site is used as a case study to apply and evaluate the multi-criteria analysis. The time span used for calculations in the study will be five years, since this is the approximated time the excavation will be open. The study will focus on several remediation techniques of various levels of complexity, that may be used in the field today. The suitability of the different remediation techniques will be compared based on several identified criteria.

1.4 Research questions

The aim of this project is supposed to be fulfilled by the research questions stated below.

- Is it possible to use a multi-criteria decision analysis to find suitable remediation techniques for the excess water? If so, are there any drawbacks with the method?
- Which remediation techniques are commonly used and preferred by construction companies in Sweden today?
- Which technique is the most suitable with regard to the pollutions present, the costs and the conditions at the Marieholm site?

1.5 Thesis outline

Chapter 1 contains an introduction to the subject, and presents the relevance and aim of the project.

The theories behind this thesis will be described in Chapter 2 and 3, where Chapter 2 describes the current methods and techniques used for remediation of excess water and Chapter 3 describes Multi-Criteria Decision Analysis (MCDA).

The methods used are described in Chapter 4, both the practical methods of MCDA and how the different remediation alternatives were derived. A literature review of uses of MCDA is also presented.

The case study is presented in Chapter 5, where the historic and future use of the area is described as well as the properties of the soil in Marieholm.

The result of the thesis is presented in Chapter 6 and discussed in Chapter 7. A conclusion and further recommendations are found in Chapter 8.

2

Methods of remediation

During excavation processes in construction projects there is the problem of surface- and ground water inflow that needs to be removed. There are ways of dealing with this problem, which may include a temporary lowering of the ground water table, placing a pump at the bottom of the excavation pit or by using a submersible pump (SGI 2009). In cases where there is a high variability of the water flow there is the option to add a retaining reservoir that can store excess water for a time to keep the flow from exceeding the limit, thereby acting as a buffer. The excess water that is pumped will need some sort of treatment before being discharged into a recipient or infiltration back to an aquifer. There are several possible actions that may be taken to ensure compliance with regulations on the turbidity and concentrations of metals and organic substances. Several of the most common methods are listed below. All information is sourced from (Magnusson and Norin 2013) and corroborated by (Caltrans 2014) unless otherwise specified. As described by Magnusson and Norin 2013, all these techniques and methods can be divided into roughly 5 levels of complexity, which are as follows:

1. Sedimentation with low surface area. Sedimentation container.
2. Sedimentation with large surface area. Sedimentation pond or lamella clarifier.
3. Rapid- and slow filters.
4. Chemical precipitation and flocculation with sedimentation.
5. Interconnected systems.

It is worth to note that there is a substantial technical leap between the second level and the third level, where the first and second levels deal with excess water with low levels of contamination and the higher levels deal with severely contaminated excess water.

2.1 Sedimentation

Sedimentation is the most commonly used method for reducing turbidity in discharges to a recipient. It is also often successful in reducing the amount of other substances, such as metals, that may have be present in the excess water as well as many substances that adhere to the surface of the particles. The process is simple, as it only involves letting the suspended particles sink to the bottom of a pond or container naturally through gravity. This process is the same in both sedimentation ponds and sedimentation containers, which are the the two most common ways to achieve ordinary sedimentation. Equation B.1 is an equation used to find the settling velocity of a particle, which is important when dimensioning a sedimentation pond. Another method of dimensioning the sedimentation pond is to use Equation B.2, that is used for dimensioning stormwater ponds. Here, the intensity of the rain can be chosen based on its average recurrence interval. The sedimentation container is the most common technique to use in treating excess water today, due to their low cost, ease of use and availability.

Sedimentation processes are normally divided into three different types, based on particle type and particle concentration. The first type of sedimentation has a linear rate of sinking, as the particles do not directly interact with one another. The second type pertains to aggregates of particles and the third type occurs when there is a high concentration of particles that hinder. The type of sedimentation that happens in sedimentation ponds and containers is of the first type. For examples of what a sedimentation pond or container might look like, see Figure 2.1.

(a) **(b)**

Figure 2.1: a) Sedimentation pond (Magnusson and Norin 2013). b) Sedimentation container (Fraktkedjan Väst 2015)

2.2 Lamella sedimentation

A lamella container is similar to an ordinary sedimentation container from an outward perspective, but is several times more effective at separating particles. A way of increasing the settlement area, which is one of the ways to increase sedimentation, is by adding lamellas to increase the sedimentation surface, and thereby the effect of the sedimentation. Inclined plates (or lamellas) are placed at an angle of 55-60° to the horizontal plane (Magnusson and Norin 2013), as can been seen in Figure 2.2. These lamellas slow down the particles and create more space on which the particles can sediment. This method of increasing sedimentation was first used by wastewater treatment plants, but the method has now been miniaturized as well. Two different models can be used, a container with a flat bottom and another with what is called a hopper, that has an opening at the bottom for easy removal of the sludge that forms. A schematic image of a lamella container of the hopper type can be seen in Figure 2.3. These types of containers are not in common use in Sweden today, but are used extensively in for example England.

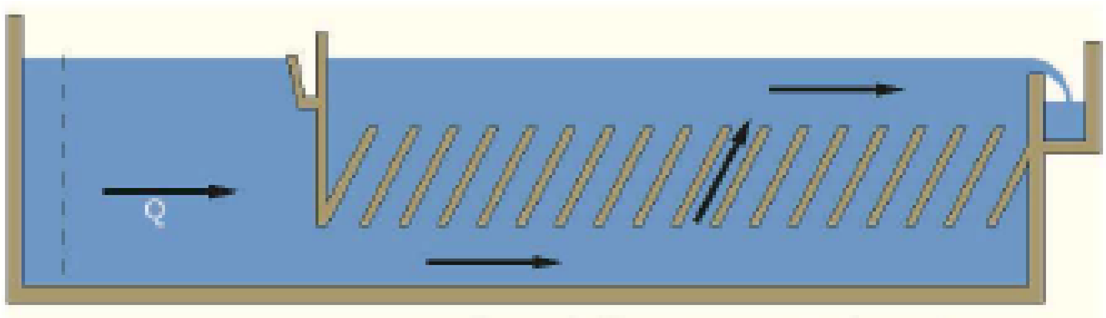
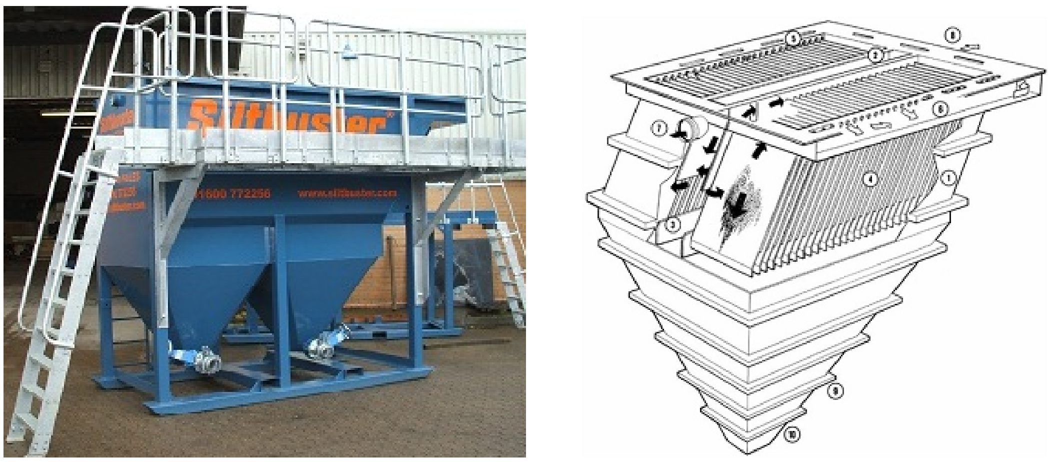


Figure 2.2: Description of a flat-bottomed lamella clarifier (Magnusson and Norin 2013)



(a) **(b)**

Figure 2.3: a) Lamella clarifier with twin hoppers (Siltbuster 2015b). b) Schematic image of hopper functionality (Polyproject 2015)

2.3 Oil/water separation

Oil separation can be achieved using several different types of equipment, such as a weir tank, a dewatering tank and oil absorbent pressurized bag filters (Caltrans 2014). The two most used methods are through ordinary gravimetric separation or with coalescing filters. Gravimetric separation occurs due to the density difference between oil and water, with baffles to keep the oil from escaping the tank. This separation can be seen schematically in Figure 2.4. Coalescence filters function by oil droplets working their way through a fiber matrix and joining together to form larger droplets that may be separated through gravimetric separation.

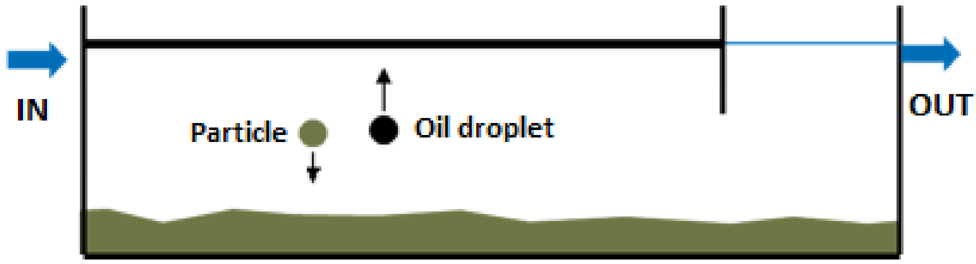


Figure 2.4: The principles of sedimentation and oil separation in a container (Magnusson and Norin 2013)

2.4 Chemical precipitation and flocculation

Chemical precipitation is a method that is mostly used for removing small mineral particles that are too small to remove using just sedimentation methods. It works by adding, often positively charged, ions that will adhere to the negatively charged surface of the mineral particles. These ions neutralize the negative charge that normally repels the particles. Chemical flocculation is done using a polymer of high molecular weight that has the ability to effectively bind the neutralized mineral particles to itself. It is necessary to sample the water to find the proper dosage for the amount and size of the particles. This method is used when the turbidity of the water is very high.

2.5 Pressurized rapid sand filter

The pressurized rapid sand filter is a tank containing a filter medium of sand, where the water is pumped into the top of the tank and seeps through the medium to the bottom. The filter will eventually get clogged by particles that remain in the filter medium, causing an increased pressure-drop in the system. This problem is solved by back-flushing the filter medium clean. This technique can under good conditions remove particles down to a size of 10 μm.

2.6 Multimedia filtration

This method is virtually the same as the pressurized sand filtration, with the exception that there are one or more layers of other materials as well (Öhman, Welander, and Andersson 2013). These layers are often anthracite, which has a low density and a high surface area, and garnet that has a high density and small surface area. A schematic image of these layers may be seen in Figure 2.5 The idea is that the largest particles will get stuck near the top of the particle bed, consisting of anthracite, and the smaller particles will get stuck in either the sand filter or the garnet filter. This has the advantage over the pressurized rapid sand filter as there is a longer time between the need for backflushing. Depending on the size of the particles, a multimedia filter may remove particles down to 10 μm if operating under good conditions

(WaterProfessionals 2015).

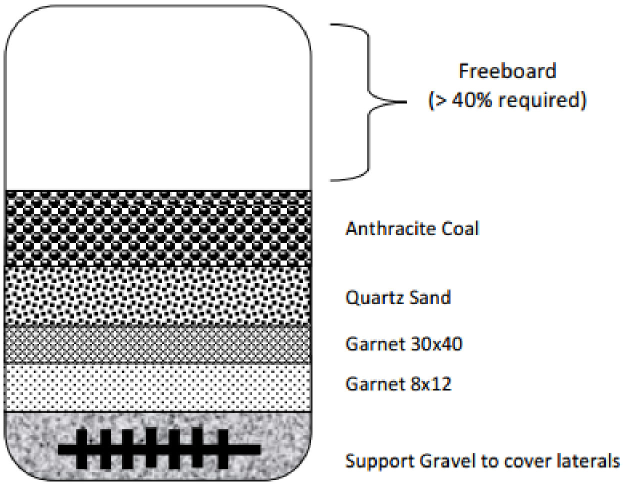


Figure 2.5: Schematic image of a multimedia filtration unit with four filter media (Puretec 2015)

2.7 Continuous filtration

In contrast to the pressurized rapid sand filter and multimedia filter, a continuous filter pumps the water from the bottom of the tank while the filter medium moves to the bottom. The filter medium containing the particles is removed at the bottom and then washed. This type of filter is used mostly at permanent installations, such as at water treatment plants, due to their large size that makes them immobile. See Figure 2.6 for a schematic view.

