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Multi-criteria decision support analysis for sustainable water treatment techniques during tunnel construction

A case study in the Vasastan tunnel at Västlänken Station Haga, Gothenburg.
Master's thesis in the Master's Programme Infrastructure and Environmental Engineering.

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Master's thesis ACEX30-24

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Abstract

Urbanization and construction projects, including tunneling activities, contribute substantially to water quality degradation worldwide. Consequently, there is an increasing need for new measures to address water quality concerns, particularly within the European Union, where there is more acknowledgement about this need. In cities like Gothenburg, escalating traffic volumes and limited road network space drive a surge in tunneling projects, potentially threatening aquatic environments. The construction phase of tunnels produces wastewater that contains pollutants coming from the construction site; this water needs to be treated before it is released into water bodies or stormwater systems. However, budgeting for water treatment proves challenging due to fluctuating costs and dynamic construction site activities. This research explores alternative solutions for wastewater treatment during tunnel construction, considering ecological, monetary, and site-specific perspectives. The study comprehensively evaluates and compares treatment alternatives using a Multi-Criteria Decision Analysis (MCDA) approach. By investigating existing treatment facilities and innovative techniques in the Vasastan tunnel at Västlänken Station Haga, Gothenburg, the research aims to identify the most sustainable and suitable solution for treating polluted tunneling wastewater. After the project was conducted, it was found that the tunneling wastewater in the case study had multiple pollutants and contaminants that had to be removed. It was also found that there are multiple techniques to accomplish the separation of pollutants from the tunneling wastewater; and there is not such a thing as a "perfect" or ideal treatment for the case study. Combining different techniques and good sedimentation are key to accomplishing a proper treatment of tunneling wastewater. The findings contribute to the design and implementation of necessary improvements in wastewater treatment systems, promoting environmentally friendly and cost-effective practices. Through thorough examination and evaluation, the study underscores the importance of addressing water treatment challenges to ensure sustainable development.

Keywords: Water quality, Tunnel construction, Wastewater treatment, Multi-Criteria Decision Analysis (MCDA), Sustainable development.

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1 Introduction

Nowadays the global economy and social health are being affected by unsustainable human development and globalization, directly affecting the water bodies´ quality. According to the United Nations World Water Assessment Program, urbanized areas are the principal reason why water quality worldwide is deteriorating (WWAP 2015); the different construction projects highly contribute to the water quality decay in the water bodies. Therefore, the need to implement new measures has increased and the awareness of needed water quality improvements of the different countries within the EU has grown.

As in many other big cities worldwide, traffic volumes in Gothenburg have increased progressively during the last decade and the available space for the road network is limited. Tunneling is being implemented more commonly nowadays and the increment in road construction may seriously affect the aquatic environment. The construction phase of these tunnels involves several manmade and natural sources of water-borne pollutants (NPRA 2011), consequently, this makes pollutant management and treatment a huge and important part of the construction plan. According to the Swedish Transportation Administration, the requirements on wastewater quality released from construction sites in Sweden are increasing and wastewater treatment facilities on sites are taking up more and more resources.

The different costs of wastewater treatment facilities and operations can fluctuate depending on the site and the specific work that is being done. Budgeting the water treatment for a project is therefore difficult to do in advance and it is often more expensive than the contractor assumes in the tender phase. As the tunnel project develops, different ongoing activities make the construction site dynamic. These activities, such as drilling, blasting, and grouting, among others, generating wastewater in various sectors of the construction site, give opportunities to make changes and improvements of the water treatment system used during the construction period. Previously, it has been noted that sustainable wastewater management on construction sites is strongly regulated by financial and legal aspects; sometimes poor understanding and communication between municipal departments and the companies make this duty complex and with multiple factors that play a role in the performance of the water treatment systems. Multiple improvements may appear throughout the project, and it is deeply important to develop/upgrade the existing techniques.

To achieve the goal to treat the water in the most sustainable and suitable way, reducing emissions, costs, and risks for the environment and people, measures have to be carried out. There are several possibilities to improve the different water treatment steps in tunnel construction, and it is crucial to evaluate and compare the different options that the technology provides nowadays in order to select the solution that best suits each specific area. Different measures that may be applied are e.g. multiple filter combinations, chemical mixes, and other treatment solutions (Kazimieras et al., 2015) are usually implemented without considering all the different variables, leaving opportunities for optimization of the processes. The performance of each alternative, including the final solution, is addressed using a Multi-Criteria Decision Analysis (MCDA) approach.

In conclusion, there is a need to study the water treatment techniques at the Västlänken construction area to design and implement the required improvements of the wastewater treatment facilities, making the most suitable and sustainable setup for the study area.

1.1 Aim and goals

The aim of the thesis was to research the sustainability of treatment methods for polluted wastewater emitted during tunnel construction, and all the dimensions of sustainable development were taken into consideration besides the technical aspects. The research was performed through a multi-criteria decision analysis (MCDA) by the investigation of existing treatment facilities at the Västlänken Station Haga in Gothenburg and comparing them with new innovative techniques, focusing on technical design, pollutant removal efficiency, sustainability, maintenance, and cost for investments and running costs. This research project explores different alternative solutions that could be implemented considering ecological and monetary perspectives and considering the site conditions. The impact of the reduction of pollutants by the wastewater treatment facility was investigated to better understanding the need for such a complex treatment facility, but also to study if there are alternative combinations to make the water treatment process less complex, more sustainable, and cheaper. The specific objectives were to:

1. Gather all the information about the study area to review the local environmental regulations and policies, the technical, and the economic aspects of the site in order to understand its current situation.

2. Conduct a literature study on the current state of the construction of water generation and management in the study area.

3. Identify the ”best management practices” (BMP) for water treatment that would be included in the MCDA, considering different indicators.

4. Establish categories for BMP evaluation that include social, environmental, economic, and technical criteria.

5. Develop an MCDA process that could support future decision-making processes for the water treatment at construction sites.

This project is not taking the MCDA results as the final stage of the investigation, instead this study intends to use the MCDA results as a tool for decision support that helps us integrate the multiple variables that our decisions must contemplate. The idea is to analyze these results and integrate them with other parameters such as results from water samples quality analysis, to come up with the final solution and conclusions of the project. This study will contribute to further decisions on the construction site and to future construction projects.

1.2 Research questions

The following research questions were answered:

1. What are the different pollutants that can occur in wastewater from tunnel construction and which of these can be found in the case study? What is the current level of contaminants and different pollutants in the study area?
2. Which treatment techniques can be performed for tunneling wastewater treatment? Are there any innovative technologies that can be used to treat tunneling wastewater?
3. What are the pollutant removal efficiency, costs, advantages/disadvantages, and maintenance requirements for water treatment techniques implemented at tunnel construction sites?
4. Which is the most sustainable and suitable solution for the treatment of polluted tunnel water at Vasastan, Station Haga?

1.3 Hypotheses

After gathering all the information from sampling campaigns and literature review, a multi-criteria decision analysis was used to compare different treatment options and support future decision-making processes that could lead to the implementation of long-term and cost-efficient wastewater treatment options in tunnel construction.

The hypothesis was that a few specific aspects would be crucial to an effective and sustainable wastewater treatment system. The aspect of reducing suspended materials from the tunneling wastewater at an early stage was believed to be crucial to the sufficient treatment of pollutants.

1.4 Limitations

Water management in tunnels is complex where process water, groundwater, in-leakage, and precipitation all play a crucial role in the construction site. This thesis will solely focus on water in the tunnel and how it reaches the wastewater treatment facility and then gets discharged in the combined sewer system of Gothenburg. The thesis will not consider the effect that the contaminated water in the tunnel has on the surrounding area. The focus will be on water in the tunnel and how it affects the circumstances inside the tunnel. Commonly used water treatment solutions cannot be implemented in this project due to reduced space. Other solutions, such as rain gardens or other vegetation techniques, are not an option due to the lack of space or sunlight inside the tunnel.

2 Theory

This chapter describes the fundamental concepts of the study project, emphasizing environmental regulations/policies in Sweden for construction water, water tunneling generation, and the different water treatment techniques for tunnel construction. The approach of the selection procedure for the best treatment solution was chosen and is described as well.

2.1 Water quality management and regulations in Sweden

In 2004 the Swedish environmental law adopted the Water Framework Directive (WFD) implemented by the European Union in 2000 (Directive 2000/60/EC) (European Commission, 2015). The main idea of this directive is to ensure the high quality of the water bodies within the European Union, this directly impacts urban areas, and different water treatment techniques had to be implemented to fulfill the requirements.

One of the main targets of the Water Framework Directive is to Identify and assess surface water bodies at risk (WISE, 2008) and sets the goal of achieving a “good status” for all European surface waters and groundwater bodies by 2015. Different studies and estimations conclude that more than 40 percent of the water bodies in the EU do not meet the 2015 objective; since this target is still far away from being reached, the new plan is to get it by 2027. Moreover, Sweden’s Parliament currently has the ”16 Swedish Environmental Quality Objectives” (Swedish EPA, 2009). Most of these objectives are directly related to the water quality for example, number 7 (Zero Eutrophication) which directly depends on the amount of nutrients that are discharged into the water, as construction projects usually contribute with high concentrations of nutrients in the tunneling water. Nevertheless, these goals’ horizon is in 2027, and none of them will be achieved considering the regulations of the past few years; that is the reason why the Swedish government has increased the requirements and regulations of water treatment. These new regulations aim to ensure high-quality standards of water management and consider the need to fulfill these policies: It is mandatory to implement new technologies and treatment techniques in order to achieve the environmental objectives.

2.2 Water pollutants generated from tunnel construction

In general, there are multiple waterborne pollutants related to tunneling. When it comes to water pollutant generation it usually includes different compounds such as some toxic metals, acidic runoff, suspended particles, oil, polypropylene fibers (PP), chemicals, radioactivity, nutrients (nitrogen, phosphorus), and some others (Kruuse-Meyer, 2006). This section explains the different pollutants found in tunneling water and how these compounds can be harmful to the environment.

Suspended materials in the tunneling water are a huge concern in terms of water pollution. This fine material is usually a combination of rock particles and clay coming from drilling and blasting. The harmful consequences of suspended material include an increase of turbidity in the water, temperature changes, less sunlight penetration, channel infilling, covering food sources for benthic invertebrates, changing in spawning conditions. These blast materials can also be splintery with multiple edges, representing a danger for the animals such as damage to fish gill tissue if released into the environment (Bilotta & Brazier, 2008).

The natural rock that is being drilled/blasted could be the origin of toxic metals, radioactive compounds, and acidic runoff emitted directly into the water. Rock weathering is a natural process that sometimes can produce acidic rock drainage when it has high contents of sulfide minerals. After being exposed to air and water, oxidation of metal sulfides (often pyrite, FeS_2) within the rock generates sulphuric acid (Hindar et al., 2010). This acidic runoff can wash out large quantities of aluminum, iron, and other harmful or lethal metals for aquatic organisms such as fish. On the other hand, rock can contain high amounts of FeS_2, metals, and Radon (Rd). Sulphuric acid is formed when different compounds such as aluminum react with water and oxygen causing expansion and decomposition of the rock followed by acidic runoff containing toxic metals such as cadmium, chromium, nickel, zinc, lead, rubidium, and some others. Radon can decompose into radioactive substances including radium. The harmful effects of radon on humans and mammals include specific organ toxicity, neurotoxicity, DNA damage/carcinogenicity, reproductive toxicity, and immunotoxicity (Meland et al., 2013).

High pH is a common problem in tunneling water. Different materials usually make the water alkaline (Alabaster et al., 1982). The usage of cement-based grout and shotcrete will increase the tunneling wastewater pH. When an organism is exposed to pH above 9 for a long-time exposure, the living being can start experiencing complications in its well-being. A pH above 11 is lethal for aquatic organisms. The tunneling water will be diluted and the pH lowered when discharged to the recipient. On the other hand, the pH of acidic runoff will increase when it is diluted with water of a high pH for example in a pond. Dilution factors and the recipient's tolerance limit are important factors that must be considered.

The main problem related to nutrients is ammonia formation which may cause eutrophication in receiving water. Nitrogen in the form of ammonium usually originates from explosives, a considerable source of nitrogen-containing compounds during the construction period (Bækken, 1998). Ammonium nitrate (NH_4NO_3) is commonly used as a tunneling explosive. Undetonated ammonium nitrate is soluble in water and enters quickly into the tunneling wastewater and runoff from waste disposals. According to Bækken (2005), the fraction of undetonated explosives varies, but it often fluctuates between 10 and 15 %; in some cases, it could have higher values for areas with difficult rock conditions.

Concerning chemicals in construction water, multiple chemical grouts with different chemical compositions are available on the market. These chemicals are often harmful to the environment. Acrylamide and hormone-mimicking substances such as phthalates from polyurethane products are good examples of such harmful chemicals.

Acrylamide and Chromium were a huge topic in 1995–1997, as grouts with this substance were used for both Norwegian and Swedish tunneling projects. Neurological effects are attributed to this substance. Moreover, Chromium is an element that constantly needs to be monitored in construction sites, the processes that control the environmental chemistry of chromium include redox transformation, precipitation/dissolution, and adsorption/desorption reactions. Commonly occurring reductants, such as ferrous iron and organic material, can transform Cr(VI) to Cr(III), but manganese oxides are the only inorganic oxidants found in the environment that cause the rapid oxidation of Cr(III) to Cr(VI). (Rai et al., 1989)

Finally, according to Kruuse-Meyer (2006), tunneling water contains oil contaminants that originate from mineral oil in explosives, diesel spills, and hydraulic oil from machinery. Oil products can contain toxic components such as polycyclic aromatic hydrocarbons (PAH), lead, and methyl-tert-butyl ether (MTBE). The concentration of oil in tunneling water varies and there are high standard regulations for oil emissions.