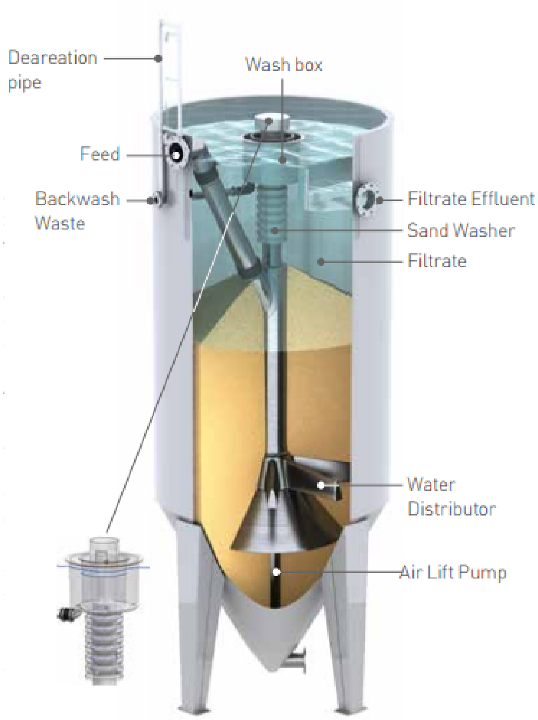


Figure 2.6: Overview of continuous filtration functions (Nordic Water 2015)

2.8 Pressurized bag filters

Bag filters consist of a textile with a certain pore size that is fitted in a casing, on which pressure is applied. The water is filtered through the textile, and is discharged while the particles remain in the filter (Caltrans 2014). The filter bags can be cleaned several times for reuse, handle flows up to 40 m^3/h and can separate particles down to 1 μm (Vattensystem 2015). In Figure 2.7 below are some examples of how filter bag casings may look like.

Figure 2.7: Examples of a pressurized bag casing (Vattensystem 2015)

2.9 Geotextile bags

This method is currently most commonly used for dewatering polluted sediment that has been dredged, but may be implemented where there is heavy pollution of sediment in the excess water. These geotextiles are called gravity bag filters, dewatering bags or most commonly, geotubes. The separation process involves pumping water with sediment into a large bag made out of non-woven geotextile. Water will seep through the bottom and sides of the bag, while the sediment remains in the bag. There is often a secondary barrier meant to capture sediment that escapes the geotextile bag (Caltrans 2014). A schematic image is shown below in Figure 2.8 They come in many sizes, as they are made to client specifications to suit the specific conditions at a site (Wortelboer 2015).

Figure 2.8: The principle behind the use of geotextile bags (Tencate 2015)

2.10 Activated carbon filtration

Activated carbon is used mostly when there are dissolved organic substances in the water, as it has a structure with a very high surface area that compounds may be adsorbed to. The carbon may come in very different shapes and form, but granulates of 0.2-5 mm are most commonly used. It is very important that there is a step before this filtration, as sediment particles would otherwise clog the filter. Therefore this filtration needs to be combined with at least one pre-treatment to remove large quantities of sediment (Magnusson and Norin 2013).

3

Multi-Criteria Decision Analysis

A multi-criteria decision analysis (MCDA) is a tool for a decision maker to choose the best available method or alternative for their specific problem (Belton and Stewart 2003). MCDA is built upon utility theory, and is supposed to facilitate the decision for a decision maker who has a problem with many different aspects to take into account. The process of creating an MCDA model begins with defining the context of the problem or objective and which decisions that have to be made. It is in this step that the different criteria which the decision is made upon are identified. Several solutions to the decision problem are then identified, and hereafter called alternatives. Thereafter, a model can be built and the different criteria can be weighted depending on their importance for the decision maker. The relevant alternatives are scored based on how well they meet the identified criteria, and the best alternative can then be found.

The different approaches to an MCDA vary in complexity, from the more simple performance matrix which can be seen in comparisons between different products, to more advanced models where the alternatives are scored based on the different criteria. The different types of approaches can be seen in Figure 3.1. These criteria are in turn weighted based on their importance relative to each other. The total score of the alternative can be calculated with different methods, which can be divided into compensatory and non-compensatory methods. If a method is compensatory, then if one alternative is low performing in one criterion, a higher score and better performance in another criterion can compensate for the poorer performance (Communities and Local Government 2009). Examples of compensatory methods are multi-attribute value theory, which is a three-step method where a performance matrix is created as a first step; the independence of the different criteria is then assured; and, finally, the scores and weights assigned to the different alternatives and criteria are calculated. Another set of compensatory methods are linear additive models, which can be described as an aggregated value of the alternative's score in one criterion, multiplied with the weight of this criterion. The scores and weights for the different criteria are added up into one value. The linear additive model is suitable to use if the different criteria have to be mutually independent. The Analytical Hierarchy Process (AHP) is yet another method to use when weighting and scoring criteria and alternatives(Communities and Local Government 2009). The criteria and alternatives are compared pairwise to assign weights and scores, based on the relative difference between the compared pair.

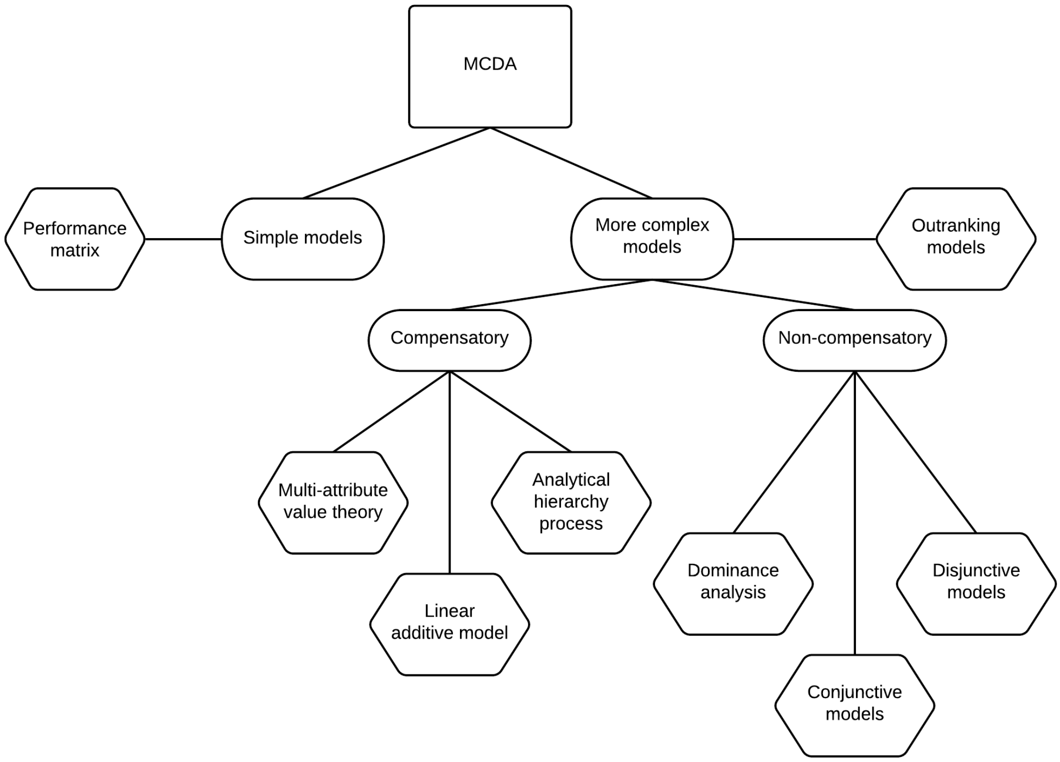


Figure 3.1: Some of the different types of MCDA models

A non-compensatory method is dominance analysis, where an alternative is rejected if it is being dominated by another. Another non-compensatory model is the conjunctive model, where a benchmark value is set and alternatives below this value are rejected. Not as strict as the conjunctive model is the disjunctive model, where the alternative has to reach the benchmark value in at least one criteria to pass.

A third version of MCDA methods are outranking methods (Communities and Local Government 2009). The idea is similar to the dominance method, where the different alternatives are compared to each other, but the different criteria are given different importance. If an alternative has outranked the other alternative in a sufficient amount of important criteria, it can be seen as the most suitable criteria.

A value tree is the organization of the criteria and the making of a hierarchy from them, based on which criteria that belongs to a parent category. The structure can be resembled with a tree, where the main objective can be seen as the trunk of the tree, the different criteria as branches and finally, the alternatives represents the leaves. The process of decision making can be outlined with the following steps, as identified in the Multi-criteria analysis: A manual (Communities and Local Government 2009). This process differs slightly from the process mentioned above, from Belton and Stewart 2003, since the order of the different steps are not the same.

- Identify objectives.
- Identify the alternatives for achieving the objectives.
- Identify the criteria to be used to compare the alternatives. To be able to evaluate the performance of each alternative in relation to a specific criterion, the criteria need to be measurable. If there are different stakeholders involved in the process, they should evaluate the different alternatives and criteria.
- Analysis of the alternatives and perform a sensitivity analysis of the alternatives
- Choosing the best alternative. The MCDA model only suggests an alternative based on the alternative fulfilling the different criteria and it is the decision makers' responsibility to make the decision.
- Feedback. To learn from the process, and to reassess the decision, feedback from the resulted choice is given to the model to improve it. This is done if the model is to used to make future decisions.

3.1 Methods for scoring

The alternatives which were identified in the creation of the value tree, are scored on a scale of how well they fulfill the different criteria in the value tree (Belton and Stewart 2003). The scale can range from the lowest value to the highest value of an alternative and have different units such as m^2 or SEK for example, range from 0 to 100; or -10 to 10. This is called a local scale, where the best performing alternative is set to 100, and the worst performing alternative is set to 0. The other alternatives are then scored with regards to this scale. Another method of scoring is to use a global scale, where the best possible technique or outcome is used as the best point, 100, on the scale. The worst possible outcome or worst performing technique or method is set as 0 on the global scale. Then, the alternatives identified for the value tree are scored based on their performance compared to this scale. Important for the decision maker to decide is whether the scale is monotonically increasing, meaning that a high score is better; if it is monotonically decreasing, where a low value on the scale is preferable; or, if it is non-monotonic, i.e. an point in between the two extreme points is preferred. There can be other scales used, ranging from 0 to 10, or -10 to 10 etc. Sometimes, the criteria do not have any attributes which are measurable. These criteria and their attribute then need a qualitative scale, where two end points are identified, and some intermediate points in between them as well. A qualitative scale should be operational, reliable and relevant for the decision makers' objective. An example of an operational scale is the Beaufort scale for wind strengths.

3.2 Methods for weighting

All criteria in a value tree does not have the same significance for the decision maker. The weights assigned to a criterion is to show its importance compared to other criteria, and the weight can be seen as a scaling factor. The swing weight method uses the decision makers' preferences to find the alternative which will increase the overall value of the value tree the most(Belton and Stewart 2003). This alternative is then assigned the value 1, the second best alternative is given a number below 1 and so on until all alternatives have been assigned weights. Within the value tree, the different levels of criteria can be weighted as well (Belton and Stewart 2003). The sum of the weights of the lower order criteria is the weight of the higher order criterion in the category. This is a top-down method for assessing the weights at different levels of the value tree.

3.3 Web-HIPRE

Web-HIPRE is an applet created by the department of systems analysis in Helsinki University of Technology (Mustajoki and Hämäläinen 2000a). It is a tool for HIerarchical PREeference in the world wide WEB. The applet develops models and enables the calculations which are included in the MCDA process and handles the weighting and scoring of the alternatives in an schematic manner. It can also perform sensitivity analyses, which are also a part of the MCDA procedure.

In Web-HIPRE it is possible to use different methods of scoring and weighting, as direct scores and weights, swing weights and smart weights (Mustajoki and Hämäläinen 2000b). The applet then normalizes the scores and weights and combines them into a single number and presents the result by their performance in columns.

3.4 Examples of MCDA in other projects

Extensive literature research was performed using SCOPUS in order to find information on MCDA as a decision support tool in construction dewatering. The search yielded no results. Examples of applications in other fields are presented below.

MCDA was used to find the most suitable remediation method of contaminated sediments in a Norwegian fjord (Sparrevik et al. 2012). The authors compared the suitability of assessment tools such as cost-benefit analysis (CBA), risk assessments and cost-effectiveness analysis(CEA). Their studies indicate that they lack a holistic view of the problem since CBA and CEA often miss the environmental aspect which is not measured in monetary terms. Here, the practitioner used the MCDA to include the different stakeholders' values for the criteria. The MCDA study in Sparrevik et al. 2012 deals with uncertainties in the performance of the different alternatives by using statistical probabilities and Monte Carlo simulations to find the best alternative to remediate the contaminated sediment in the fjord. Also when handling contaminated sediments in the New York/New Jersey harbor, an

MCDA was used in combination with a risk assessment (Kiker, Bridges, and Kim 2008). Here, eight different alternatives were evaluated based on seven different criteria. MCDA methodology was also applied to the Bay of Santander, to find different sites in need of remediation and the appropriate managing alternative for each specific site (Alvarez-Guerra, Viguri, and Voulvoulis 2009).