2.3 Water treatment techniques for tunnel construction

Wastewater construction has become an important concern during the last few years, not only because of its generation but also the way the water needs to be treated. In the last decade, innovative new techniques have been introduced and these techniques are becoming more efficient and sustainable. In terms of tunnel construction, the pollutants that originate from the blasting, i.e. the suspended solids, and the chemicals present in the wastewater tunnel construction make the water treatment a complex procedure (Plato, 2024). In general, the maintenance complexity can significantly differ depending on the site and the amount and characteristics of the water it generates; however, it is well known that by diminishing the concentration of suspended material, a significant portion of pollutants is effectively removed, consequently reducing the necessity for chemical treatment and alternative remedial measures. This makes sedimentation and filtration processes crucial in water treatment (Johansson, 2024). This chapter describes the most common and innovative water treatment techniques for tunnel construction depending on different parameters such as suspended solids and pollutant removal, and pH adjustment. In Scandinavian countries, Norway is considered the world leader in tunnel construction because of the development of efficient construction methods. Norway has a total of 1043 road tunnels, 34 of which are subsea. Every year, 20–30 km of new tunnels is built (Vikan & Meland, 2013). This master thesis project considers different documents that explain how wastewater management is made in Norwegian tunnel constructions to contemplate innovative solutions.

2.3.1 Ditches

It is estimated that the suspended solids concentrations in the tunneling wastewater at the source are around 5.000 –10.000 mg/l. The tunneling water is transported out from the working space using pipelines and basins to a sedimentation area. In the beginning, early sedimentation in the tunnel can increase the efficiency of the treatment facilities. The first sedimentation step takes place close to the working space; the particle settlement can be accomplished by building tunnel ditches along the construction site with provisional thresholds or doorsteps (Vikan et al., 2013). Significant amounts of sediments will settle behind the thresholds.

The efficiency of the ditches varies depending on the dimensions, the flow rate, the number of thresholds along the ditches, the temperature of the water, the composition of the sediments (granulometry), how frequently the ditches are being cleaned, and some other parameters. In general, it is a good practice to decrease the amount of suspended material in the tunneling wastewater before using chemicals or other treatment methods. This is a passive way to take advantage of the reduced space in the construction site and a sustainable procedure to separate the suspended sediments from the tunneling water. The tunneling wastewater is usually pumped to sedimentation ponds after the ditches.

2.3.2 Sedimentation ponds/containers

Among many wastewater treatment methods, sedimentation ponds are used to create a steady environment for water treatment, allowing particles to settle (Lavieille, 2005). Pollutants are frequently attached to particles, and as they settle into sediment, they can be removed from the wastewater pond and treated. Toxic metals, nutrients, and polycyclic aromatic hydrocarbons (PAH) can commonly be found in tunneling water. Wet pond treatment systems have been identified in Sweden as a strategic method to treat polluted water, especially that comes from construction sites, due to its low investment and maintenance costs (Andersson et al., 2018).

A recognized solution to treat tunneling wastewater and decrease the amounts of pollutants entering wildlife and natural habitats is to implement sedimentation ponds in the cycle of the construction water. The purpose of these ponds is to treat polluted water through sedimentation. The efficiency of the pond in the removal of pollutants varies heavily and is dependent on the overall design of the pond, the temperature of the water, and the nature of the sediments (German & Svensson, 2005). Well-dimensioned sedimentation ponds can purify tunneling water to approximately 400 mg/L Suspended Solids (SS). Particle contents below 100 mg/L can be obtained by complementing with other processes (Vikan et al., 2013).

According to Vikan (2013), certain types of rock contain high concentrations of toxic metals. Water with high SS content may thus also have high concentrations of toxic metals. Organic contaminants such as oil and PAH are also often particle bound. Removal of suspended particles from the tunneling water is thus an important and relatively simple measure of water treatment. However, in a biological context, the removal of particle-bound contaminants may not be sufficient as dissolved contaminants are considered more bioavailable and, thus, more detrimental to the aquatic biota. This is why also steps with other more advanced treatment techniques are needed.

2.3.3 Lamella separator

A lamella separator is a high-rate settler that reduces solid particles and suspended materials in tunneling wastewater. It has the same characteristics as a traditional sediment pond but takes up one-tenth of the area (Lekang et al., 2001). In the lamella separator the water flows through several parallel passages separated by lamella curtains. The passages can be oriented with horizontal flow or upward flow, depending on the manufacturer, as seen in Figure 1.

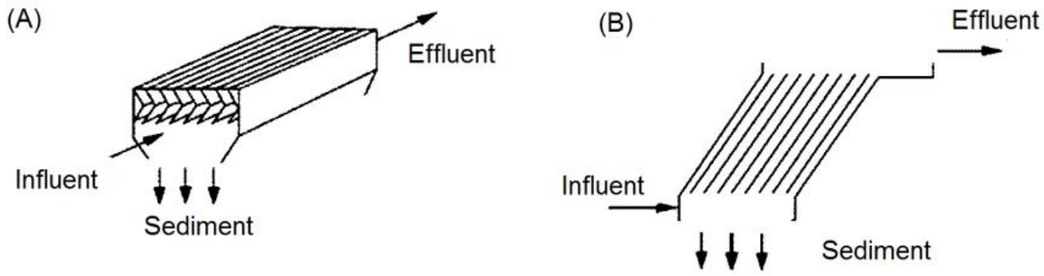


Figure 1. Geometry alternatives for high-rate settlers (Vasconcelos et al., 2014).

The idea is that by adding several parallel passages, each passage in the lamella works as an independent sedimentation area, which means that the particles have less space to move vertically, and the particles will encounter the lamella curtains and sediment earlier. It reduces the short-circuiting of water in the container or basin by orienting the water flow through the lamella curtains. This also reduces the turbulence that can occur when water flows freely, such as in open ponds or containers (Vasconcelos et al., 2014). A lamella separator can be installed by connecting an inlet and outlet to a pre-constructed container, as seen in Figure 2, or by adding lamella units to an existing sediment pond, as seen in Figure 3.

Figure 2. Lamellaseparator LS (Nordic water, 2024).

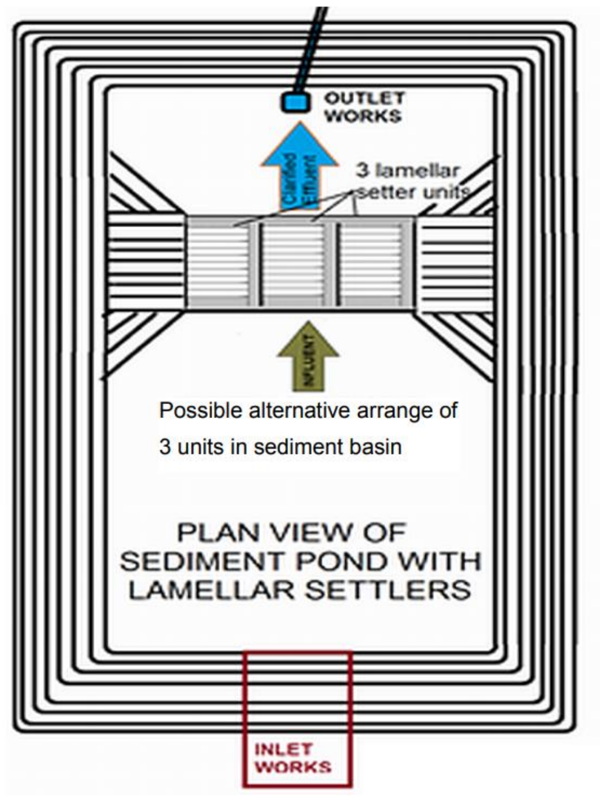


Figure 3. Arrangement of three high-rate lamella settlers in a sediment basin (Vasconcelos, et al., 2014).

The maintenance of a lamella is relatively low. The settled particles will gather on the lamella curtains and then sink to the bottom of the lamella. From there, a sludge pump is connected to a sludge container for emptying the sludge from the lamella. The sludge pump must run for a few minutes every other day, depending on the amounts of suspended materials in the wastewater. The sludge car will then empty the sludge container whenever it is full. The lamella curtains also need to be cleaned but less frequently. The lamella curtains are cleaned with a pressure washer that pushes the sedimented materials down to the rest of the sludge (Pettersson, 2024).

2.3.4 Carbon-based sorption filters

The implementation of carbon filters in the treatment chain is becoming more common nowadays. This section describes two different carbon filters used in industry: the conventional activated carbon filter and biochar as an innovative alternative.

Active carbon filter

Activated carbon filters are becoming important in the treatment of construction wastewater; they can address the unique challenges that this type of wastewater may present, and often contains suspended solids, toxic metals, and various organic and inorganic pollutants. The adaptability and efficiency of activated carbon make it particularly suitable for treating the diverse range of contaminants found in construction wastewater. Activated carbon's ability to adsorb heavy metals like lead, chromium, and cadmium is well documented. Suspended solids and particulate matter are prevalent in construction runoff, necessitating effective filtration methods.

Active carbon is a treatment method based on carbon filters that uses chemical and physical sorption to reduce contaminants. The carbon gets activated when exposed to high temperatures which gives the carbon a large exposure of surface area and a well-developed pore structure that can sorb the contaminants (Lu & Sun, 2020). The active carbon filter comes in prefabricated pressurized modules (Eurowater, 2024). The pressure pushes the water through the filter, and it removes mostly organic pollutants. It can also remove some metals up to 20%. It also somewhat reduces suspended materials, but for the active carbon filter to operate efficiently, the suspended materials should be removed in an earlier stage of the treatment. This is because the suspended materials clog the filters and prevent them from sorbing other pollutants. When this happens, the pressure after the filters lowers, and it needs to be backwashed to rinse the filter. The backwashed water gets pumped to the beginning of the wastewater treatment facility to get treated again. The pressure is often monitored with pressure monitors both before and after the filter to calculate the difference. When the filter’s activated carbon is saturated with pollutants, the filter needs to be changed into a new one (Naturvårdsverket, 2017). The change of filter for construction wastewater is estimated to be every three months for a tunnel such as Vasastan (Pettersson, 2024). An issue regarding the activated carbon filters noted by Pia Hildesson (2024) at other construction sites is that the filters can release arsenic. In Figure 4, a granule of activated carbon with saturated pores is shown.

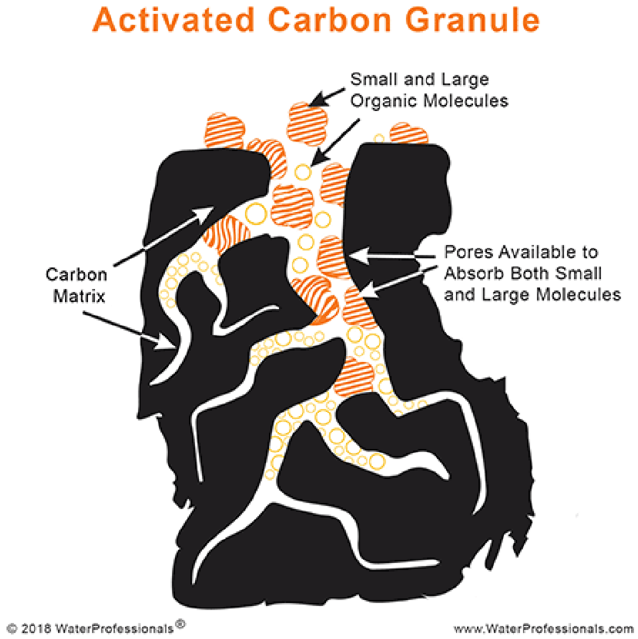


Figure 4. Active carbon granule. (Water Professionals, 2024)

Moreover, activated carbon filters are a strong tool in treating tunneling wastewater that can handle the complex mixture of pollutants typical of this sector. Their use helps with the treatment of wastewater, protecting water resources, and adhering to environmental regulations. This makes companies create new innovative techniques related to carbon-based filtration.

Biochar

Different authors describe biochar as a porous carbonaceous material produced during the thermochemical decomposition of biomass feedstock in the presence of little or no oxygen. This biomass feedstock can be any organic waste materials, including crop and forest residues, wood chips, algae, sewage sludge, manures, and organic municipal solid wastes (Colantoni et al., 2016; Xiong et al., 2019). Following Xiang et al. (2016), biochar is a promising agent for wastewater treatment. Biochar has been extensively used as an adsorbent to remove toxic metals, organic pollutants, and nutrients from wastewater. Biochar is an effective, low-cost, and environment-friendly sorbent (Cha et al., 2016)

Different types of biochar have been implemented in industrial wastewater treatment. Its composition and performance depend on the different pollutants that must be removed from the water. Biochar can sorb 20–43% of ammonium and 19–65% of phosphate in flushed dairy manure within 24 hours (Ghezzehei et al., 2014). For tunneling wastewater treatment, there is a popular type of biochar called “Bio-media filter”, which is a recently implemented solution in construction wastewater treatment.