Another similar study used MCDA to find a suitable method of removing naturally occurring flouride from drinking water in Ethiopia (Osterwalder et al. 2014). The study identified three criteria and twelve sub-criteria by which the different alternatives were evaluated. Several stakeholders were included, such as federal and local governments, NGOs and academia. The different stakeholders' views were combined in the weighting process, where the different views and interests were represented by a numerical value. As a result of the MCDA, it was found that there is no single-most preferred solution to the problem, since the different remediation techniques are site specific. The weighting of the different criteria vary with the stakeholders at different sites. The method of MCDA as a decision support was found to be transparent, and the information was made accessible for an audience with a varying knowledge of the different techniques of removal. Another study investigates the best method for removing micropollutants from drinking water in India (Sudhakaran, Lattemann, and Amy 2013). In this article, the different remediation alternatives were evaluated in three different MCDA models, where the first one included economic, technical, and social aspects, while the second and third models focused on the alternatives ability to remove the contaminants, but with different data used. The authors found the method to be a transparent one, but concludes the study with the need of complement of a system design to their decision support model.

Within the field of construction design, MCDA has been used to find the most suitable design of building parts (Bitarafan et al. 2012),(Rogers 2000),(Turskis, Zavadskas, and Peldschus 2009). MCDA can also be used to find the most viable combination of renovation measure for a house (Alanne 2004), and also in selection of the most suitable design type for a bridge at a specific site (Pan 2008).

4

Method

The following chapter will describe the methods used to perform the MCDA more in depth and the online tool Web-HIPRE. Depending on which type of MCDA that is performed, the methods can vary. Here, the process of a hierarchical value tree is presented.

4.1 Multi-Criteria Decision Analysis

The MCDA was created by using concepts from the online learning material connected to the applet Web-HIPRE, and the different steps mentioned in the theory chapter. The four steps have been developed further for increased precision, and are presented as 7 steps. These were followed when the model was developed.

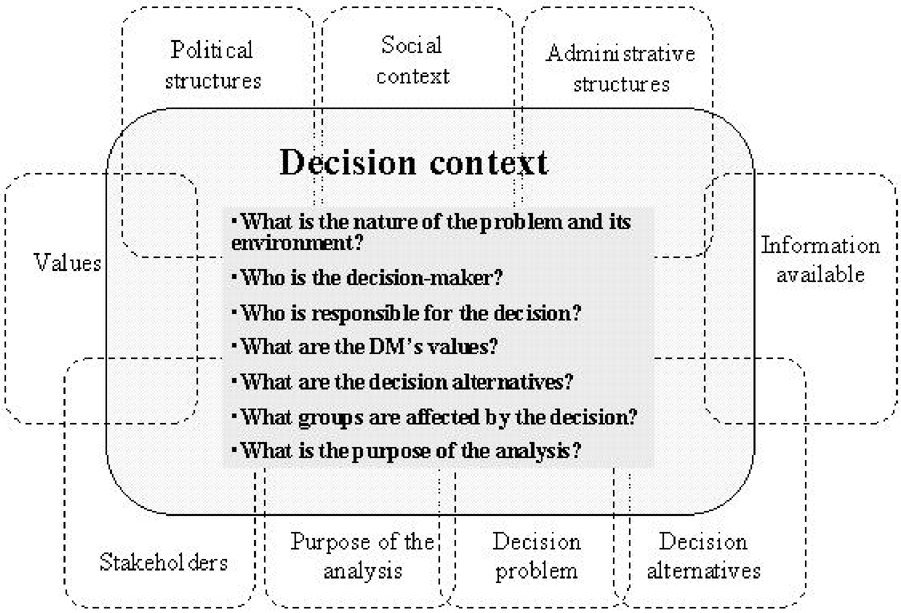


Figure 4.1: Decision context main factors (Helsinki University of Technology 2002)

1. **Creating a decision context.** First, a decision context was defined by using

a list of components which should be included, see Figure 4.1. The overall goal of the project was identified as remediation of the excess water to an acceptable level at the lowest cost possible. From the context, it was possible to develop the different criteria.

2. **Finding criteria.** The different criteria were elicited by using different stakeholders perspectives, examination of literature and by fulfilling the regulations set by the environmental administration. Informal conversations with Niklas Edvinsson and other colleagues at COWI Gothenburg, who are practitioners in the field, were the basis for the ideas for the criteria, as well as the decision context formed in the previous step. The independence amongst the criteria was controlled by examining if it was possible to score an alternative without knowing the score of the alternative in another criterion.

3. **Finding Alternatives.** The basis for the alternatives for remediating the excess water were found in literature, different case studies and from interviews. Descriptions of the main features of the techniques used can be found in section 2.

4. **Scoring the alternatives.** The characteristic values and performance levels for each alternative of remediation was found in literature and data from manufacturers or rental companies. The data was then used to score the alternatives' performance in the different criteria, where the different values were put into the applet Web-HIPRE. Where direct scores were not possible to find, the AHP method was used to compare the different alternatives in a pairwise manner.

5. **Weighting the criteria.** The criteria were given weights based on their importance by at the Swedish Transport Administration. 100 points were allocated between the criteria, where the most important criterion was given the highest points and the less most important criteria were given lower points to reflect the relative importance between the criteria. The points were then converted into weights.

6. **Combining scores and weights.** The scores and weights were calculated by using the applet Web-HIPRE.

7. **Sensitivity analysis.** A sensitivity analysis was performed, both by using the built-in application in Web-HIPRE and by changing the weights of the different criteria. This was done to examine if the alternatives were sensitive to changes and if there were any changes to the ranking of the alternatives.

4.2 Application of model

The MCDA model created was applied on Marieholm, to examine the applicability of the method. Further explanation regarding the case study is found in chapter 5.

5

Marieholm

The planned project

The infrastructure project planned for Marieholm, called Marieholmsförbindelsen, consists of one road tunnel and one railway bridge (Trafikverket 2014). The tunnel is supposed to be 500 meters long and 50 meters wide. The project is needed to decrease the vulnerability of the infrastructure and to manage the increasing traffic flow through the region. The Tingstadtunnel is already used beyond its capacity, and the planned project at Marieholm would increase the robustness of the infrastructure. Picture 5.1 shows the plans for the tunnel and bridge. The railway bridge is scheduled for opening in 2017, and the tunnel in 2020 (Trafikverket 2014).

Marieholm is located between the south beach of the Göta Älv river and the river Säveån. The area is flat and the soil consists of both natural soil as sediment and filling material (Åberg 2012). Some of the filling material is believed to come from a change of the direction of Säveån and the filling material contains of coarse material as cobbly gravelly sand with some finer materials such as silt and clay, while the origin of other parts of the filling material is unknown. The thickness of the layer of filling material varies between 2-4 meters below the surface. The layer underneath the filling material consists of clay and in some places mud. Some parts of the filling material is contaminated with metals, different oil fractions, PAH and cyanide.

Historic use of the area

Marieholm has developed from being used as agricultural land in the 17th century to an industrial area in the 20th century (Samuelsson 2004). Due to the location, at the connecting point of two valleys and the Göta Älv river that runs through the area, it has been developed towards being more industrialised. Harbour activity gave important transport possibilities in the 17th century, and a railway was built in the area around 1900. The harbour has been replaced by roads in modern time. As described earlier, the development has gone from mainly agricultural activities to various industrial use, workshops and warehouses.

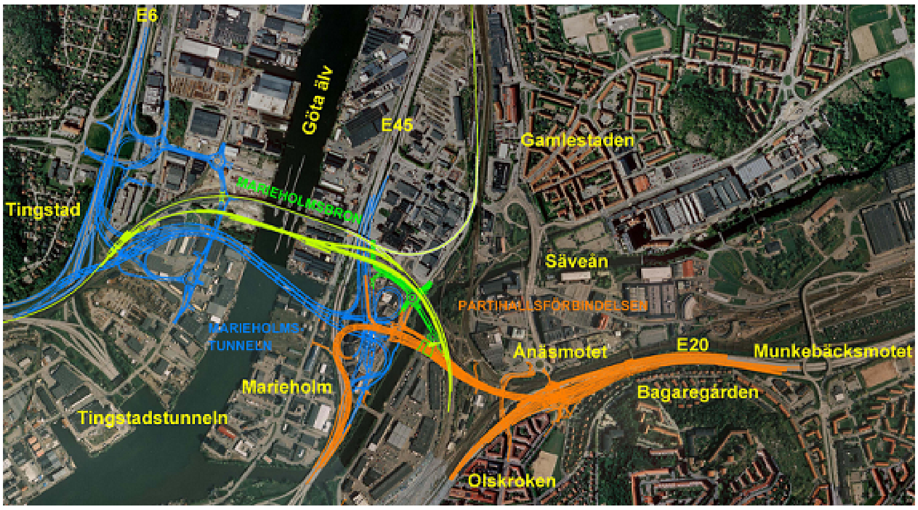


Figure 5.1: Overview of planned projects in Marieholm (perpixel.se, 2015)

Contaminations in soil and water

Due to the previous activities at the site, some parts of the area planed for development have concentrations of different pollutants that exceed the guideline values for less sensitive use of the area. The pollutants found from different investigations were mostly heavy metals and hydrocarbons. The contaminants consist mainly of polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, volatile hydrocarbons, copper and lead. They are mostly present in the filling material found at the site (Samuelsson 2004). At the moment, the excess water from all excavation sites is treated by a sedimentation pond, dimensioned to manage a flow of 60 m^3/h, before the water is released into a stormwater pond located nearby (Askmar 2015). The water from this stormwater pond is then connected to the city's stormwater system. The sedimentation pond has been found to have trouble removing particles at a flow rate of 20 m^3/h.

Case study

Due to the previous mentioned difference in dimensioned flow of 60 m^3/h and the flow where the pond's efficiency was not sufficient, a hypothesis regarding flow rate was created. Two flows were chosen to examine if there were any differences in the result if the flow rate was changed. One flow was calculated using the mean flow for January 2015, since this month had the highest recorded flows in the period from June 2014 to February 2015. The mean flow in January was 6 m^3 per hour, and the mean absolute deviation which was 4 m^3 per hour. These together give a projected upper mean flow of 10 m^3 per hour. The other flow was chosen as 30 m^3 per hour, as this was close to the highest flow that had been measured in the above mentioned time period. An assumption regarding the case study is that the excavation pit will be open for the duration of the project, from 2014 until approximately 2019. The

Table 5.1: Measured and calculated volume and flows during January 2015 used for deciding on an average high flow. Calculated from data provided by the QHSE-officer at PEAB (Askmar 2015)

Flow types	
Total volume	3681 (m^3)
Mean flow	6 (m^3/h)
Median flow	5 (m^3/h)
Maximum flow	31 (m^3/h)
Standard deviation	6 (m^3/h)
Mean absolute deviation	4 (m^3/h)
Median absolute deviation	2 (m^3/h)

calculations made were based on a constant flow from the excavation. For measured and calculated values of the volumes, see Figure 5.1

6
Results

The results from this thesis presents the chosen criteria for the multi-criteria decision analysis and weighs them, while also presenting the alternatives of water remediating techniques in eight configurations and how they were scored. The best result is presented and a sensitivity analysis details the changes in results that different weighting of criteria and sub-criteria may cause.

6.1 The decision context

The objective of this MCDA is to provide decision support for decision makers regarding which remediation method is the most appropriate for a specific site. The model that has been generated is a general model that is evaluated by using data and knowledge from a project at the Marieholm site. This decision maker can be either the purchaser or a contractor.

Stakeholders and key players in the process are the Swedish Transport Administration, COWI AB and other consultancy firms, the Environmental Administration and the contractors who will perform the work. The Swedish Transport Administration is the decision maker and also purchaser of the Marieholm project. They put a demand on the contractor to fulfill a certain surface loading, and the contractor is then free to choose which method of remediation they find suitable. This MCDA can be seen as a tool for the Swedish Transport Administration to provide guidance or even suggest an appropriate remediation method to a contractor.

The Swedish Transport Administration, has found the environmental aspect of sufficient remediation of the excess water, as well as the economical aspect of the choice of remediation method, as important values for their decision. The alternatives for the decision can be found in section 6.3.

The group that is affected the most by the decision made is the contracting firm, since they are the ones that have to act on the decision. The owner of the project, in this case the Swedish Transport Administration, is also affected since they ultimately pay for the project. The objective of the multi-criteria analysis is to provide the decision maker with decision support on which method that is most suitable for the area of concern, and the remediation needed.

6.2 Criteria for evaluation

Three different categories were identified; design considerations, contaminant removal and contractor views. To each of these categories, two subcategories were identified. The subcategories were the following: space requirements, water flow variability, particle removal, ability to remove dissolved metals and pollutants, cost and independence of manual monitoring .

6.2.1 Design considerations

There are different characteristics for every site. The size of the available area at a site can vary, making the size of the remediation technique an important aspect. The soil fractions can vary and if there is, for example, a large amount of clay in the soil fraction, the groundwater flow is lower than in a sandy soil. Combined with a heavy precipitation the water flow into the excavation can vary, causing flow spikes. Some alternatives are better than others at handling these problems, as described in the following two sub-criteria.

Space requirements

This sub-criterion was chosen since space is sometimes limited at a building site, and the remediation technique should not disturb or hinder the main work at the site. The alternatives are scored based on how much space they require in m^2, where less space needed was preferred to larger requirements, i.e the alternative with the smallest area got the best score, and the scale varies from the smallest to the largest alternative.

Water flow variability

Since the water flow into the excavation is not constant, but depends on amount of precipitation, groundwater flow and the catchment area of the construction site. The remediation techniques ability to handle the variations in the water flow is therefore a measure of its effectiveness. Some of the alternatives have a fixed flow to which they can treat the water from the excavation pit, others lose their effectiveness to remove contaminants with higher flows. The capability to handle variations in the incoming flow is therefore an important aspect when choosing a remediation alternative. The alternatives were compared pairwise with the AHP method.

6.2.2 Contaminant removal

The chosen remediation technique should remove the contaminants and the particles so that the treated water will fulfill the environmental standards for the area, since this is the main reason for remediating the excess water. Two sub-criteria were found, since there are different problems that need to be handled.

Particle removal

The techniques used for remediation of the excess water should meet the environmental standards in the area. Turbidity can be a problem for aquatic organisms and since many contaminants are adsorbed to particles, this criteria focuses on the removal of particles. According to the guideline values set by the Environmental Administration of Gothenburg, 90 % of the particles smaller than 0.1 mm must be removed (Carlsrud and Mossdal 2013). The different alternatives are scored based on how small particles they are able to remove, measured in microns (μm). It would be preferable to use reduction of turbidity as a measure of particle removal effectiveness, but this kind of data is more difficult to find as the removal efficiency depends on the amount of particles, soil type and flow rate (Magnusson 2015). Therefore, the particle size was chosen as the metric for this criterion.

Ability to remove dissolved metals and pollutants

In some areas there are problems with dissolved metals and contaminants which are not bound to particles. These dissolved contaminants can have severe effects on biota, and are therefore necessary to remove. These problems do not occur in the Marieholm area that is the basis for the case study. The alternatives were scored with 1 if they possess the ability to remove dissolved contaminants, 0 if they do not.

6.2.3 Contractor views

The contractor would be interested to know how independent the technique is from manual monitoring, if a special technician is needed and how much surveillance the alternative needs, since there has to be someone available to do this additional task in that case. A need of extra monitoring can in the extension be seen as an additional cost. The cost of the remediation alternative is also an issue since a low cost is more advantageous in the procurement procedure.

Cost

The remediation technique should be possible to install and maintain at a reasonable price. Some techniques are more favorable than others during different conditions. For example, if the need of a remediation technique is over a short period of time, the over-all cost could be lowered by using a sedimentation container instead of building a sedimentation pond. The price per hour might be higher for the container, but the initial cost of construction for the sedimentation pond might make the price per hour of use higher. The different alternatives will be evaluated by adding the total cost of all techniques for each alternative. The scores will be assigned to the alternatives based on their estimated total cost for the period of five years, since this is the time span of the case study.

Independence of manual monitoring

If the remediation technique is complex and needs attention, then it is dependent of manual monitoring which can add costs to the project. The alternatives were scored on how often they needed attendance which ranged from once a day, equalling a score of 365, to once a year, equalling a score of 1.

MCDA model

The criteria hierarchy can be seen in Figure 6.1. All alternatives were evaluated based on the two different flows, a 10 m^3/h flow and a worst case scenario flow of 30 m^3/h.

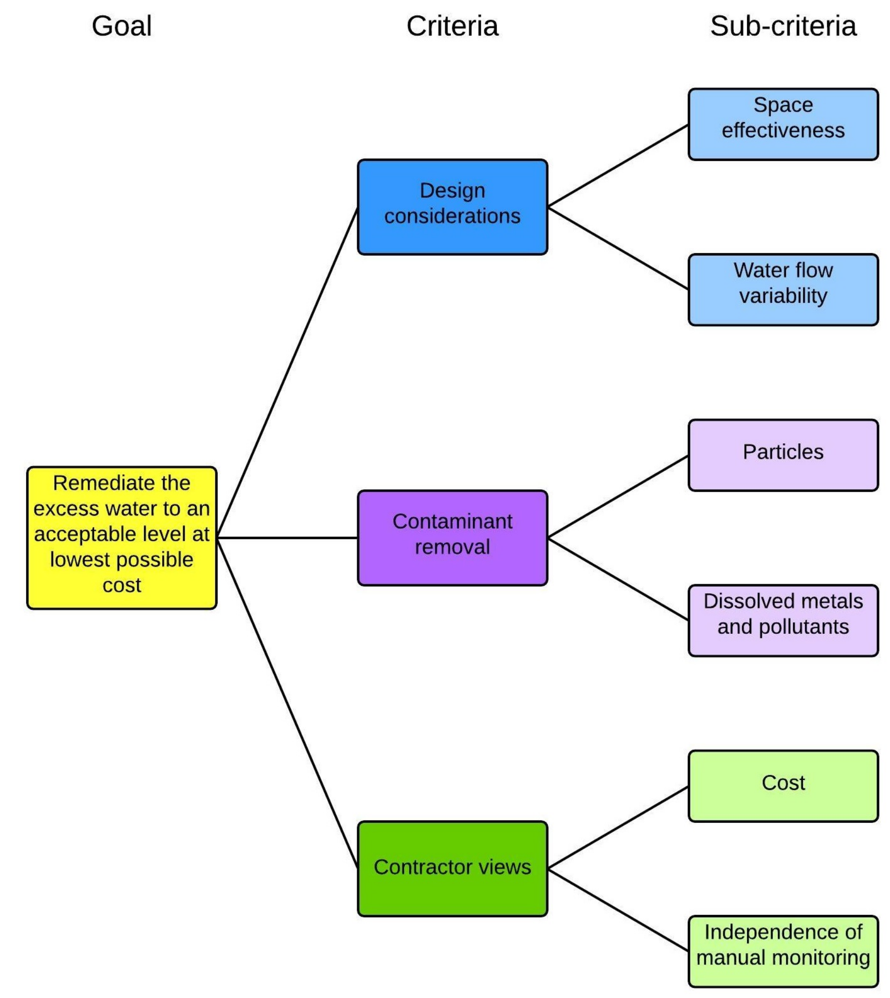


Figure 6.1: The criteria hierarchy.

6.3 Remediation alternatives

Depending on the contaminants at a site, the complexity of remediation techniques needed will vary. More complex alternatives are often combinations of two or more methods designed to comply with the criteria mentioned in 6.2. Listed below are alternatives that may be implemented as methods to deal with the excess water, due to the different conditions and restrictions that may apply. Note that the methods composed of several units are normally delivered in a container-system according to set specifications. As mentioned in chapter 2, there are several levels of complexity. The alternatives included in this thesis represent all levels of complexity except level 3.

Alternative 1 - Sedimentation pond

A sedimentation pond is an easy way to reduce particles down to the size of coarse silt, about 20 μm in diameter. The size of the pond can vary depending on factors such as the expected water flow and available space. The depth of the pond is important, as well as the shape of the pond, as seen in Figure 6.2 (Magnusson and Norin 2013). The size of the pond used in the model is the actual pond located in Marieholm, with an area of 300 m^2 which should theoretically handle 60 m^3/h while having a surface loading of 0.2 m^3/m^2h. Information we have received through communication with the Quality, health, safety and environment (QHSE) officer at the construction site claimed that the pond could actually only handle about 20 m^3/h before efficiency problems were encountered (Askmar 2015). The pond has the same dimensions in both the 10 m^3/h and the 30 m^3/h flow, as it was dimensioned to handle much higher flows than both flows discussed in this report.

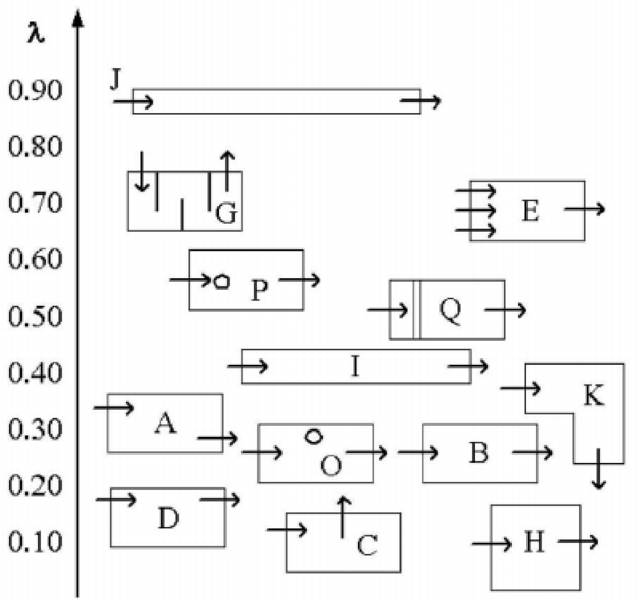


Figure 6.2: λ represents the hydraulic efficiency of different pond shapes, meaning the efficiency of sedimentation of particles in the pond (Magnusson and Norin 2013)

Alternative 2 - Sedimentation container

An open sedimentation container works by slowing down and distributes the excess water evenly and giving the sediment time to settle at the bottom of the container. Several containers can be connected in series to increase the degree of sedimentation, or in parallel to handle larger flows. A container can handle anywhere between 5-50 m^3 per hour, depending on the type of container and reduce particles down to a size of 60 μm (Magnusson and Norin 2013). For the case of the 10 m^3/h flow of water the decision was made to use two containers, as each container has a volume of about 10 m^3 it seemed unwise to rely on just one sedimentation container. Likewise six containers were chosen as the basis for the calculations for the 30 m^3/h flow.

Alternative 3 - Lamella clarifier

A lamella container can handle between 5-50 m^3/h and can remove particles down to the size of coarse silt, about 20 μm if operating efficiently (Magnusson and Norin 2013). According to Magnusson 2015, there is only one company supplying one flat-bottomed container and one with so called twin hoppers in Sweden today. For this case the choice has been the flat-bottomed type, as an interview with the supplier of these containers made it clear that there is no need for the container with twin hopper unless flocculant has previously been added to the water (Magnusson 2015). This type of container is capable of handling 50 m^3/h flows, and is therefore used in both the 10 m^3/h and the 30 m^3/h flow (Siltbuster 2015a). A schematic image of such a container can be seen in Figure 6.3.

Figure 6.3: Flat-bottomed lamella container (Siltbuster 2015a)

Alternative 4 - Sedimentation pond and pressurized bag filter

If the efficiency of a sedimentation needs to increase, a bag filter may be added after the pond (Vattensystem 2015). The filter used should have a pore size of at a minimum 5 μm, as a smaller pore size would clog the filters too often due to the high flow of water through the filters. This is an estimation, and depends on the effectiveness of sediment separation in the pond and the initial turbidity level of the water entering the pond. Two filters are used in a 15 m^2 container into which water is pumped from the pond. The filter types are the same in both the 10 m^3/h and the 30 m^3/h flow.

Alternative 5 - Sedimentation container, precipitation, flocculation, lamella clarifier and geotextile bag

For excess water with a high degree of fine particles, the water can be pumped into two ordinary sedimentation containers in parallel, from which the water can be pumped into a dosing unit that adds a flocculant that binds fine particles. The water is then pumped to a lamella clarifier of the twin hopper variety, since a significant amount of sludge will form settle in the hoppers. The sludge is then led to a geotube for dewatering while the water is released to a recipient. The geotube has a capacity to hold 18 m^3 of sediment in the 10 m^3/h flow and 60 m^3 in the 30 m^3/h flow. An example of a combination of methods can be seen in Figure 6.4. In this case water is pumped from a pond to a chemical dosing container, then to a twin hopper lamella container, followed by a ordinary container from where the water will be pumped to a container containing bag filters and an activated carbon filter.

Figure 6.4: Image from a soil remediation project (NCC 2015)

Alternative 6 - Sedimentation container, precipitation, flocculation, lamella clarifier, geotextile bag and rapid sand filtration

This system is the same as in alternative 5, but with the addition of three parallel rapid sand filters for the 10 m^3/h or two larger filters for the 30 m^3/h flow. This system is not normally used at construction sites on non-contaminated soil. This configuration is among the most expensive, but necessary if the recipient is extra sensitive.