Bio media filter is a specially developed form of activated carbon made from pyrolyzed wood. The pyrolyzed wood undergoes a different type of heating process than active carbon filters, making it 10 times more effective by creating a different surface chemistry. Bio-media filters are a more environmentally friendly treatment solution that reduces the amounts of dissolved metals such as copper, lead, and zinc, as well as organic pollutants such as aliphatics, PAH, benzene, and chlorinated hydrocarbons. The flow rate for a bio-media filter is measured to be twice as large as the flow rate for activated carbon filters. The bio-media filter is also cheaper and easier to maintain than activated carbon filters due to its composition. Most particles end up in the top layer of the filter, which makes it easy to do efficient cleaning of the filter with a pressure wash instead of using backwashing, which might not have the same efficiency and then the need to change filters earlier (Swedish Hydro Solutions, 2024). Instead of using pressure to push water through the filter, as for active carbon filters, the bio media filter uses gravity, which makes it more reliable, and less electricity is needed. The bio-media is packaged in bags which means it is possible to change different layers when saturated. The bags in the top layer will be saturated first and then it is possible to just change that layer (Pettersson, 2024). The main difference with a conventional activated carbon filter is that the Bio-media filter contains carbon with a larger sorption area on the pores, which means that the pore media is larger to sorb more molecules and stick them to the surface area; this also makes the lifetime of the filter somehow longer.

2.3.5 Filters (oil, sand, metal, silt curtains, and some others)

Filtration processes are well-known techniques implemented for water treatment. Filters are structures that use physical and chemical processes to achieve pollutant removal (Woods-Ballard et al., 2015). They are commonly used in multiple water treatment facilities. These systems differ depending on the type or manufacturer of the filter, but the principal processes that occur inside the filter´s structure are sedimentation, filtration, sorption, and precipitation.

Filters can also remove dissolved substances in the water through sorption, but their performance depends on the technology used in the system. The type of filter media is important and depends on what pollutant to remove. A wide range of materials can be used as filter media, and the most common are leaf compost, pleated fabric, cellulose, activated charcoal, perlite, and sand (Woods-Ballard, et al., 2015). New innovative techniques are appearing on the market that fulfill the requirements for each facility with multiple components.

Filters have several complications, and one of the main problems associated with these systems is peak flows because they do not have a proper capacity for dealing with high flow rates. Therefore, when the flow rate frequently fluctuates, peak flow structures need to be installed before the inlet of the filter media to control the flows. Moreover, overflow structures are sometimes placed in the system to prevent structural damage.

The reliability of these systems also depends on the sediment loading rates. For tunneling construction, filters present a high probability of clogging under high sediment loadings, which leads to continuous monitoring, maintenance, and replacement needs. This usually implies difficulty in the identification of malfunctioning or failure events. The frequency of filter replacement varies depending on different aspects such as the site- and system-specific characteristics. Maintenance of well-mounted filters consists of replacing the filter media. This should be done with intervals of 6-12 months depending on the pollutant load (Alm et al., 2015). Usually, when the pressure in the filter's outcome decreases due to saturation, instead of replacing it, backwashing is also an option to rinse the filter and make its productive life longer (Pettersson, 2024). The water that comes from the backwashing is pumped back to the first step of the treatment process, ensuring the most accurate treatment of the water.

Filter systems are usually sold under prefabricated standards, and their capital cost is often lower when compared to other structures. The wide variety of filter designs available on the market provides various treatment processes that lead to different results. The nature and load of pollutants, and the filter's characteristics, determine the performance of a specific device to treat stormwater runoff appropriately. There are also specially engineered filter units, known as proprietary treatment systems (Woods-Ballard et al., 2015d). Filters do not provide benefits to biodiversity, but its properties allow the practical implementation of surface areas to different types of procedures that make this kind of treatment very flexible and with multiple options for the customers.

2.3.6 Acid addition for pH regulation

In wastewater treatment for tunnel construction, the pH of the water tends to be more alkaline due to the different chemicals used in the site. Usually, an acid solution is added to the water to achieve an optimal pH balance.

Multiple acids are used in the water treatment industry, but two acids are mostly used for pH adjustment. Hydrochloric acid (HCl), or muriatic acid, is hydrogen chloride dissolved in water (Austin & Glowacki, 2000). It is an inorganic, strong acid widely used for pH adjustment. For water treatment, hydrogen chloride is stored in gas bottles and dosed into the wastewater where it dissolves and acts as a pH adjustment chemical. Hydrochloric acid can be used to neutralize alkaline water from tunnel construction by lowering the pH and for regeneration of ion-exchange resins (US EPA, 2022a). Hydrochloric acid can also be used to treat polluted water through coagulation. It binds with particles in the wastewater and creates polyaluminium chloride and zinc chloride among others. However, an excessive dosage of hydrochloric acid can cause damage to the environment. Maintaining and operating with an acid is also a health and safety risk for the workers (Pettersson, 2024).

2.3.7 Carbon dioxide for pH regulation

During tunnel construction, high pH in the water commonly occurs due to the different chemicals used. In the last decade, carbon dioxide (CO_2) has emerged as a preferred method for pH control in wastewater treatment plants due to its effectiveness, safety, and cost-efficiency. This method is usually compared with the addition of acids into the water, such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and some other traditional methods for pH regulation. In contrast, carbon dioxide presents minimal safety concerns, making it a safe alternative for use in wastewater treatment facilities. Al-mutaz et al. (2001) investigated the efficiency of CO_2 usage for pH adjustment in wastewater treatment plants for sewage water, comparing carbon dioxide with sulfuric acid as a conventional method. It was found that carbon dioxide gives better control of pH than sulfuric acid. Carbon dioxide is also less hazardous to use and reduces high pH levels quickly. It is non-corrosive to pipes and equipment, reducing the risk of infrastructure damage and minimizing maintenance requirements. Moreover, carbon dioxide does not produce harmful by-products or emissions during treatment, contributing to overall environmental sustainability. On the other hand, after performing multiple experiments, CO_2 showed self-buffering as it reached neutral pH levels. This self-buffering feature allows precise end-point control without the danger of overshooting into undesirable low pH levels. Carbon dioxide for pH regulation requires less equipment and monitoring costs. It also exhibits a larger storage capacity, making it possible to store up to twice as much neutralizing agent in the same amount of storage space with no increase in weight. CO_2 requires no handling costs. It can be utilized via a completely automated system, minimizing the risk of human errors.

In some cases, introducing carbon dioxide into wastewater streams may affect biological processes or microbial communities. Monitoring is needed to ensure that CO_2 addition does not interrupt the biological treatment processes. Moreover, some equipment used in Wastewater treatment plant may not be compatible with carbon dioxide, especially if injected in its gaseous form. Specialized equipment may be required for safe and effective CO_2 injection, which can add complexity and cost to the treatment process. The overall cost-effectiveness of CO_2 for pH adjustment depends on factors such as availability, transportation costs, and infrastructure requirements (USEPA, 2023). Depending on the source of CO_2, the production and transport processes can contribute to greenhouse gas emissions if not sourced sustainably. The use of CO_2 may indirectly contribute to climate change. A large amount of CO_2 sold in the commercial market is recovered as a byproduct of ethanol, ammonia, and hydrogen production. In terms of costs, the overall costs due to purchasing price might be higher when using CO_2 than using acids (Petterson, 2024).

2.3.8 Flocculation

Flocculants are long chains of repeating molecules that are dissolvable in water. Once dissolved in water, the molecules bind with suspended materials increasing the settling velocity. The bound molecule’s weight becomes larger, and the molecule settles. Coagulants are charged particles added to the water to neutralize the oppositely charged contaminants and become a larger particle coalition. There are differences in the chemical processes between flocculation and coagulation (Kazaz et al., 2024), see Figure 5.

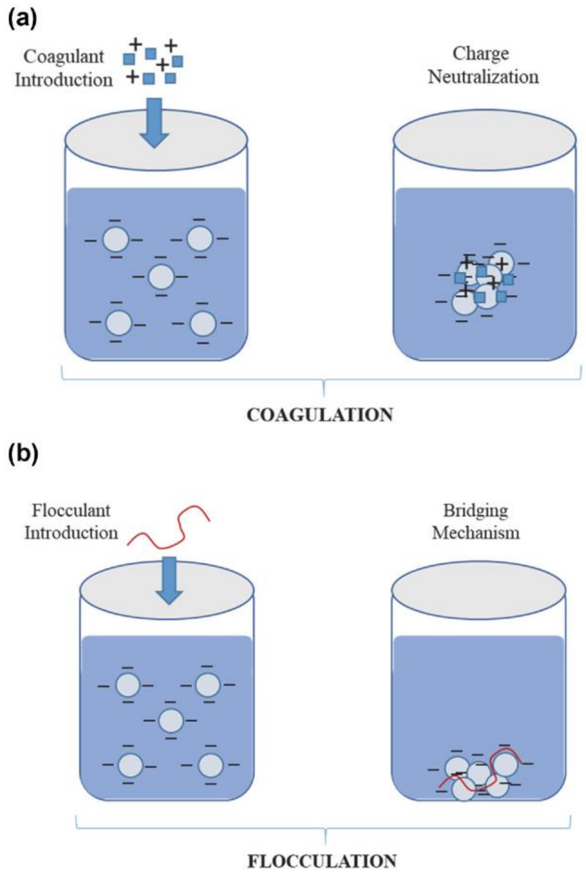


Figure 5. Comparison of coagulation and flocculation mechanisms (Kazaz et al., 2024).

Flocculants can be divided into four different groups: synthetic, inorganic, bio/natural, and stimuli responsive.

Synthetic flocculants can be divided into four groups based on their charge: cationic, anionic, nonionic, and amphoteric. Cationic flocculants can bind with fish gills, making them a threat to aquatic life. Anionic flocculants are commonly used for industrial wastewater plants due to their low toxicity compared to cationic flocculants. Nonionic flocculants cannot bind suspended materials through charge and rely solely on bridging mechanisms with solid particles. Amphoteric flocculants can have both an anionic and a cationic charge depending on the wastewater pH. This makes amphoteric flocculants effective in reducing a wide range of charged contaminants. A commonly used synthetic flocculant is polyacrylamide (PAM) because of its efficiency and low environmental impact (Kazaz et al., 2024).

Inorganic flocculants are used in stormwater treatment facilities due to their low cost and effective flocculation. These flocculants have a lower molecular weight and smaller particle size than organic flocculants. A commonly used inorganic flocculant is polyaluminium chloride (PAC). On the other hand, bio/natural flocculants are based on animals or plants, making them less harmful to the environment. However, overdosing of a bio/natural flocculant can still be harmful to aquatic life. A bio/natural flocculant commonly used in wastewater treatment plants is chitosan which is expensive but when dosed properly can give effective flocculation results (Kazaz et al., 2024).

Stimuli-responsive flocculants change their physical and chemical properties based on the characteristics of the wastewater. Based on characteristics such as temperature, pH, and magnetic properties the flocculant is differently charged and can bind differently charged suspended particles. Two stimuli-responsive flocculants used in stormwater treatment facilities are aluminium sulfate and polyacrylamide (PAM) (Kazaz et al., 2024).

Flocculants can be added to the tunneling wastewater in several forms: powder, blocks, liquid, or socks, as seen in Figure 6.

Figure 6. Typical flocculant forms for additional treatment of wastewater (Kazaz et al., 2024).

2.3.9 Ion exchange

This procedure is a powerful tool for the elimination of dissolved substances, such as toxic metals and nutrients present in the water. This technology is also an efficient biological treatment technology that has been widely applied in practical engineering in recent years to remove nitrate (NO_3^-) (Chen et al., 2022; Zhuang et al., 2022). Persistent organic pollutants (POP) originating from undetonated explosives can be degraded into other compounds and cause eutrophication and some other issues in wildlife; the wastewater needs to be treated and cleaned from these POPs before being released into the environment. Nitrogen, ammonia, ammonium, nitrate, and nitrite removal can be achieved by implementing an ion exchange methodology for the removal of nitrogen containing ions. Ion exchangers are insoluble resins that contain soluble and mobile exchangeable ions. When the resin is contact with water, the ion dissociates and becomes mobile, though an exchange occurs when there are ions in the aqueous phase that can replace those on the exchanger and thus maintain the resins overall charge neutrality. The overall charge must be maintained, otherwise the resin will attract or repel ions to maintain the charge balance (Jorgensen 2002). Figure 7 shows how chemical equilibrium is reached when an ion exchanger containing “A” ions comes in contact with “B” ions in an aqueous solution.