Alternative 7 - Sedimentation container, precipitation, flocculation, lamella clarifier, geotextile bags and pressurized bag filter

An alteration of alternative 6, this method uses two bag filters as the last step in the purification instead of sand filtration. While the water purity will increase, the maintenance will also increase due to clogging of the bag filters over time. The filter casing and the filter bags are the same for both the 10 m^3/h flow and the 30 m^3/h flow.

Alternative 8 - Sedimentation container, precipitation, flocculation, lamella clarifier, geotextile bag, pressurized bag filter and activated carbon filtration

This is the same system as alternative 7, but with the addition of two activated carbon filters. This system could be an option if the sediment carries with it heavy metals or organic compounds such as pesticides. The quality of the water becomes very high in the end, reaching near drinking quality (Magnusson and Norin 2013). Therefore this is suitable for excess water that is discharged into a very sensitive recipient or during remediation of soils that are contaminated.

6.4 Scoring the alternatives

The different alternatives were scored based on the different criteria mentioned above. The different scores can be found in Table 6.1 and Table 6.2. The criterion ”Water Flow Variability” was scored using the AHP method, as explained below. The scores for the different alternatives differ between the 10 m^3/h and the 30 m^3/h flows, since the area needed, costs and capability to handle the water flow variability are not the same. The other parameters have the same scores for both flows. Costs for the different alternatives were calculated using Equation B.3 and Equation B.4 in Appendix B.

Table 6.1: The alternatives and their assigned weights based on the different criteria for the flow of 10 m^3/h. Note that the criteria Water flow variability is not included here (Askmar 2015)(Magnusson and Norin 2013)(Fraktkedjan Väst 2015)(Magnusson 2015)(Vattensystem 2015)(Winge 2015)(Wortelboer 2015).

	Criteria				
Alternative	Space requirement (m^2)	Particle removal (µ)	Ability to remove dissolved metals and pollutants (Yes/No)	Total Cost (SEK)	Need of monitoring (days/year)
1	300	20	No	100 000	1
2	12	60	No	252 000	6
3	7	20	No	720 000	12
4	315	5	No	2 284 000	26
5	49	2	No	4 317 000	365
6	64	2	No	6 468 000	365
7	64	1	No	6 501 000	365
8	64	1	Yes	7 003 000	365

Table 6.2: The alternatives and their assigned weights based on the different criteria for the flow of 30 m^3/h. Note that the criteria Water flow variability is not included here (Askmar 2015)(Magnusson and Norin 2013)(Fraktkedjan Väst 2015)(Magnusson 2015)(Vattensystem 2015)(Winge 2015)(Wortelboer 2015).

	Criteria				
Alternative	Space requirement (m^2)	Particle removal (µ)	Ability to remove dissolved metals and pollutants (Yes/No)	Total Cost (SEK)	Need of monitoring (days/year)
1	300	20	No	100 000	1
2	36	60	No	756 000	6
3	7	20	No	720 000	12
4	315	5	No	3 306 000	26
5	113	2	No	4 763 000	365
6	128	2	No	8 441 000	365
7	128	1	No	8 468 000	365
8	128	1	Yes	9 374 000	365

When using the AHP method, two alternatives at a time are compared to each other and ranked according to how well they fulfill a certain criteria, in this case ”Water Flow Variability” The process is naturally subjective, as it is the assessor that gives an opinion on the relative difference between two alternatives. Even if the decision is backed by data, there is still a large subjective component to the process. The AHP is done in this case due to too small differences between the alternatives to accurately point to an aspect that differs. Therefore, the alternatives are compared in a pair-wise manner, with results shown in Table 6.3a. The key to understanding the numbers and what degree of preference they represent can be seen in Table 6.3b.

After inserting the different characteristics of the alternatives in Web-HIPRE, the program automatically converts the input value to a normalized score. This makes it possible to add the different scores of the different criteria although the unit of the input is not the same. The scores were assumed to vary linearly between the best performing and worst performing alternatives, i.e a linear value function. It is possible to use a piece-wise linear value function or an exponential function, but for simplicity, a regressive linear value function was used for all criteria except the water flow variability since the AHP method was used.

Table 6.3: Description of the AHP processes.

(a) Table showing preferred options relative to another.

Alternative	8	7	6	5	4	3	2	1
8	1	1	1	1	0.33	0.2	0.5	0.2
7	1	1	1	1	0.33	0.2	0.5	0.2
6	1	1	1	1	0.33	0.2	0.5	0.2
5	1	1	1	1	0.33	0.2	0.5	0.25
4	3	3	3	3	1	0.25	7	1
3	5	5	5	5	4	1	7	1
2	2	2	2	2	0.14	0.14	1	0.2
1	5	5	5	4	1	1	2	1

(b) AHP key.

Number	Preference degree
1	Equally preferred
2	
3	Slightly preferred
4	
5	Strongly preferred
6	
7	Very strongly preferred
8	
9	Extremely preferred

6.5 Weighting the criteria

An environmental specialist at the Swedish Transport Administration, Malin Egardt, assigned weights to the identified criteria, with the motivation as follows: ”The lay-out of the remediation technique should be adapted from the site-specific conditions, as the available area and contaminants present on site. We are assuming a normal TRV-excavation without any severe contaminations, some oil and metals bound to particles. The excavation is situated in a densely built area. This is in our meaning the most common scenario” (Egardt 2015). This makes the weights assigned by Malin Egardt applicable to the Marieholm case as well. She was asked to assign 100 points between the three criteria, where the amount reflected the importance between the criteria. 100 point were assigned to the sub-criteria within each criterion, with the same principle. The weights assigned to the different criteria are not changed between the two flows.

The weights were assigned to the criteria as can be seen in Table 6.4.

Table 6.4: The weights assigned to the criteria.

Criteria	Weight	Sub-criteria	Weight
Design considerations	40	Space effectiveness	60
		Water flow variability	40
Contaminant removal	40	Removal of particles	100
		Ability to remove dissolved metals and pollutants	0
Contractor views	20	Cost	40
		Independence of manual monitoring	60

6.6 The combined results

The result from the combined scores and weights for the two flows are shown in Figure 6.5 and Figure 6.6. As can be seen in the figures, the top ranked alternatives for both flows is alternative 3 followed by alternatives 5 through 8 in a group.

Figure 6.7 and Figure 6.8 show the sub-criteria contribution to the result. The sub-criteria sharing the same criterion has the same nuance of either green, purple or blue. The differences in the results between the two flows are small, since the weights assigned to the criteria are the same. As can be seen here, the contribution from the criteria ”Particle removal” and ”Space requirements” are contributing the most to the result, and alternative 3 is performing relatively well in all criteria. Due to its weight of zero, the criterion ”Ability of removing dissolved metals and pollutants” is not present in the figures.

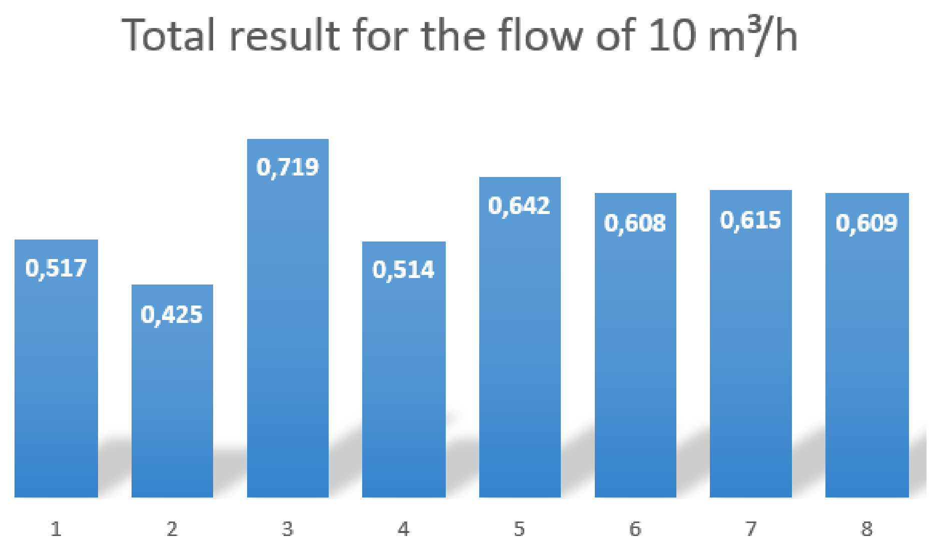


Figure 6.5: The final result for flow 10 m^3/h.

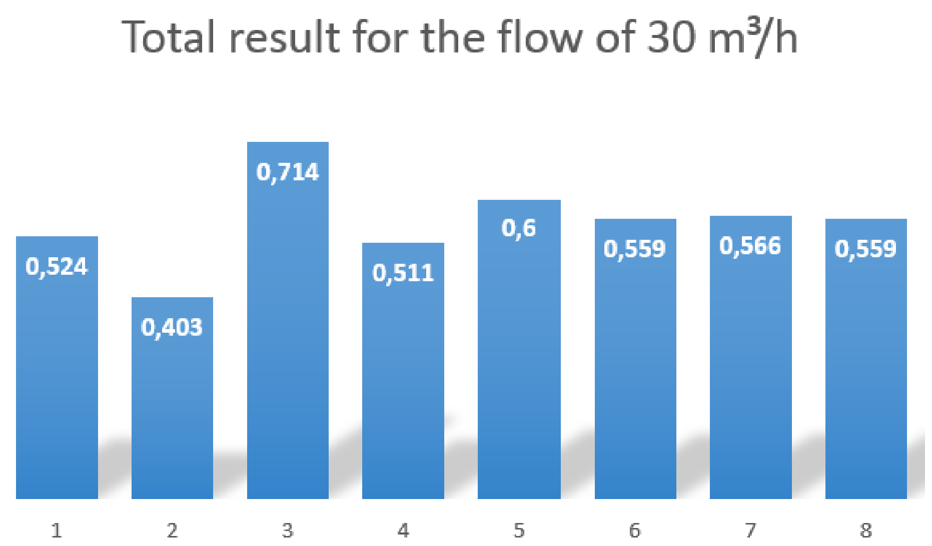


Figure 6.6: The final result for flow 30 m^3/h.

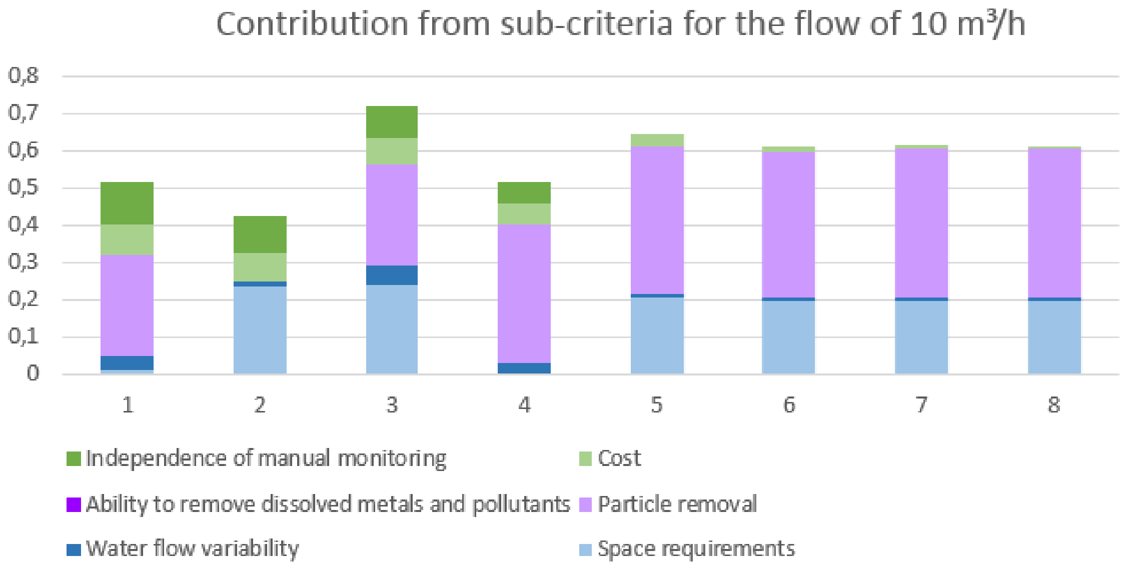


Figure 6.7: Contribution from the different criteria to the result for the flow of 10 m^3/h

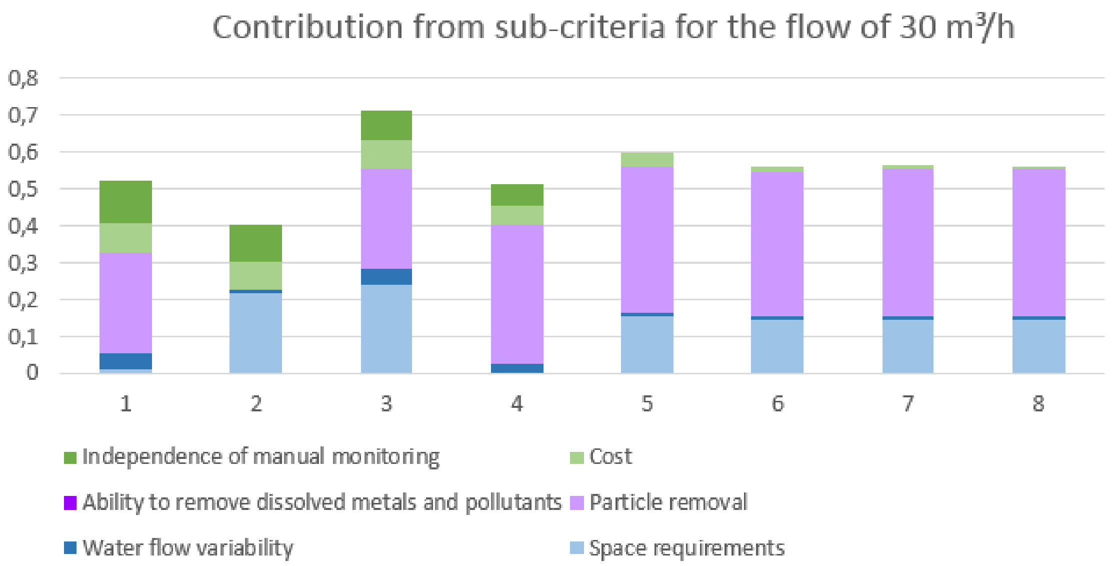


Figure 6.8: Contribution from the different criteria to the result for flow 30 m^3/h

6.7 Sensitivity analysis

The sensitivity analysis showed how the total result varied when the weights of the different alternatives were changed. Since the result from the two flows are similar, as can be seen in Figure 6.5 to Figure 6.8, the sensitivity analysis will focus on the flow of 10 m^3/h. The figures associated with the flow of 30 m^3/h are placed in Appendix C for comparison.

Design considerations

Alternative 3 is the top ranked alternative in this criterion, for most weights. When the weight was lowered to 10 points instead of the original 40, the result changed the top three alternatives, making alternative 2 and 4 the best option. Otherwise, the rank of the alternatives was stable until the weight of the criterion was changed to 85, where alternative 2 would be ranked as the second best alternatives, but alternative 3 was still preferable. Figure 6.9 shows the changes of the different alternatives with changing weight. With regards to this criterion, the top result is not sensitive to change in weights unless the criterion is weighted very low.

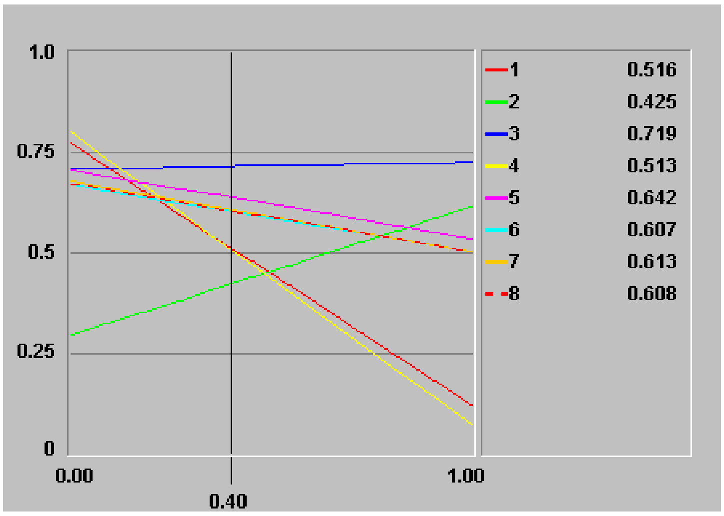
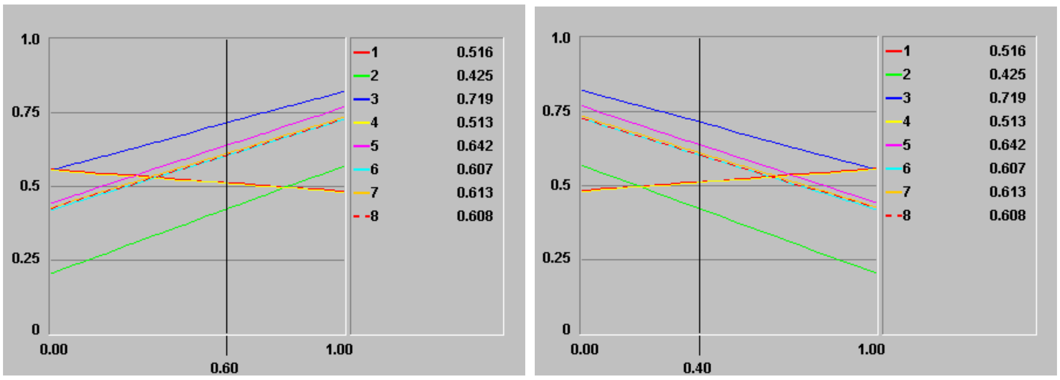


Figure 6.9: Sensitivity analysis for Design considerations. The result from this criterion is non-robust.



(a) Space requirement

(b) Water flow variability

Figure 6.10: Note that the two sub-criteria in a) and b) are mirror images of each other.

Space requirements

For this criterion, alternative 3 is the most preferable one. If the importance of this criterion is lowered to below 30 instead of 60, the rank of the alternatives would change. When the weight is smaller than 30, alternative 1 and 4 are ranked as the second and the third best alternative. This can be due to the large area that the sedimentation ponds need. See Figure 6.10a for more details.

Water flow variability

Alternative 3 is the top alternative in this criterion regardless of weight. If the weight is changed to 70, alternatives 1 and 4 are ranked higher than alternatives 5 to 8 compared to the present rank and weight shown in Figure 6.10b. Alternative 1 and 4 will shift place with alternatives 5 to 8 at 70 points, making the result of the criterion sensitive to the weighting.

Contaminant removal

At the original weight of 40 point, the favourable alternatives were 3, 5 and 6 to 8. The ranking of the alternatives changes internally as the assigned weight is higher than 50, where alternative 5 to 8 are more preferred compared to the result of the current weight. The conclusion is therefore that the result with regard to this criterion is sensitive to the weight assigned, as can be seen in Figure 6.11.

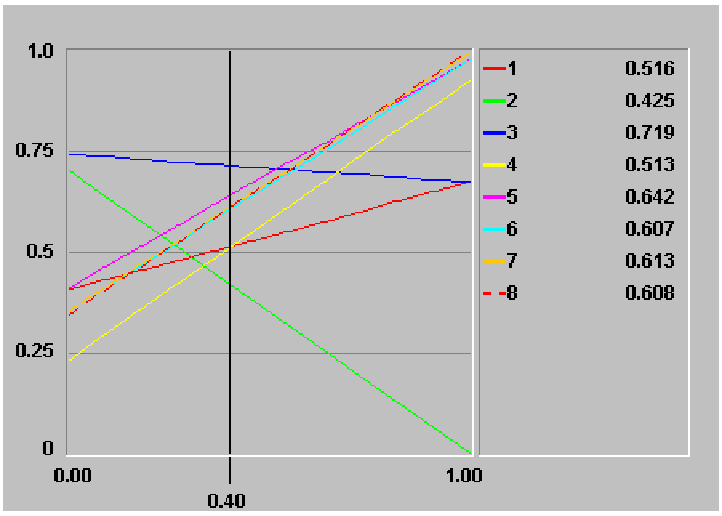


Figure 6.11: Sensitivity analysis for Contaminant removal. The result from this criterion is non-robust.

Contractor views

For this criterion it is evident that alternatives 1 and 2 increase sharply with an increased weight of the Contractor views. Alternatives 3 and 4 are also increasing slightly, while alternatives 5 through 8 are decreasing sharply. With an increase weight of 40 points, both alternative 1 and 2 have higher scores than all the other alternatives except alternative 3. At a weight of 65 points, alternative 1 has passed alternative 3 to become the best alternative. Figure 6.12 shows this analysis.

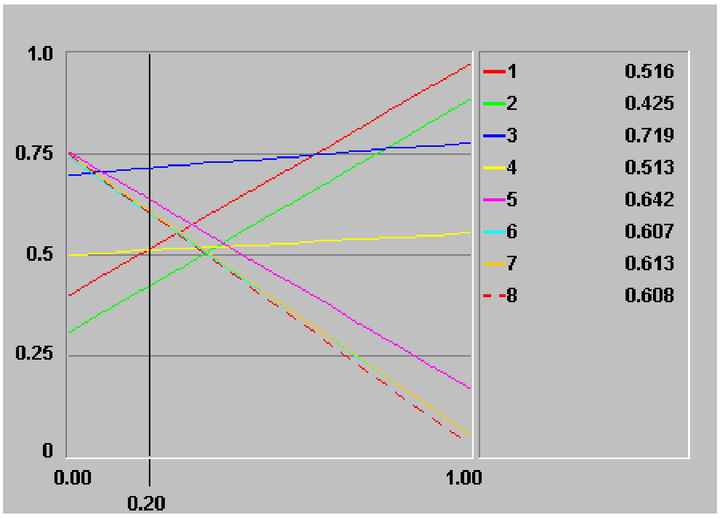
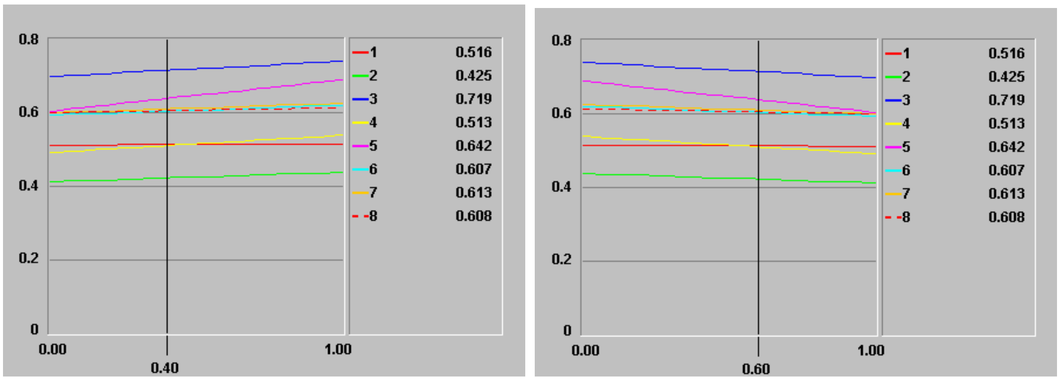


Figure 6.12: Sensitivity analysis for Contractor views. The result from this criterion is non-robust.



(a) Cost

(b) Independence of manual monitoring

Figure 6.13: Note that the two sub-criteria in a) and b) are mirror images of each other.

Cost

The weight assigned to this criterion is 40. The consistently highest ranked alternative is alternative 3, followed by alternative 5 and 7, 6 and 8 in a cluster. The score for this cluster and for alternatives 1 and 4 change very marginally with increasing weight, but does not affect the overall result. The analysis can be seen in Figure 6.13a.

Independence of manual monitoring

Since the Cost and Independence of manual monitoring sub-criteria are mirror images of each other in the sensitivity analysis, the conclusions from the above analysis are valid here as well. Alternative 3 is still the alternative with the highest score, regardless of weight. It is followed by alternative 5 and 7, 6 and 8 in a cluster. The scores do not change to any significant extent, and so the overall result does not change depending on the weights, as can be seen in Figure 6.13b.

The sensitivity of the model as a whole

The result can be seen as robust, since alternative 3 is the best option in four of five sensitivity analyses.

To make the result less sensitive, the uncertainty in scoring the alternatives regarding criteria such as water flow variability and cost should be reduced. By adding a retaining reservoir, a cistern or a container it is possible to reduce the flow tops for the techniques with a fixed flow. This would decrease the uncertainty regarding the water flow variability. The costs for some alternatives are dependent on how many bag filters and filter material are needed and the rate of change, as well as the amount of additives for precipitation and flocculation that is needed. These variables are hard to estimate since they require testing of the water.

6.8 Recommendations based on the MCDA

The result, as can be seen in chapter 6.6, indicate that the most appropriate remediation alternatives were alternatives 3 and, since they had very similar scores, 5 through 8 in a group. Alternative 2 - Sedimentation container, was the worst alternative with the lowest scores, although this alternative is a common technique used to handle the problem with excess water. Alternatives 5 through 8 are ranked highly and have very small differences between them, mainly in the cost criterion, and are therefore unlikely to be chosen for the project at Marieholm. The analysis shows also that every alternative can be the most appropriate choice, depending on the weighting, except alternatives 2, 6 and 7.