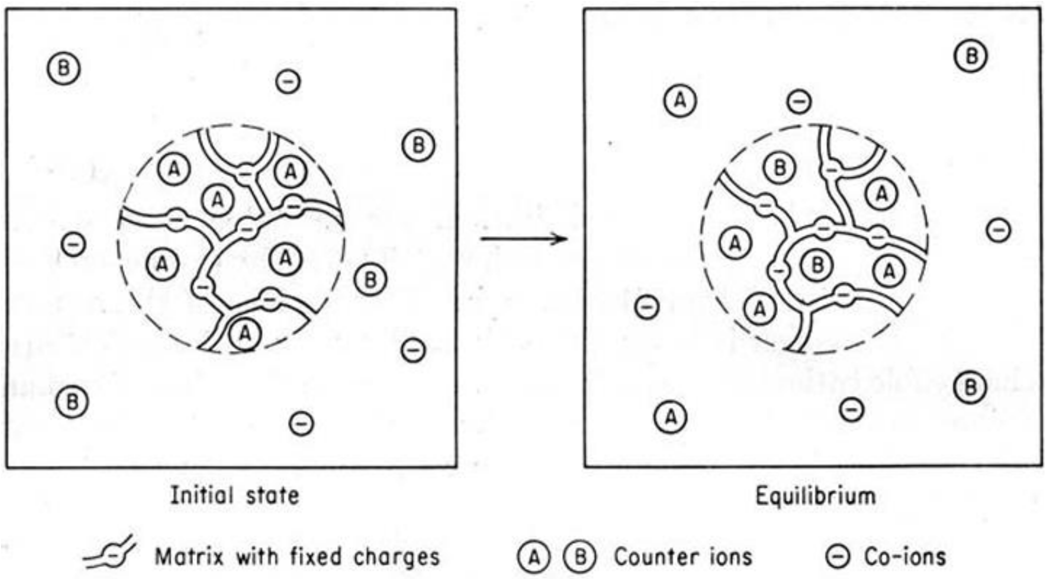


Figure 7. Ion exchange equilibrium. (Jorgensen, 2002)

When the resin is in contact with ions in the aqueous phase equilibrium may be established. The equilibrium concentrations are difficult to predict because inside the resin there are high concentrations of charged groups (Slater, 1991). Following Gaikwad (2010), other applications for this method in excavation projects include water purification from toxic metals, but in tunneling wastewater treatment, the removal of charged organic contaminants is the main purpose (Vikan et al., 2013).

According to Lizunkov et al., (2016), there are several chemical and physical methods to complete an ion exchange procedure for removal of nitrogen containing compounds; The most used in construction wastewater is ion exchange in packed columns passing the water through a sorbent bed (Zeolites, Clinoptilolites, etc). The ion exchange water treatment method advantageously differs because it does not require a continuous dosing of reactants and impurities removed from water do not form a precipitate (Suzdalova et al., 2015). The advantages of ion exchangers include the ability to fully automate systems and regeneration, which allows the use of ion exchangers in multiple recurrent filtration cycles. One disadvantage is that relatable procedureis only possible if the dissolved substances are present in low concentrations. Large columns of resin would be needed when large amounts of water want to be treated. Another uncertainty is the mixing of substances. Having too many different substances dissolved in the water may cause problems because ion exchange is usually implemented for specific substances and when there is a constant variation of concentrations, there is a high risk of desorption. A third uncertainty is that the ion exchange filter can increase the pH. This can happen when the backwashing after charging the filter is not sufficient. To charge the filter, first hydrogen ions are added, and after that sodium hydroxide is added. Excessive sodium hydroxide which is not backwashed sufficiently can travel with the water through the rest of the treatment system and increase the pH (Hildesson, 2024).

2.4 Multi-criteria decision analysis (MCDA)

Regarding environmental management, different approaches can be implemented to obtain an accurate result. In this case, many different aspects play a role in a complex construction project, a multi-criteria decision analysis (MCDA) was performed to integrate all the different criteria, obtaining the best possible result.

Multi-Criteria Decision Analysis (MCDA), also known as Multi-Criteria analysis (MCA), is a powerful methodological framework that helps handle complex decision problems (DCLG, 2009; Munier, 2011). This methodology evaluates multiple aspects that play a role in the decision-making, scoring, and weighting of the different criteria to select the most viable alternative.

There are multiple ways to address an MCDA. Every approach has a different type of scoring and weighting. For this project, a Linear additive model was followed as the method. Other approaches, such as simple ranking among alternatives, where the solution deemed to have the best performance in each criterion is awarded the highest rank, and the other alternatives follow in a falling order. This approach was adopted in a French case study by Ellis et al. (2004). Finally, a third type of scoring is pairwise comparison, which is the foundation of the popular Analytic Hierarchy Process (AHP) and the more advanced Analytic Network Process (ANP) (Munier, 2011).

2.4.1 Establishment of the decision context

The stakeholders, the involved parties also known as experts, and the aims/objectives are the three principal components that can make the decision context of an MCDA (Department for Communities and Local Government, 2009). Since the goals and preferences are established by the experts, they are crucial to making the final decision. The MCDA method is based on the coherence and consistency of preferences between the parties, even if conflicts and different opinions may cause misunderstandings between the parties. MCDA is not just limited by the experts' opinions. Key players also significantly contribute to the process. Even though the final decision does not rely on them, they indirectly influence the project. Any party or individual with a potentially contributing to the MCDA plays an important role by providing their advice and opinion. All different perspectives must be taken into consideration to cover all the angles.

For all MCDA dealing with environmental concerns, Munier (2011) considers four entities that have to be taken into account: technicians who supply quantitative and qualitative information, citizens who are being affected by the project, an analyst who processes the raw data, and the decision-making entities who have the last word on how to deal and manage the project.

On the other hand, the identification and selection of possible alternatives is also an important part of an MCDA method. The primary source of alternatives is the experts ́ experiences and interests. Alternatives can range from policies to specific projects determined (Department for Communities and Local Government, 2009). However, another good source of alternatives can be found in previous practices and initial research. Following the DFCLG, 2009, Depending on the characteristics of the alternatives, a huge amount of information can be found as part of the literature review, depending on the global development and their application. Further steps in an MCDA may lead to a reevaluation of the alternatives previously established, creating an iterative process that in the end can integrate all different results.

2.4.2 Criteria selection

For water resources and environmental management, it is crucial to select the most appropriate criteria for the evaluation: The high number of variables related to this topic make complex decisions that may involve all sustainability aspects: technical, environment, economy, and society to achieve defined targets (Zarghami Szidarovszky, 2011). The criteria are the major established components on which the alternatives are judged, and the final decision is made (Department for Communities and Local Government, 2009). This means they represent the conditions or restrictions that the project is subject to (Munier, 2011). The criteria need to be flexible and dynamic to be adapted and redefined to meet modifications, or further implementation, of the different aspects that each alternative can include.

As mentioned before, the execution of sustainable water treatment techniques may accomplish social, environmental, technical, and economic objectives to achieve the goal of handling and managing contaminated water in construction projects. Considering this environmental framework, the principal purpose of constructing an MCDA in this project is to evaluate how different alternatives or solutions can fulfill different established criteria (Rosen et al., 2013).

2.4.3 Scoring strategy

There are different options when it comes to scoring the alternatives. The most common implementation is the one that uses a linear scale which presents the worst possible value to the ”best possible” value. Each alternative will be scored with a maximum of five points based on each criterion's impact (Martin et al., 2006). Multiple authors such as Martin et al. (2006), Jia et al. (2013), and Bergqvist (2014) have used this method before to score each alternative. This is useful for criteria that can be easily quantified, such as costs of operation (Munier, 2011). On the other hand, it is not as easy for the criteria that have a qualitative nature. For this specific type, the scale is often simplified and is associated with subjective descriptions. For example, on the same scale of 1-5, a score of five means that the alternative had a very good performance, and with a score of 1, the performance of the alternative was bad compared with the other alternative.

2.4.4 Weighting strategy

Weighting in MCDA is done to ensure that experts' interests are reflected in the decision process (DCLG, 2009; Munier, 2011). It is a way to balance the scores so that the criterion most valued by the experts will have the highest effect on the final results. It is important to note that the weighting of criteria may vary between different sites due to differences in experts' interests and site conditions (Ellis et al., 2004). For this project, the weighting of criteria is achieved by comparing the relative importance of each criterion against each other (Department for Communities and Local Government, 2009). The weighting of criteria is usually a very subjective process, and therefore, the values recorded for a process can present high variability when comparing the same criterion with the intent of replicating them in another process. The aim of this step is to rate the importance of each criterion based on the preferences of the experts. The weighting process reflects the range of differences between the options and their importance (Department for Communities and Local Government, 2009).

2.4.5 Final evaluations

Following the methodology, after scoring and weighting are done, the ranking of alternatives was calculated using a linear additive model (Department for Communities and Local Government, 2009), by multiplying the score (s) of each alternative by the weight (w) of each criterion. By representing Sij, the score of the alternative (i) against the criterion (j), the overall score for the alternative is then defined as the following formula, showing an order of preference for the different alternatives:

$$S_i = w_1 s_{i1} + w_w s_{i2} + \cdots w_n s_{in} = \sum_{j=1}^{n} w_j s_{ij}$$

$S_i = total\ score\ of\ alternative\ i$

$W_j = weight\ of\ criterion\ j$

$S_{ij} = score\ of\ alternative\ i\ in\ criterion\ j$

$n = number\ of\ criteria$

j= Criterion j

After obtaining the final results, a sensitivity analysis was performed to evaluate the behavior and the accuracy of this project.

3 Case study and area description

The city of Gothenburg is the second largest urban area in Sweden and the municipality is working to improve the transportation system in the city by making tunnels that will connect different points of its territory. The construction of these tunnels generates wastewater that must be treated before reaching any water body. The current wastewater treatment system in the tunnels generally consists of a facility that focuses on three treatment categories: pH adjustment, suspended materials, and diluted pollutants in the water. Guideline values on the tunnelling wastewater have been introduced to ensure that the released water is not harmful to the environment, and companies' attention is starting to be more focused on how to handle the wastewater efficiently.

3.1 Västlänken Station Haga

Västlänken Station Haga is one of three stations of Västlänken. The purpose of Västlänken is to make traveling in Gothenburg and the western part of Sweden by train easier, faster, and with fewer layovers (Trafikverket, 2023). The contract for Station Haga covers 1700 meters of rail tunnel with 1450 meters through rock. The area reaches Stenpiren in the north and Landala Square in the south and is divided into three construction sites: Haga, Otterhällan, and Vasastan. In Figure 8, the division of Västlänken is presented.

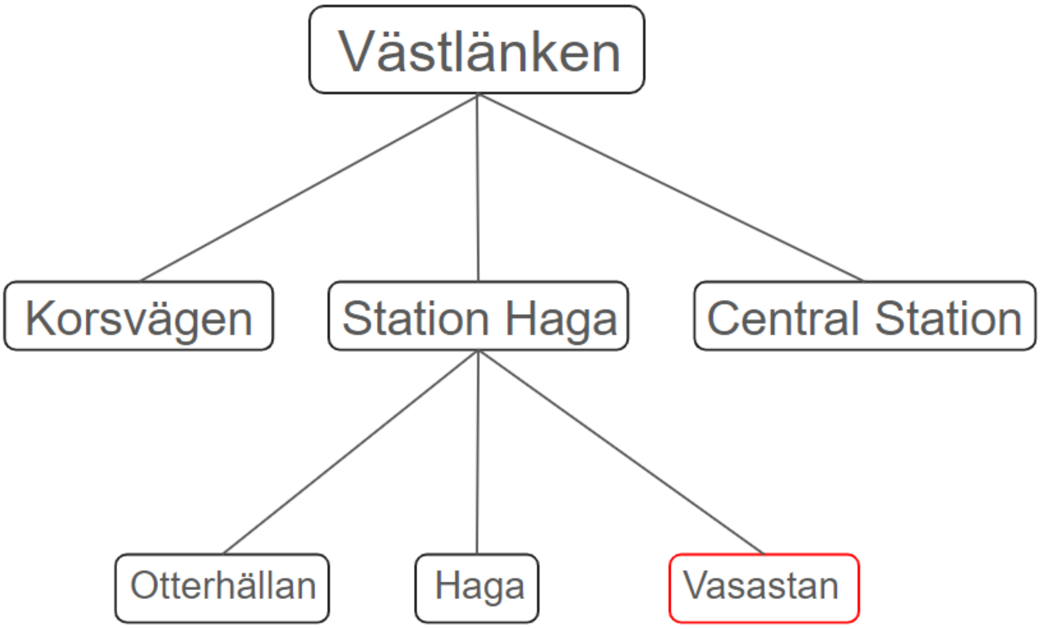


Figure 8: Västlänken contract tree.

The station will be located at Haga and will be an underground station with three access points: School of Business, Nya Allén, and Pustervik. Otterhällan is constructed as an add-on through a service tunnel for Götatunneln and from there the construction of the main tunnel has started. At Vasastan, a service tunnel has been constructed from Linneplatsen and reaches one kilometer into the rock towards Landala where the construction of the main tunnel has started (Trafikverket, 2022).

3.1.1 Vasastan

The focus of this report is on the Vasastan site. The site covers a one-kilometer service tunnel that leads to the main tunnel. The main tunnel will reach from Landala square where the tunnel will meet the construction site of Korsvägen, to the church of Haga where the solid rock changes into clay and the construction site of Station Haga starts. A service tunnel will run alongside the main tunnel and other spaces for ventilation shafts, drainage basins, and installations. The exact drawings are not officially released due to an ongoing procurement for finalizing the project, but in Figure 9, the current tunnel is portrayed. The black lines indicate the outline of the Vasastan construction site. The red tunnel indicates the completed service tunnel, and the blue tunnel indicates the completed main tunnel. The pink tunnel indicates the not yet finished tunnel and the “explosive warning” signs indicate the areas where blasting is undergoing.

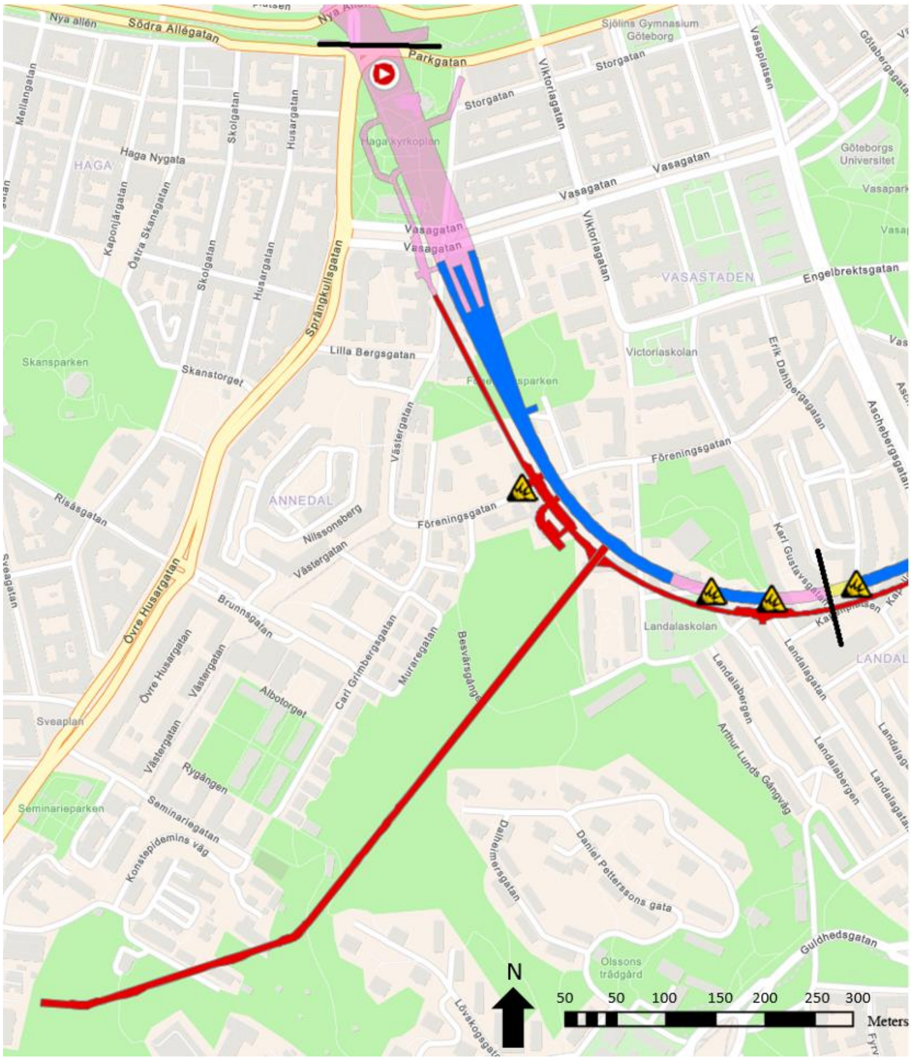


Figure 9. Map of Västlänken (Trafikverket, 2024).

3.2 Climate in Gothenburg

The precipitation in the Västra Götaland region has been increasing during the last few years, as can be seen in the graph in Figure 10, there is a notable increase in the maximum daily precipitation since 2020.

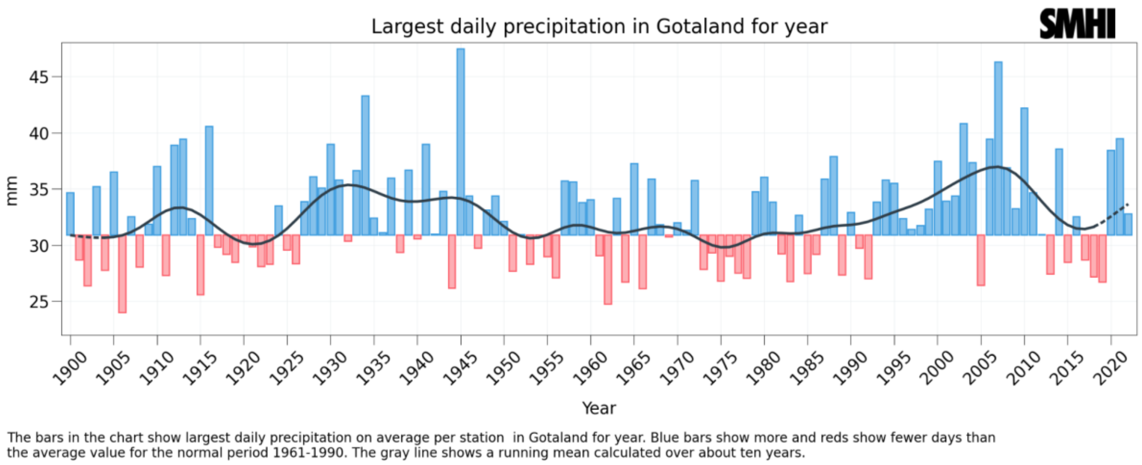


Figure 10. Largest daily precipitation in Gotaland for year (SMHI, 2022).

According to the quantitative map classification of world climates made by Kottek et al. (2006), Gothenburg city has a warm-summer humid continental climate where the coldest month average is below 0 °C with no notable precipitation difference between months and seasons. Following the Swedish Meteorological and Hydrological Institute (SMHI), the city of Gothenburg has an average annual precipitation of around 840 mm/year.

However, the precipitation in 2017 was 993 mm, while the normal average precipitation registered in Gothenburg between the years 1961-1990 was 758 mm. The largest precipitation events were registered in 2006 with an annual precipitation of 1264 mm (SMHI, 2017). The constant precipitation in the area, combined with the multiple construction projects being implemented in the city, makes stormwater management a crucial factor in maintaining the well-being of the activities and schedule in the different projects.

3.3 Geological and hydrogeological conditions

In 2014, the Swedish Transport Administration published a background report on the geology and hydrogeology of the area around Västlänken (Trafikverket, 2014).

Several in-field investigations were done such as geological mapping of the rock in the area, both on exposed rock and rock underground in existing tunnels and other underground facilities. They also performed core drilling and geophysical measurements. Laboratory samplings were done to estimate the strength, physical, and chemical properties of the rock.

Both field and laboratory investigations were made for the geotechnical aspect of the project. Various types of probe testing were performed, such as soil-rock probing, CPT probing, impact probing, and pressure probing. Further soil testing included pore pressure measurements and sampling of soils and settling investigations of ongoing settling in the area. Laboratory examinations were performed to determine the soil classification and other physical and mechanical properties of the soil.

The hydrogeology of both soil and rock was determined by drilling observation wells and taking samples for laboratory examinations of water-bearing capacity and other chemical conditions of the groundwater. Other investigations included hydraulic tests, groundwater level measurements, and pumping tests.

The results of the investigations show that the construction site Vasastan is located in an area of solid rock. The rock is suitable for tunnel construction as it is relatively tight with good rock quality and has relatively few cracks. There are some zones where the rock quality is more problematic, and in these zones, radon can be released during construction. Radon can be a health problem for workers in the tunnel as well as the environment if it spreads to the surrounding areas. Sulfur also occurs in the rock as a natural mineral and can react chemically when the mineral is in contact with air and water during production. However, in the extent it appears in the rock in Gothenburg, sulphur will not impact the construction for Västlänken.

The tunnel will be constructed almost exclusively in gneiss, a metamorphic rock with some zones with pegmatite and metabasite. The cracks in the rock are filled with mostly calcite, chlorite, and clay. The cracks filled with clay need more reinforcements than areas where the cracks are filled with other minerals. Most of these cracks are located towards the Korsvägen construction site. Therefore, the closer construction gets to the Korsvägen construction site the more likely it will be to find geological obstacles that will require additional reinforcement.

As it is determined that most of the Vasastan tunnel will be constructed in relatively tight solid rock, there are fewer possible problems regarding settling, lowered groundwater, and stability. However, the areas where larger amounts of clay and soil are located can be a problem. The soil layer above the rock is relatively thin, but there are valleys and cracks where water can be drained, and problems can occur.

3.4 Tunnel construction techniques in Västlänken Station Haga, Vasastan

In order to understand the construction techniques used in the Vasastan tunnel, an interview with Gay Plato (2024), the site manager at Vasastan, was conducted. The tunnel construction techniques were decided based on various aspects. In the first place, the results of the background report on geology and hydrogeology played a role in the decision, but also other aspects such as costs, experience, and site access then influenced the choice of technique used to construct the tunnel.

In the case of the Vasastan tunnel, the tunnel is constructed in solid rock. Drilling and blasting are the chosen technique. A drilling rig of the model Epiroc Boomer XE3 C is used for most of the drilling in the different steps of construction. The drilling rig uses about 150 l/min of fresh water for cooling when it is drilling per drilling arm. Usually, in the Vasastan tunnel, two arms drill at the same time, but when production is running at a maximum pace, three arms can be used. This water and the rock powder created when drilling is one of the most critical construction techniques regarding water contamination. The water from drilling floods into the tunnel ground, entering the water cycle, which must be treated.

The first step of the tunnel construction is spiling, performed at the tunnel entrance or when entering a new section of the tunnel with unknown rock characteristics. Spiling is a way to stabilize the rock by drilling long bolts in the shape of a circle segment from the cross-section of the tunnel. When the stability of the rock is sufficient, the next step is to drill holes for grouting around the area that is going to be blasted. This is to increase the stability of the rock and prevent water-bearing cracks from opening and releasing large amounts of water into the tunnel. The first round of grouting is performed using concrete, which is injected into cracks in the rock. After the first round of grouting, a second round of grouting is performed using a chemical called Silica Sol. Silica Sol is a colloidal silicon dissolved in water. The Silica Sol gets mixed with sodium chloride before getting used which starts a chemical reaction that makes it expand and harden when it gets sprayed into the cracks (Funehag, 2011). When the two rounds of grouting are done, control holes are drilled, and a water loss measurement is performed to ensure the in-leakage from the rock into the tunnel is within the limits. If the requirements are still not fulfilled, a third round of grouting will be needed, otherwise blasting is the next step in the construction plan. The grouting is normally performed in sections of 24 meters and gets blasted in three rounds, each 6 meters in depth. This leaves 6 meters of unblasted rock for every section. The reason for this is safety protocols to ensure the new tunnel face is stable for the preparation of the next section. The in-leaking water during these construction steps contributes to water pollution as the water will bring pollutants from the concrete, rock powder, and Silica Sol. These pollutants will then enter into the tunnel’s water cycle and need treatment.

For blasting, the first step is to drill holes where the explosives are inserted. The explosives are electronically detonated and after they are detonated the loose rock gets sprayed with water to prevent dusting when the rock gets excavated out. This step affects the water cycle in the tunnel because it transports the pollutants released from the steps ahead. Radon and sulfur can also be released after blasting. Radon is measured over a period through small containers that attract the radon once every year. Sulfur is detected by smell and will start to smell long before it reaches levels that can harm the workers. Therefore, sulfur is not measured in a time-frequency but whenever someone detects the smell of it (Hellhager, 2024). The blasted rock is stored in the tunnel for some time before it is transported away.

The newly blasted tunnel face is then scaled for loose rock, first by machine and then by hand. Then, the face gets pressure washed and scaled once more before a geologist maps the surface and determines the Q value for the cracks presented on the wall. The Q value determines the thickness of shotcrete, a thin layer of concrete that is sprayed over the whole tunnel surface, both walls and ceiling. This concrete will have a similar effect on the water cycle of the tunnel as the concrete grouting but to a lesser extent as less water now enters into the tunnel. The Q value also determines the amount, length, and distance between the bolts. The bolts prevent large blocks of rock from falling into the tunnel.

After the bolts are placed and tightened further supplementary steps can be taken if needed. If the in-leakage of groundwater or stormwater is significant, it is possible to use chemical grouting to fill the cracks when general grouting is not sufficient to seal. This is performed by using small handheld drills and then injecting a chemical substance that expands in contact with water. The chemical substance is composed of Resfoam and Purgel. These chemicals generate a pollutant called methylenedianiline or MDA for short (European Union, 2005). While it expands and hardens it is important to gather all water that gets in contact with the chemicals. Once the chemicals have hardened the waste product can be considered as general waste. All water that has been in contact with the chemical grouting is collected in IBC containers, which are small 1x1 meters containers, and this is to prevent contaminated water from entering the tunnel's water cycle. The MDA-polluted water is then stored in the IBC containers until the MDA is decomposed and thereafter released into the wastewater treatment facility The MDA oxidizes to ammonium and then to nitrate when stored in water, having a half-life of 11 days (ATSDR, 2023).

It is also possible to extend the general grouting or add more bolts to prevent in-leakage and instabilities. When the tunnel meets the requirements regarding stability, safety, and in-leakage a final layer of shotcrete can be applied to give it the final touch.

Further construction steps that can cause water pollution in the tunnel are oil leakage from machines. Oil changes and other services are therefore carried out in a workshop with a concrete slab underneath. The concrete slab is surrounded by a drainage gutter that leads to an oil separator so that no possible spills and leakage reach the tunnel's water cycle. The oil separator is then emptied with a sludge car.

The effluent restrictions are the most problematic aspect of water treatment this far in the project. The outlet is connected to Gothenburg combined sewer system, which leads to the Gryaab wastewater treatment plant. Gryaab has set a limit of 8 m^3/min and when the incoming water is higher than that at Gryaab, the water from the tunnel cannot be released. This means that at times with high precipitation or in the snow-melting season, the water must be stored in the tunnel for several days at a time until the weather conditions change.

3.5 Water quality regulations for Västlänken Station Haga

The water quality regulations for Västlänken Station Haga are especially strict compared to other construction sites. The Swedish Transportation Administration prioritizes the environment and safety during this contract since it is a ”protection contract”, meaning that the priority is to preserve the construction site while planning the new contract for the final years of construction. During this period, production occurs but not at full capacity and the speed of construction is not the highest priority. The contract is also designed as a cost-plus contract. This means that all construction-related expenses are paid for as well as an agreed-upon extra percentage by the Swedish Transport Administration (Ellis, 2023). The contract is also currently on-going, which means that new orders of construction are regularly added.