7
Discussion

The MCDA model gave the result of the best performing alternative with regards to the chosen criteria. The overall results for the ranking of the alternatives were the same for both flows, but with small differences in the scores between the first flow of 10 m^3/h compared to the second flow of 30 m^3/h. The top alternatives for both flows were alternative 3 and followed by a group of alternatives 5 through 8, as these more complex alternatives were very similar in their scores. The model was adapted for the specific site conditions at Marieholm, but can be modified to suit other sites as well. The result of the model is sensitive to changes in the weighting of the different criteria according to the performed sensitivity analysis. The weighting will reflect the views of the Swedish Transport Administration, the different site specific needs and environmental requirements. For example, a site in central Gothenburg would not have the same weighting for the design considerations criterion as a site with large open spaces where the available space is no issue.

The results from the MCDA were somewhat unexpected. The two examined flows gave similar results, which was not expected compared to the hypothesis. The small differences in the results may be due to the chosen flows, meaning that if the maximum flow was higher and the minimum flow was lower, the differences in the results might have been more distinct. Alternative 1 was expected to be ranked higher since it is a simple and relatively inexpensive alternative, but due to the weighting it received a low total score. Alternative 2 has a very low performance score in the criterion contaminant removal as can be seen as the yellow field in Figures 6.7 and 6.8. Alternative 3 was not expected to be the unquestionably best alternative in the start of the thesis, but it became clearer that it could be a valid option as the thesis progressed and more information regarding the case study site was retrieved. It was found that the model is possible to use as a support in decision making for the Swedish Transport Administration.

The choice of studied flows was based on calculations of the upper mean flow for the month with the most intensive flow, which was January, as well as the highest flow measured during the same month. Thus the flows of 10 m^3/h and 30 m^3/h were chosen. The aim was to see if the most preferred alternatives would change with changing flows, which was the reason for choosing two different flows. Another way to calculate the flow is by calculating the flow that storm water drains should be able to withstand using a rain intensity with an average recurrence time of five years, which can be calculated with Equation B.2. However, it is not economically reasonable to scale the alternatives to a peak flow. This, together with lacking information about the site, was the reason this method was not applied.

The MCDA was performed by following the steps of a multi-criteria decision analysis, presented in ”Multi-criteria analysis: a manual” (Communities and Local Government 2009). When scoring the different alternatives against the criteria, a direct score was calculated by the java applet Web-HIPRE. The applet made it possible to use different methods of scoring, but the knowledge about the characteristics of the different remediation techniques was limited which caused uncertainties in the model. When scoring the alternatives against the criterion water flow variability, the AHP method was used. The scoring in this case was based upon our knowledge and subjective judgement, which means that other practitioners might score the alternatives differently. This uncertainty would however be removed if a retaining reservoir is applied to all alternatives. This would lead to the removal of the water flow variability criterion, due to the elimination of water flow variability in the processes. If this would be done, the top alternatives would stay the same, while alternative 1 and 4 would perform the worst, since the space effectiveness and particle removal criteria would have a higher importance in the final result. It is important to note that if the criterion water flow variability is removed, new weights need to be assigned, and the final result might differ form what is mentioned here.

Since the differences between the two flows were small, an alteration to the case study would be interesting to investigate. Two sites with different properties and site locations could be compared using the model, to examine if there are any differences between the results of this thesis and a new study. This would demand different weighting and therefore a different result should be expected. This would also test the applicability of the model further.

There are uncertainties within the model, regarding the scores of the different criteria. The space requirements criterion has small uncertainties, since the area required for the different remediation alternatives are defined by the providers of the different techniques. The exceptions are the size of the geotextile tubes, that can be made entirely according to specifications set by the purchaser, and the sedimentation pond. In this study two very rough estimations of the sizes for the geotextile tubes were made, one for each flow. The space required for the sedimentation pond is based on the assumption that the pond has an elongated shape, for the most effective removal of contaminants (shape J, Figure 6.2). If the shape is different than the the longest one, the area needed for the pond will likely increase. The area of the pond was set to the area of the actual pond at the site, which was 300 m^2, so that it could theoretically handle 60 m^3/h. By using Equation B.2, a more correct flow could be determined, from which a sedimentation pond could be dimensioned.

The criterion that affects the result the most is particle removal. The degree to which the different techniques are able to remove particles is a theoretic value and relates to the particle size that can be removed. In reality, turbidity levels may be more accurate to use, since there is a demand from the Environmental Administration to keep it under a certain level. Due to the many variables determining the level of turbidity as well as lack of information from suppliers of water remediation/purification units, particle size was used as the unit of measurement instead. In bigger projects with large budgets, it could be reasonable to perform tests in real conditions to determine the real efficiency of the different techniques, and thus the uncertainty regarding this matter can be reduced. For smaller projects where the budget is limited, the particle size can be seen as an acceptable proxy. Another criterion that affects the result, though not as much as the particle removal is the criterion water flow variability. Literature studies found that all alternatives handled flow variations poorly, but by adding a retaining reservoir to the site it would be possible to reduce the impacts from a variable water flow. This could lead to a redundancy of this criterion in the model, and could therefore be removed. If the criterion is to be kept, test and experiments should be performed for all alternatives to receive accurate data, as mentioned above for the particle removal criterion.

The independence of manual monitoring criterion was estimated very roughly, given that no information was found on the amount of maintenance or supervision needed. This meant that what information about the processes was gathered had to be enough to determine the frequency of labor. This could be reduced by inquiring about similar projects that have used the same or similar methods.

The costs could be more exact when taken into account in the model, like including the labour cost for the alternatives that need attention and supervision. This was hard to estimate, since it requires more knowledge about the operation of these techniques and their associated costs than was available. The cost of the precipitation and flocculation agents are omitted from the calculations for all alternatives that have a precipitation/flocculation step. The costs are excluded due to the uncertainties of the amounts used as well as the type of agent. The costs of sand filter material and bag filters have been used, but the rate at which the filter material or bag filters need to be replaced depends on the turbidity of the water. This makes it difficult to estimate an accurate rate of replacement, so a rough estimation by the supplier has been used. A rough estimation of the size and rate of replacement of the geotextile bags was performed, due to the same uncertainties as mentioned above. A variation in turbidity could change the rate of replacement, which in turn could cause a large variation of several tens of thousands SEK over the five year period. Further, the need of manual monitoring is also an uncertainty. The scores assigned to the different alternatives are estimations based on how often and how many days per year the alternative need attention, but another dimension of this is if the personnel handling the remediation facility need some special education. This aspect can affect both the cost and the amount of monitoring needed. Since the total costs of the different alternatives vary from one hundred thousand to several million SEK, it is reasonable to discuss whether or not some kind of limit should be applied to this criterion. A proposal for such a limit could be a percentage of the total budget for the project as a whole, but due to the lack of experience with these kinds of projects, such a limit was exempted from the study.

To reduce uncertainties within the different criteria, probability distributions could be produced as in the case of the contaminated sediment in a Norwegian fjord.

A criterion that can be added to manual monitoring is the need of qualified or expert personnel for the different alternatives, which could indicate a higher operational cost. Also, as mentioned, better information about the costs for the different alternatives should be added into the model. Another aspect that might be worth considering is the availability of the components of each method. There are for example only two lamella clarifiers in Sweden available for rent, whis is a constraint on the ability to choose alternative 3 and other alternatives with a lamella clarifier as a component.

The guideline values set by the Environmental Administration in Gothenburg are the acute toxic levels from the directive 2013/39/EU. These values are meant to secure the water quality from instantaneous pollution, and the question can be raised towards the suitability of the strict levels these guidelines brings, since the discharges from excavations are rather long term. Also, the sensitivity of the river, stream or water body the excess water is released into should be reflected in the guideline values.

The thesis can be seen as an extension to the work done by Magnusson and Norin. Their report ”Hantering av länsvatten i anläggningsprojekt: Användbar teknik och upphandlingsfrågor” lists different remediation techniques, which have worked as a foundation for the model and its alternatives. This report is built on their work and develops a tool for the Swedish Transport Administration to choose the most suitable remediation technique for a specific site.

8

Conclusions and recommendations

The main conclusions from this study are:

- The MCDA model created was found to be a useful support tool for the Swedish Transport Administration in the process of finding a suitable remediation alternative. The MCDA made it possible to include several aspects into the model, and the model is possible to adapt to different sites and site conditions.
- As of today, the sedimentation container is the most common remediation method in Sweden, due to its simplicity and low cost.
- Regarding the case of Marieholm, alternative 3 - lamella clarifier, was found to be the most suitable with regard to site conditions, while alternative 2 - sedimentation container was the least preferable.
- The hypothesis regarding the flows of 10 m^3/h and 30 m^3/h was proven wrong, the results did not differ.
- Uncertainties regarding particle removal could be reduced by tests in real conditions for larger projects. In smaller projects, particle size can be used as a proxy.
- It is possible to add more critera to the model, one example of this is availability of the techniques, and the need of educated personnel.

An interesting aspect to investigate further is the application of the model on different sites to see if the result would differ. These sites should have different locations and properties. Also, to reduce mentioned uncertainties in the model, the remediation techniques should be tested in real conditions and further knowledge of the different costs associated with the remediation techniques should be acquired.

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A

Background to guideline values

Already in the 1970a and 80s, citizens of the European Union showed interest and expressed concerns regarding the quality of the water and problems connected to water. The concerns of the citizens was the basis for the Water Policy, and was confirmed by a survey in 2012 called the Water Barometer, which recognized that a majority of the respondents, 68%, believe that water problems are serious (Gallup Organisation 2009). To handle the different problems, the European Union has adopted the Water Policy which aims to protect clean waterbodies, and make already polluted waters clean again. The Water Framework Directive was adopted in December 2000 as an operational tool for the Water Policy, to set objectives for the future.

> "the Commission presented a Proposal for a Water Framework Directive with the following key aims:
>
> - expanding the scope of water protection to all waters, surface waters and groundwater
> - achieving "good status" for all waters by a set deadline
> - water management based on river basins
> - "combined approach" of emission limit values and quality standards
> - getting the prices right
> - getting the citizen involved more closely
> - streamlining legislation"
>
> (European Commission 2015)

An approach to reach the overall goal of improved water quality in the European Union is the joint implementation, where member states should adapt their regional and national laws to the Water Directive. The Swedish implementation of this can be seen nationally in the Environmental Code, and in the Gothenburg region as the guideline values from the Environmental Administration.

To be able to control the chemical status of the different waterbodies, the directive 2013/39/EU has listed 45 substances as prioritized, 21 of which are marked as hazardous (Council of European Union 2013). The directive also sets environmental quality standards (EQS), for the prioritized substances. The EQS are divided into two different standards, an annual average (AA-EQS) and a maximum allowed concentration (MAC-EQS). The AA-EQS aims to establish the quality of the aquatic environment on a long term perspective while the MAC-EQS has the purpose to limit the instantaneous pollution releases. The AA-EQS is a lower value than the MAC-EQS.