All regulations regarding water quality can be found in the Administrative Regulations (AF) from the Swedish Transport Administration. The Swedish Transport Administration has decided on the regulations based on the rules set by County Administration. Länsstyrelsen is the organization that monitors these parameters and has the responsibility to notice if they are not upheld. Länsstyrelsen however, bases their regulation on the Water Framework Directive as well as an environmental court ruling for Västlänken (Johansson, 2024). The AF states that all the water inside the construction site must be accounted for. There needs to be a work plan and a control plan of what kind of water is being generated and how it will be managed. The minimum requirements for water treatment are that it needs to be treated to remove particles and in oil separation, as well as meet the requirements for discharge to the Gothenburg combined sewage system. The requirements set by the Swedish Transport Administration in the AF for the discharge of the tunneling water to the combined sewer system are shown in Table 1.

There is a requirement for continuous measurements of the water volume discharged as well as water sampling and chemical analysis of the discharged water. The water samples should be taken once a week or quarterly and show that all parameters in Table 1 meet the requirements.

Table 1. Parameters and limit values, discharge to the combined sewage system

Parameter	Continuously	Weekly	Limit	Comment
pH	x		6.5-10	
Oil index		x	5 mg/l	
Cadmium		x	0.0005 mg/l	
Copper		x	0.2 mg/l	
Chromium		x	0.05 mg/l	
Chromium VI		x	0.007 mg/l	
Nickel		x	0.05 mg/l	
Zinc		x	0.2 mg/l	
Lead		x	0.05 mg/l	
Suspended material		x	150 mg/l	
Temperature 45 degrees	x		45 degrees (max)	
Conductivity	x	x	500 mS/m	
Sulfate		x	400 mg/l	
Magnesium		x	300 mg/l	
Ammonium		x	60 mg/l	
Chloride		x	2500 mg/l	
Nitrification 20% water			20% collection	quarterly or when exceeding
Nitrification 40% water			40% collection	quarterly or when exceeding

3.6 Wastewater treatment procedures at Västlänken Station Haga

There are several water treatment steps and methods implemented in the Vasastan tunnel at Västlänken Station Haga. All these methods treat the water before it gets discharged into the combined sewage pipe network of Gothenburg. In Figure 11 the map of the water management in the tunnel in January of 2024 can be seen. The names of each tunnel are shown, as well as how the water gets pumped through sediment containers, a collection point, a sedimentation pond, and a wastewater treatment facility (Ramboll, 2024). Since January two extra sediment containers have been added in ST-101, and the ditches that are running on one side of all tunnel sections are missing as well.

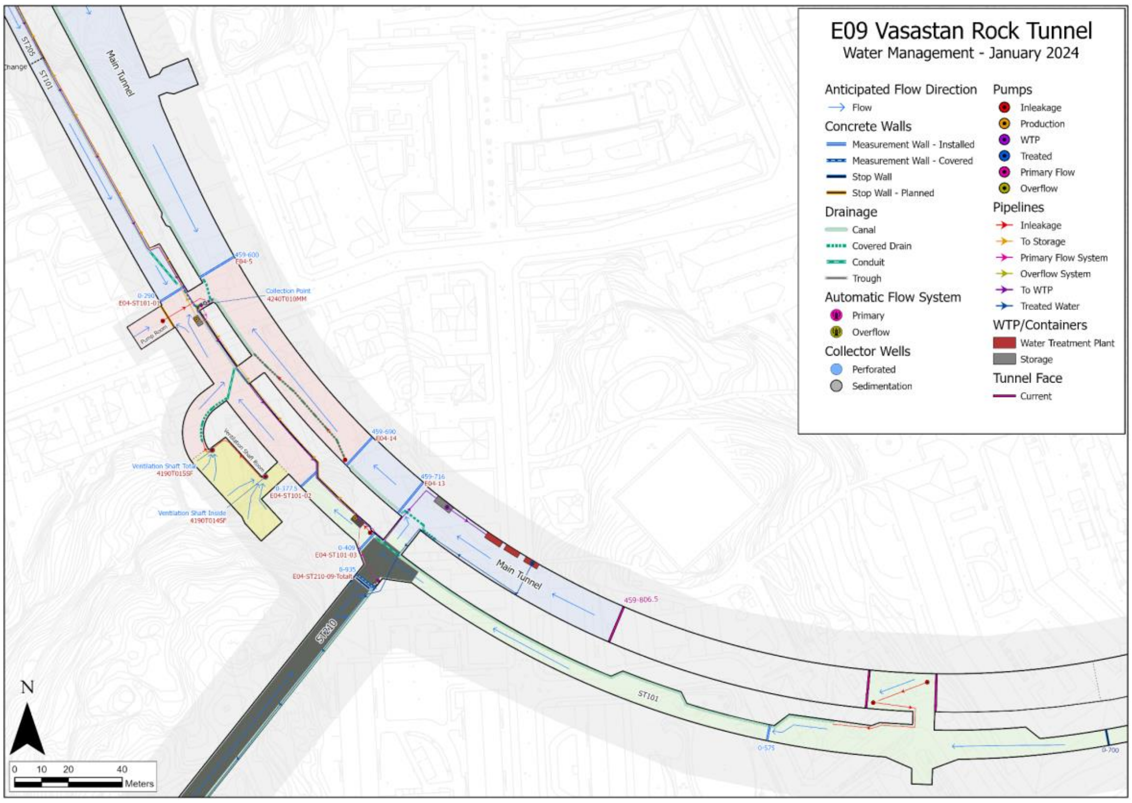


Figure 11: The tunneling water flow and water treatment system in E09 Vasastan Rock Tunnel (Ramboll, 2024).

3.6.1 Ditches

Throughout the tunnel, ditches run on one side of each tunnel section as seen in Figure 12. These ditches are approximately one meter wide and half a meter deep. The purpose of the ditches is to let in-leaking water and abundant production water that cannot be pumped through pipes flow slowly down to the collection point, which is the lowest part of the tunnel. By slowly flowing through the ditches the aim is to let particles in the water settle on the way to the collection point. The settled particles then must be excavated and put on trucks for transportation to Ragn-Sells managing the masses. The maintenance of this is approximately one time a week for two hours. The excavator, the worker on the ground, and the truck will block the tunnel and prohibit production vehicles from driving past therefore this is done during times when there is little to no ongoing production (Plato, 2024). In Figure 12 a ditch in the service tunnel ST-101 of the Vasastan tunnel is shown.

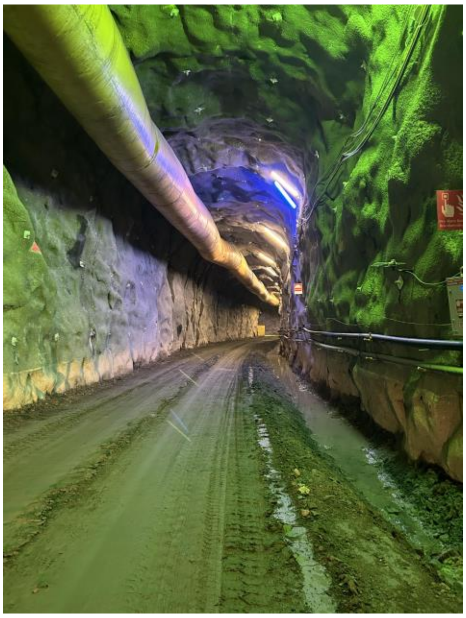


Figure 12. Ditches in the service tunnel (ST-101) for removal of particles through sedimentation.

3.6.2 Sedimentation containers

There are several sedimentation containers placed throughout the tunnel, as shown in Figure 12. There are two in tunnel section ST-101, which is the south service tunnel. There is one at the bottom of tunnel section ST-210, which is the service tunnel leading down from the entrance. There is one by the collection point and one in front of the tunnelling wastewater treatment facility. The purpose of these sedimentation containers is to remove the particles from the production water. The reason for not just having the ditches is that the quantity of water flowing for short periods during production would be too high for the ditches and it would flood the tunnel. The sediment containers can instead store the water and automated pumps let the container fill up with water so that the particles have enough time to settle. When the actual container is full, the water is pumped to the next container. This is done using flotation devices connected to the pumps. The flotation devices are placed at the top of the container and work as a switch and will turn on the pump when it gets full of water. The other is placed in the bottom of the container and will turn off the pump when the container is empty. This is done for most of the production water and enables the water to have time to sediment in each container until it reaches the collection point. The sediment container is also automated with flotation devices but there it has two purposes: to regulate the flow into the treatment facility and to let particles in the water settle before the water is pumped to the next step of treatment. The sediments are removed with sludge cars every other week. This somewhat impacts production as the sludge car will stop traffic in the tunnel during the time it operates. To minimize the impact there must be good communication regarding when and where in the tunnel the sludge car will be at what time (Plato, 2024)

The amount of sediment containers and how they are placed changes with production and need. The aim is to minimize the amount of sediment containers due to space limitation but mainly for the risk of pump failures. The more pumps running the more risk of one crashing, and if one of these pumps crashes, then the whole chain of treatment gets interrupted.

3.6.3 Sedimentation pond

After the collection point, all water in the tunnel that originates from both production water and in-leakage water is pumped to a sedimentation pond in tunnel section ST-205, which is the north end of the service tunnel. The sedimentation pond's capacity is approximately 1700 m^3 (Prokes, 2024). The water volume of the pond is normally held at around 800 m^3. This gives a buffer for the possibility of malfunctions or when discharge restrictions from Gryaab are active. The water enters the pond at one end where it first flows through a macadam bed before entering and then is pumped to the sedimentation container by the wastewater treatment facility at the other end of the pond. This gives the water plenty of time to decrease the turbidity by allowing particles to settle. In Figures 13 and 14 the sedimentation pond is displayed.

Figures 13 and 14. Sedimentation pond in tunnel ST-205.

3.6.4 Wastewater treatment facility

The wastewater treatment facility is the final step of treatment before the water gets discharged into the city's combined sewer system. The treatment facility is developed by Swedish Hydro Solutions (SHS) and is made to treat large amounts of water to meet the pollutant restriction levels in the contract. The facility can treat up to 20 m^3/h depending on the characteristics of the water. The facility consists of a first step with a pH regulation container with a capacity of 24 m^3, and then a so-called Hydrobox where chemicals are added and particles are flocculated, and thereafter a lamella separator for sedimentation connected to a sludge container for the settled particles, and finally a collection container (Swedish Hydro Solutions, 2023). A drawing of the treatment facility is shown in Figure 15.

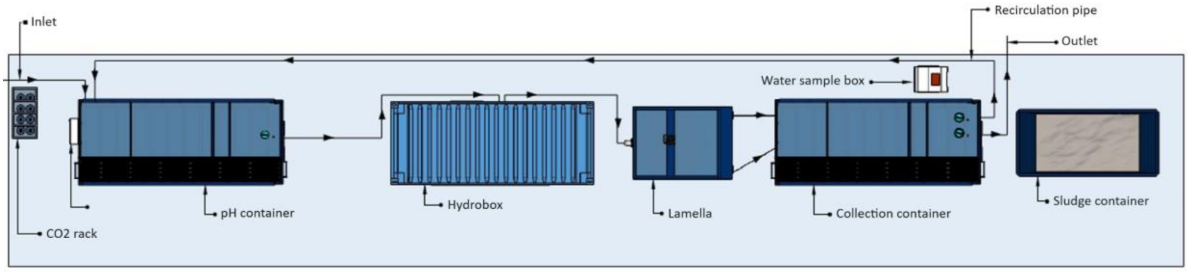


Figure 15. Water treatment plant Vasastan (Swedish Hydro Solutions, 2023).

3.6.4.1 pH regulation container

The pH regulation container (see Figure 16) is the first treatment step in the facility, and it will automatically release carbon dioxide to lower the pH when the incoming water has a pH value over 9. The pH container is only equipped with carbon dioxide and can only lower pH, not increase it. The reason for only having regulation possibilities for lowering pH is that all different types of construction in the tunnel that affect the pH generate water with an increased pH value (Swedish Hydro Solutions, 2023).

Figure 16. The pH regulation container (Photo by the authors).

3.6.4.2 Hydrobox

The Hydrobox is where the chemicals are added for flocculation. There are three chemicals used for the water treatment: Chitosan, PAX, and RedOx. The PAX and RedOx get dosed in liquid form while chitosan is dosed in the form of socks (Swedish Hydro Solutions, 2023).

Chitosan

Chitosan, also called chitosan lactate, is an active flocculant based on crab shells making it completely degradable. The chitosan is positively charged, which means it binds to negatively charged particles from suspended materials and particle-bound pollutants. In wastewater from tunnel production, silicon particles often appear and get flocculated with chitosan. Dual bag polymer (DBP) socks, also called HaloKlear 2100 DBP, are sometimes used as a supplement for chitosan, which has the same application but is based on another biological flocculant chemical that flocculates non-charged particles instead (Pettersson, 2024). In Figure 17, the three chitosan socks and one DBP sock are shown. The chitosan socks are the ones with a label and the DBP sock is the one without. The water flows on the board, gradually emptying the socks of the flocculant chemicals.

Figure 17. Chitosan socks inside the Hydrobox (Photo by the authors).

PAX

Aluminium salts are powerful chemicals used for pollutant removal on tunneling water. Phosphorus, for example, is one of the most common pollutants in construction water. Basically, the immobilization of phosphorus in sediments may be described as the aluminium flocculation accumulating on the sediment surface, allowing precipitation, and inactivating sediment with phosphorus. The restoration of water bodies using aluminium salts depends on many factors, e.g. pH, temperature, presence of oxygen, floc distribution, etc. (Rydin and Welch 1998; Zhao et al. 2011).

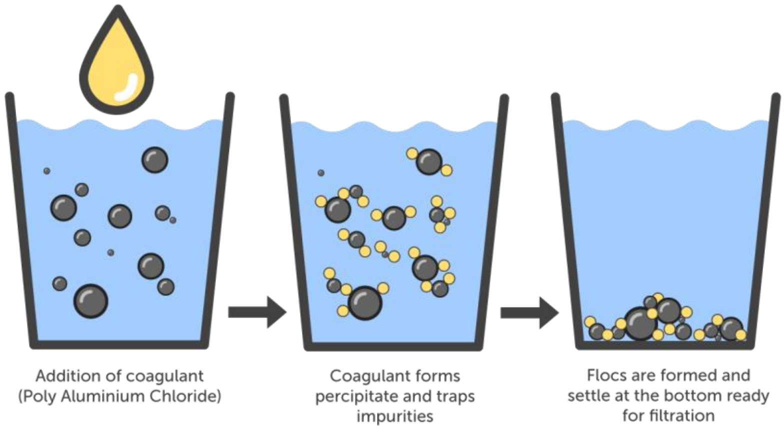


Figure 18. Polyaluminium chloride hydroxide (PAX) used as coagulant for water treatment (Chant, 2022).

PAX consists of polyaluminium chloride hydroxide and works as a flocculant, as seen in Figure 18. PAX is trivalent positively charged, which makes it possible to flocculate highly negatively charged particles that otherwise would repel each other. This chemical can stay dissolved in the water and is generally used for flocculation and sedimentation of metals and phosphorus. The aluminium makes the colloids with multiple substances (organic matter, phosphorus, metals, etc) flocculate and then sediment (Pettersson, 2024).

RedOx3

RedOx3 consists of iron (II) sulfate and works as a reduction chemical and a flocculant. It reduces chromium VI into chromium III, which is not as dissolvable in water and makes the particles sediment more effectively. Chromium III is also less harmful to humans and animals as it cannot pass through cell membranes and into the body where it can affect the cells and cause cancer (Pettersson, 2024). For the construction site, the treatment chemical named RedOx3, has been developed by Swedish Hydro Solutions. RedOx3 is used in the treatment process to remove hexavalent chromium (Swedish Hydro Solutions 2022). Chromium VI has a priority in water treatment since it is carcinogenic. In figure 19, the IBC containers from where PAX and RedOx are dosed is shown.

Figure 19. PAX and RedOx flocculants dosed from IBC containers (Photo by the authors).

3.6.4.3 Lamella separator and sludge container

After the flocculant chemicals are added to the water, the water enters the lamella separator, where the flocked materials sink to the bottom of the lamella separator, and the water can flow through on top of it. The sludge and flocked materials are emptied manually through a pump on the bottom of the lamella separator leading to a sludge container (Swedish Hydro Solutions, 2023). The sludge container is emptied by a sludge car regularly. The lamella separator and sludge container are shown in Figure 20 and 21.

Figure 20 and 21. Lamella separator used for sedimentation and connected sludge container (Photo by the authors).

3.6.4.4 Collection container

The collection container is the final step of the tunnelling wastewater treatment facility, and its purpose is to let the sediment in the water settle before the water gets pumped to the city's combined sewer system. In the collection container, there is also an automated ISCO sampler and a so-called EXO probe that monitors and gives continuous values on pH, turbidity, and conductivity. The automated ISCO sampler is used for taking flow proportional weekly water samples. It automatically fills up small containers of water depending on the volume of water that gets pumped out of the facility (Swedish Hydro Solutions, 2023). Figures 22 and 23 show the collection container and the automated ISCO sampler the collection container and the automated ISCO sampler are shown.

Figure 22 and 23. Collection container before discharge and automated ISCO sampler (Photo by the authors).

3.6.5 Costs

The costs only include costs for sub-contractors and their purchases and working hours and do not include the hours that Veidekke's tunnel workers and supervisors spend on running and maintaining the treatment facility. This is because they use only a part of their day to work on the wastewater treatment, and it is therefore hard to estimate the exact cost of their work.

The reference for the numbers in Tables 2 and 3 are received from Veidekke's invoice log.

Table 2: Initial implementation cost for the tunneling wastewater treatment facility.

Total cost for wastewater treatment facility	3 090 000 kr
Sediment container	155 000 kr
Hydrobox	1 950 000 kr
Lamella and sludge container	654 000 kr
Collection container	40 000 kr
Outgoing pump	26 000 kr
Gas alarm	215 000 kr
Installation	50 000 kr

The initial implementation costs shown in Table 2 do not include any of the costs for pipes, pumps, measuring wells, water level sensors, and sediment containers in the rest of the tunnel or the cost for the workers installing those components.

Table 3: Monthly costs for the tunnelling wastewater treatment system.

Total cost for wastewater treatment system	215 000 kr
Chemicals	50 000 kr
Maintenance and operation	45 000 kr
Sludge cars	120 000 kr

The average monthly costs for the facility since its installation are shown in Table 3. The cost for the chemicals is around 2-3 SEK per cubic meter of water going through the facility. For Maintenance and operation, the cost of Swedish Hydro Solution service technicians, which costs 850 SEK/h, as well as continuous measurements for 500 SEK/month and weekly water samples for 2 160 SEK/month are included. However, it does not include any of the tunnel workers' maintenance hours or the daily checkups of the treatment. The sludge car cost includes all sludge cars operating for all procedures in the facility, ditches, and the sedimentation pond.

4. Method

This investigation was performed by using a multi-criteria decision analysis (MCDA) approach applied to a case study area, in which four main aspects were evaluated: social, economic, environmental, and technical aspects. For each aspect, several criteria were scored and weighted against each other to reach the best combination of treatment procedures. This was conducted through a series of steps: A literature review (1), water chemical analysis based on sampling (2), questionnaires and interviews with identified experts (3), and the implementation of an MCDA (4). The results were compared to the current treatment procedures in the Vasastan tunnel at Västlänken Station Haga to contemplate any possible improvement that could be made. Each step is based on the goals and objectives established for the project. Therefore, all the different components of an MCDA must be built from the initial step of establishing the goals. Usually, these exclusion criteria hold a technical or scientific nature, and clarify inherent imperfections, or impairments of the alternatives related to physical constraints (Elliset al., 2004). This step is considered in the MCA and evaluated in the initial steps of the planning.

The investigation used raw data from water and sediment samples, literature studies, and invoices. Additional information was also gathered from other projects. Interviews were also held with tunnel workers.

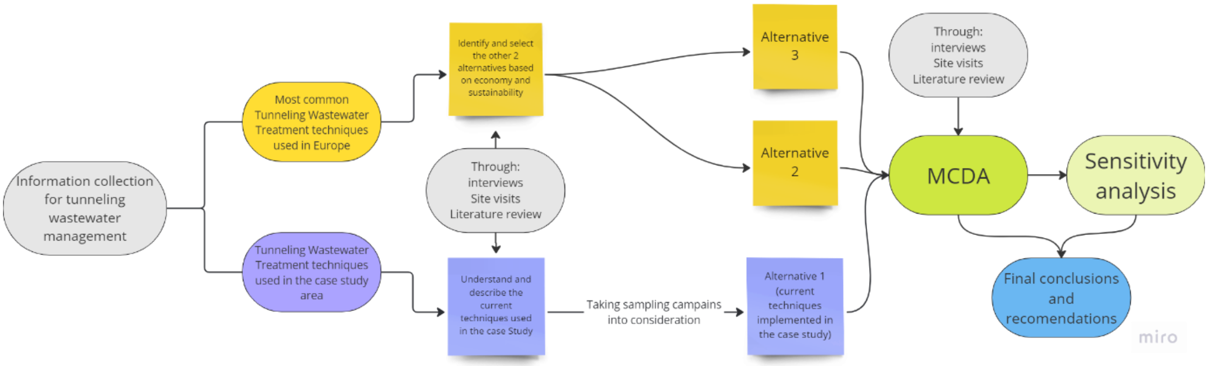


Figure 24. *Conceptual models for the MCDA methodology used in this project.*

4.1 Water quality sampling analysis

4.1.1 Water sampling

The water sampling was carried out as follows:

The first step was to determine which construction step generates the most suspended materials by using a handheld turbidity meter. The wastewater tested was collected directly by the source of the water generation. After an interview with Gay Plato

(2024), the construction steps that possibly generate the most suspended materials is drilling. Therefore, all the water samples were taken during the same drilling event.

The water sampling for the laboratory tests was performed in three different locations in the tunnel marked with red circles, as shown in Figure 25. At the first location, which is the tunnel face, wastewater directly from underneath the drilling rig was sampled. In this location, the water has no time to settle, and the result will reflect untreated water directly from the source. At the second location, the wastewater after the sedimentation steps was sampled. The water has then settled over several ditches, sediment containers, and a sedimentation basin. The third location was from the sample box at the outlet of the tunneling wastewater treatment facility, which shows the final water quality being released into the stormwater network. With these samples, the aim was to understand the impact of sedimentation on the water quality and what parameters the sedimentation reduced.

To determine the impact on water treatment for each step in the treatment process, a handheld turbidity meter and handheld pH monitor were used. By receiving values on turbidity and pH before and after each treatment step, the difference can be calculated and show the impact of each step. Measuring of turbidity and pH were also done after the sedimentation containers and the sedimentation pond to follow these parameters throughout the treatment process. The units used for turbidity are FNU, which stands for Formazin Nephelometric Units, and means that the instrument is measuring scattered light from the sample at a 90-degree angle from the incident light. FNU is most often used when referencing the ISO 7027 (European) turbidity method (Hach, 2022).

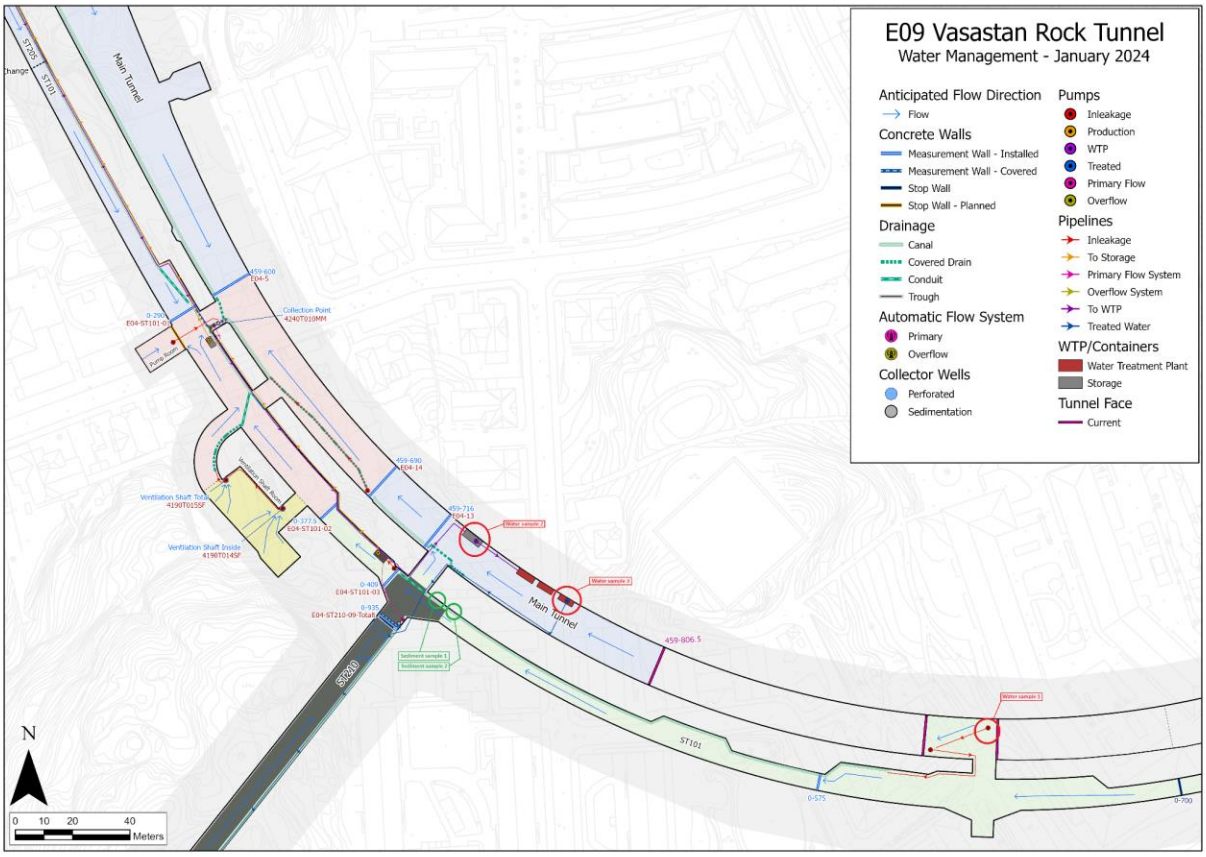


Figure 25. E09 Vasastan rock tunnel (Ramboll, 2024).