B

Equations and calculations

Stokes formula for the settling velocity of a particle

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

v_s = settling velocity (m/s)

g = gravitational constant (m/s^2)

ν = kinematic viscosity of water (m^2/s)

ρ_s = density of the particle (kg/m^3)

ρ_w = density of the water (kg/m^3)

d^2 = diameter of the particle (m)

Formula for calculating the stormwater flow

$$q = A \times \varphi \times i(t) \tag{B.2}$$

q = stormwater flow (l/s)

A = runoff area (ha)

φ = runoff coefficient

$i(t)$ = dimensioned rainfall intensity $(l/s \times ha)$

t = duration of rainfall

Formula for calculating the cost of geotextile bags used during the project

$$C = p \times e \times V \times f \times y \tag{B.3}$$

C = total cost for the geotextile bags (kr)

p = price per cubic metre dewatered ($euro/m^3$)

e = exchange rate from EUR to SEK ($kr/euro$)

V = volume of the geotextile bag (m^3)

f = how often the geotextile bag needs to be replaced ($year^{-1}$)

y = duration of project ($year$)

Table B.1: Variables for equation B.3

	p	e	V	f	y	C
10	45	9,25	18	6	5	225 300
30	10	9,25	60	6	5	166 510

Formula for calculating the cost of filter material and filter bags used

$$C = n \times w \times p \times f \times y \tag{B.4}$$

C = total cost for used filters (kr)

n = number of filters

w = number of units needed for a filter ($unit$)

p = price per filter unit ($kr/unit$)

f = number of times that filter needs changing per year ($year^{-1}$)

y = duration of project ($year$)

Table B.2: Values for variables from equation B.4 for the 10 m^3/h case

	n	w	p	f	y	C
Alternative 4	2	1	99	365/3	5	120 450
Alternative 6	3	1	7670	3	5	87 900
Alternative 7	2	1	99	365/3	5	120 450
Alternative 8	2 & 2	1 & 9	99 & 1970	365/3 & 2	5	652 350

Table B.3: Cost for 10 m^3/h techniques

	Starting cost	Renting cost	Unit purchasing	Total 5 years (SEK)
Sedimentation pond	100 000	0	0	100 000
Sedimentation container	0	70 SEK/day	0	252 000
Lamella clarifier (flat bottomed)	0	3 000 SEK/week	0	720 000
Lamella clarifier (twin hoppers)	0	4 000 SEK/week	0	960 000
Chemical precipitation and flocculation	0	12 000 SEK/week	0	2 880 000
Pressurized rapid sand filter	10 000	1125 SEK/day	2 930 SEK	2 151 025
Pressurized bag filter	10 000	1125 SEK/day	99 SEK	2 183 575
Pressurized bag filter & activated carbon filtration	10 000	1125 SEK/day	99 & 1 970	2 685 475
Geotextile bag	0	0	810 EUR	225 300

Table B.4: Total costs of the different alternatives

Alternative	Total cost (SEK)
1	100 000
2	252 000
3	720 000
4	2 283 575
5	4 077 300
6	6 228 325
7	6 260 875
8	6 762 775

Table B.5: Values for variables from equation B.4 for the 30 m^3/h case

	n	w	p	f	y	C
Alternative 4	3	1	99	365/3	5	180 675
Alternative 6	2	1	2930	3	5	153 400
Alternative 7	3	1	99	365/3	5	120 450
Alternative 8	3 & 2	1 & 23	99 & 1970	365/3 & 2	5	1 086 875

Table B.6: Cost for 30 m^3/h techniques

	Starting cost	Renting cost	Unit purchasing	Total 5 years (SEK)
Sedimentation pond	100 000	0	0	100 000
Sedimentation container	0	70 SEK/day	0	252 000
Lamella clarifier (flat bottomed)	0	3 000 SEK/week	0	720 000
Lamella clarifier (twin hoppers)	0	4 000	0	960 000
Chemical precipitation and flocculation	0	12 000 SEK/week	0	2 880 000
Pressurized rapid sand filter	12 000	1925 SEK/day	7670 SEK	3 678 525
Pressurized bag filter	12 000	1925 SEK/day	99 SEK	3 705 800
Pressurized bag filter & activated carbon filtration	12 000	1925 SEK/day	99 & 1 970 SEK	4 612 000
Geotextile bag	0	0	600 EUR	166510

Table B.7: Total costs of the different alternatives

Alternative	Total cost (SEK)
1	100 000
2	756 000
3	720 000
4	3 805 800
5	4 762 510
6	8 441 035
7	8 468 310
8	9 374 510

Table B.8: Areas per technique for the 10 m^3/h case

	Area/unit	Number of units per alternative							
Technique		1	2	3	4	5	6	7	8
Sedimentation pond	300	1			1				
Sedimentation container	6		2			2	2	2	2
Lamella clarifier	7			1		1	1	1	1
Filtration container	15				1		1	1	1
Chemical dosing unit	15					1	1	1	1
Geotextile tube	15					1	1	1	1

Table B.9: Areas per technique for the 30 m^3/h case

	Area/unit	Number of units per alternative							
Technique		1	2	3	4	5	6	7	8
Sedimentation pond	300	1			1				
Sedimentation container	6		6			6	6	6	6
Lamella clarifier	7			1		1	1	1	1
Filtration container	15				1		1	1	1
Chemical dosing unit	15					1	1	1	1
Geotextile tube	55					1	1	1	1

C

Sensitivity analysis figures

C.1 Flow 2 - 30 m^3/h

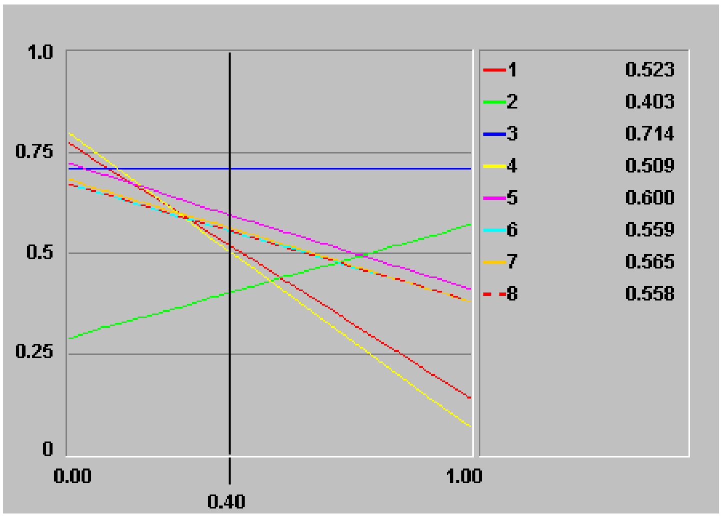

Figure C.1: Sensitivity analysis for Design considerations.

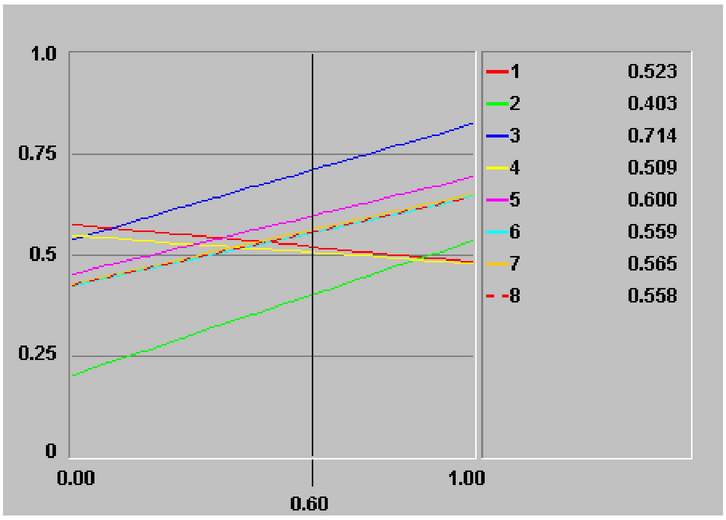

Figure C.2: Sensitivity analysis for Space requirement.

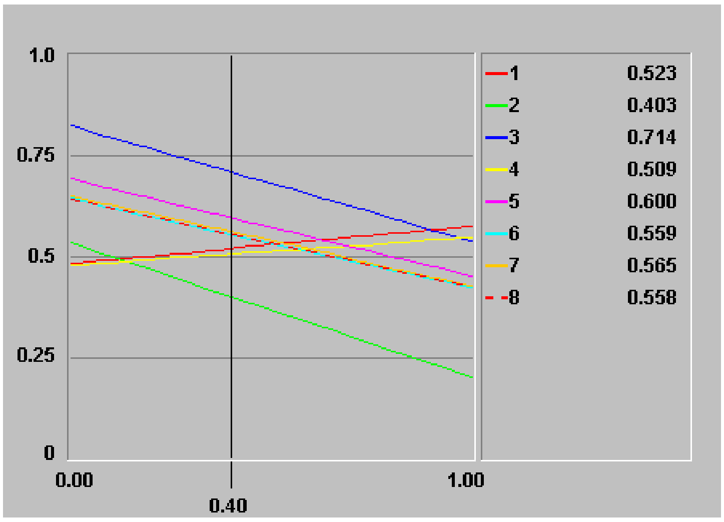

Figure C.3: Sensitivity analysis for Water flow variability.

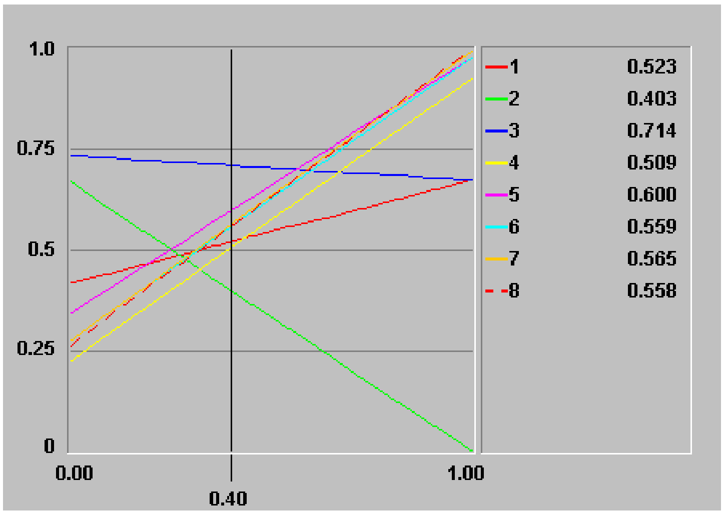

Figure C.4: Sensitivity analysis for Contaminant removal.

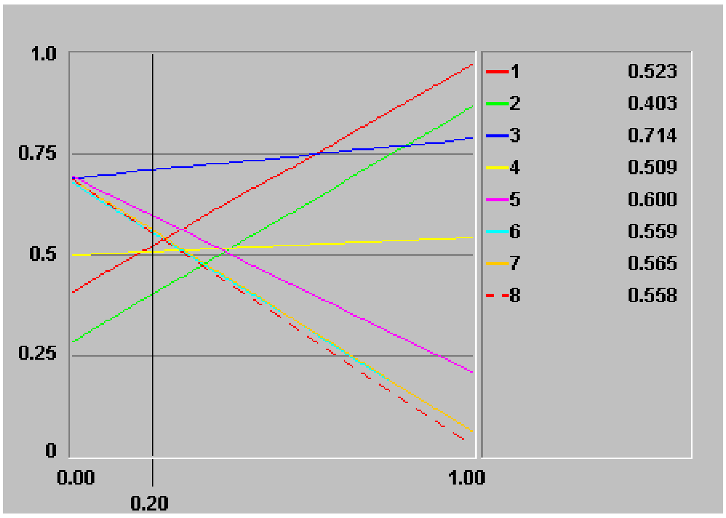

Figure C.5: Sensitivity analysis for Contractor views.

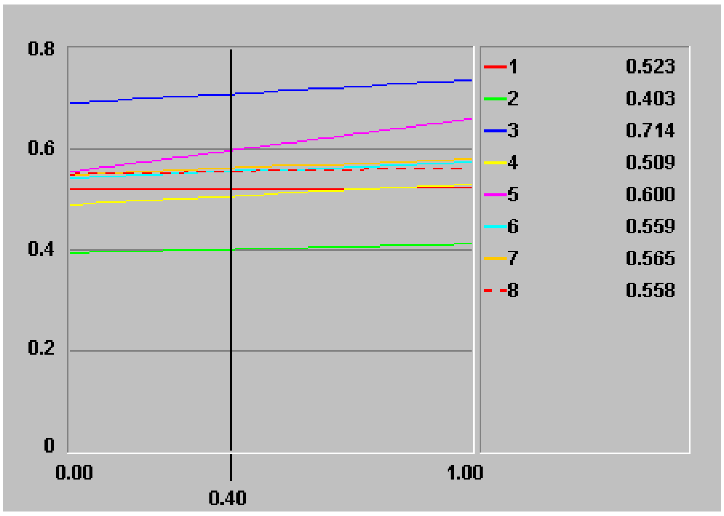

Figure C.6: Sensitivity analysis for Cost.

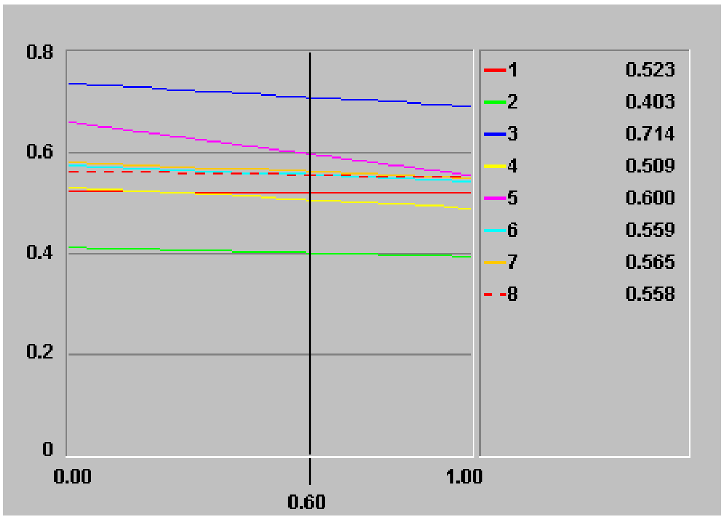

Figure C.7: Sensitivity analysis for Independence of manual monitoring.