4.1.2 Sediment samples

In addition to the water samples, two sediment samples were taken from the ditches. The idea with these samples was to conduct a chemical evaluation to determine the concentrations of the different compounds that occur in the tunneling water.

4.2 Criteria evaluation of different aspects

This chapter describes how the criteria will be evaluated in terms of the different aspects investigated.

4.2.1 Environmental aspects

For the evaluation of the environmental aspects, four criteria were investigated: waste management, pollutant removal efficiency, energy and fuel consumption, and chemical consumption. Information regarding the different criteria was collected through the literature study and interviews with experienced personnel such as the site manager at Swedish Hydro Solutions. For the pollutant removal efficiency, further investigations of the Vasastan tunnel were gathered through water sampling and chemical analysis, analyzed both in laboratory and on-site. The laboratory samples were collected in small containers and sent to a laboratory where several chemical parameters were measured. The parameters were pH, conductivity, ammonium, magnesium, chloride, suspended materials, nitrogen, lead, cadmium, copper, chromium VI, chrome, nickel, zinc, and oil index. The measurements for metals were conducted by adding aqua regia to extract the total amount of metal in the water, both dissolved and solid. The on-site measurements of the samples were made using small handheld monitors that can detect pH and turbidity. The laboratory samples were performed once every week at the end of the treatment process in the wastewater treatment facility. By following the tunnel work schedule, it was possible to determine the treatment efficiency, the reduced environmental load, and the impact depending on the type of construction work that the water had passed through. Additional laboratory samples were performed before and after the investigated treatment process to determine the impact on the parameters.

The in-situ samples were performed in complement to the laboratory samples to assure the accuracy of the results through multiple measurements and the correlation between turbidity and suspended materials. The values on turbidity and suspended materials are especially interesting because most pollutants are bound to the suspended materials. Therefore, reducing the suspended materials reduces most of the pollutants as well. This minimizes the stress of the rest of the water treatment solutions and will lower maintenance (Pettersson, 2024).

Two sediment samples were also performed to determine the pollutant levels of stackable sediment and wet sediment from the ditches.

The water samples are also going to be compared with other construction sites where there are alternative solutions for treating water.

4.2.2 Technical aspects

For evaluation of the technical aspects, interviews were held. The site manager at Swedish Hydro Solutions provided information on the different solutions and estimated how well each solution performs based on four criteria: flow rate and volume capacity, reliability, maintenance and control systems, and space. In addition to the interview with the site manager at Swedish Hydro Solutions, an interview with the Veidekke site manager at Vasastan was held to further gather information, mainly regarding the maintenance.

4.2.3 Economic aspects

The economic aspects were divided into two aspects: implementation cost, and operational/maintenance cost. These can be evaluated by investigating past costs from treatment procedures already in place, by asking for quotations from contractors, or asking experienced tunnel supervisors for estimated budgets. If other projects with different treatment solutions are willing to show their treatment expenses it would also help.

The implementation cost can involve the purchase cost of materials for the treatment solution, the transportation costs to deliver it, and the cost of construction vehicles and tunnel workers needed to implement the solution.

Maintenance costs can involve purchasing chemicals, waste management, and maintenance of treatment solutions as efficiently as possible by tunnel workers and their construction vehicles.

4.2.4 Social aspects

The social aspects will consist of only one criterion, and it is worker's health and safety. It can be evaluated by looking at past risk assessments of treatment procedures already in place, and interviews with the health and safety department of the tunnel at Veidekke to get information regarding treatment procedures. The health and safety risk can be assessed both on implementing treatment procedures and the maintenance and presence of a treatment procedure.

4.3 MCDA application

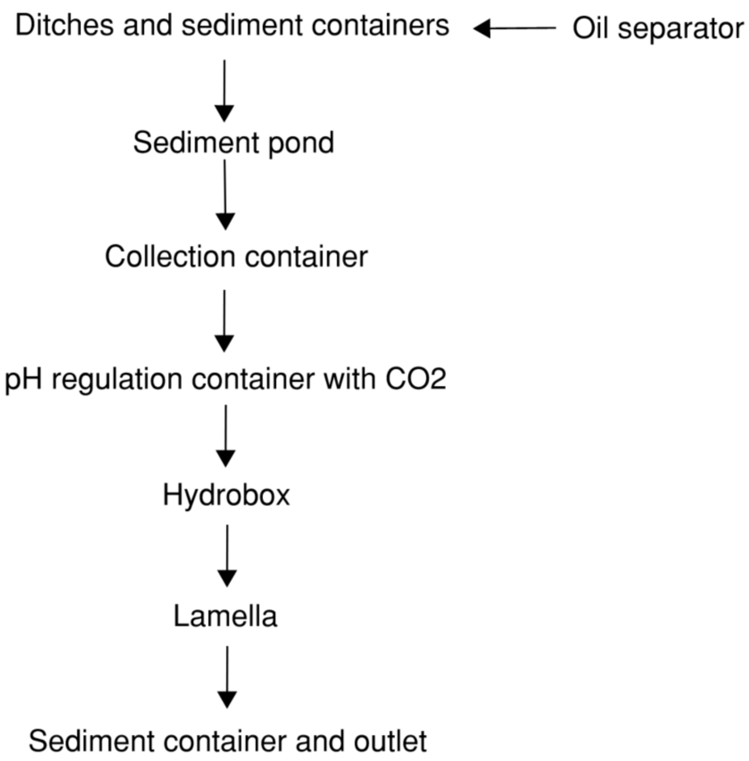
An MCDA was used to compare the tunneling wastewater management alternatives under defined criteria. The objective was to identify and rank possible solutions that can be adapted in the case study, based on the information gathered from the literature review, local preferences, regional trends and environmental requirements. Based on the MCDA application, the idea was to identify important factors and based on this information find even better treatment combinations for the case study area.

After interviewing the experts, the tunneling wastewater alternatives of interest for the study area were established. Moreover, information of interest for the MCDA was produced through discussions with different people who play a role in the decisions of the site, being aware of sustainable and low-cost parameters. Based on the review of available tunneling wastewater treatment techniques and the sampling campaign results, the scoring process was conducted considering the current situation as the baseline to which positive or negative impacts of the proposed alternatives were compared. From the questionnaire, input data for the weighting of the objectives and criteria were obtained. This way, the MCDA was performed based on the different experts and their points of view. The information gathered along the MCDA process was used as input and the sampling campaign results in a final evaluation discussion that showed further improvements that could be implemented in the study area.

4.3.1 Treatment solution combinations

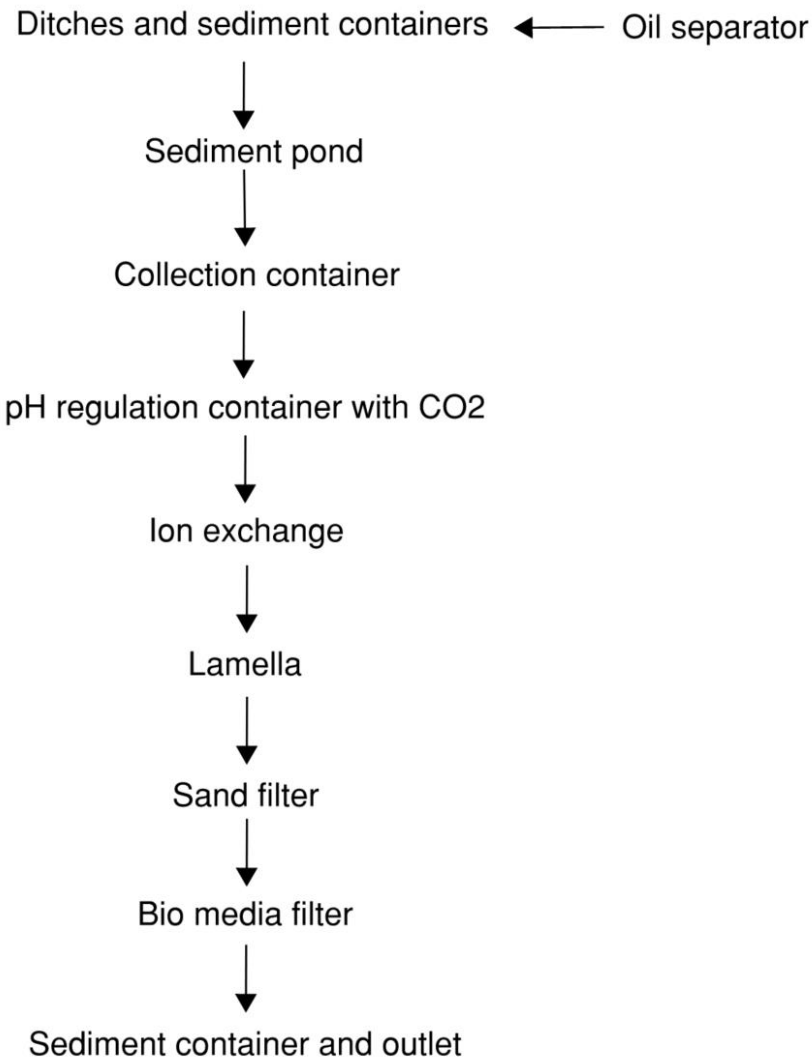
The different treatment solutions do not work alone. Water treatment facilities are a combined system of multiple solutions that in conjunction perform as a whole. Multiple combinations are implemented to fulfill the requirements. Based on the literature and interviews, three separate combinations of solutions were applied to the MCDA to receive the most realistic results. These combinations should in theory be able to treat the wastewater for all parameters with a limit value set by Länsstyrelsen. The first combination is the already existing water treatment combination at the Vasastan tunnel. The second is a water treatment combination that focuses on being environmentally friendly, as in low consumption of chemicals, fuel, and energy, and for the chemicals used, they will be as environmentally friendly as possible. The third is a water treatment combination that focuses on the cost for implementation and maintenance.

1st treatment solution combination (existing)



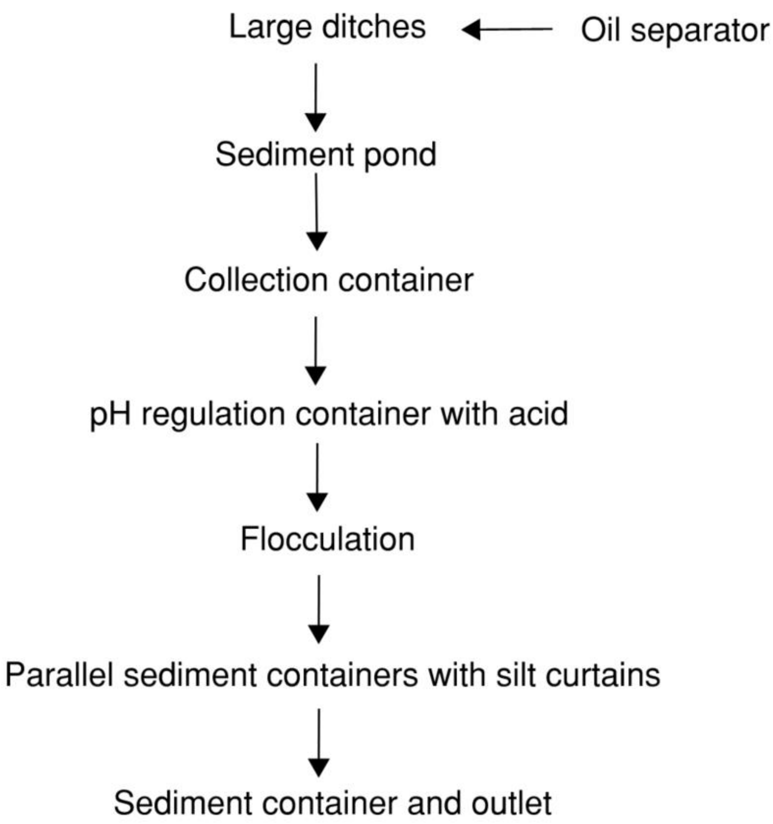
The ditches, sediment containers, and sedimentation pond reduce the amounts of suspended materials in the tunneling wastewater. The pH regulation container lowers the pH of the wastewater. The hydrobox adds flocculants to the tunneling wastewater to bind pollutants and allow them to settle. The lamella separator makes the rest of the suspended materials, and the flocculant-bound pollutants settle. The last sedimentation container works as a collection container for water to settle, making outlet pumping and water sampling possible.

2nd alternative treatment solution combination



The second alternative solution combination was developed with an environmental focus. The first four procedures in the environmentally focused solution combination and the existing treatment system are the same. After the pH regulation, ion exchange is proposed instead of flocculation. As explained in the theory section, ion exchange is a good technique to eliminate dissolved substances such as toxic metals. This procedure is more environmentally friendly since it does not generate as much waste as other techniques, also not having as much energy consumption as other techniques. When the ion exchange has bound the pollutants, they settle in a lamella before reaching a sand filter that reduces the suspended materials enough to let the water effectively be treated in the bio media filter. The last step is the same as the existing system where the water settles a final time and thereafter released into the combined sewer network.

3rd alternative treatment solution combination



The third alternative solution combination was developed with an economic focus. The large ditches give a higher flow capacity than the existing ditches in the Vasastan tunnel. The higher flow capacity removes the need for sediment containers, which cost money, as well as the pumps and pipes that both cost to implement and maintain. The sedimentation pond is a relatively cheap way to sediment water due to the only material needed is the pipes and pump that moves the water to and from the pond. The pH regulation container that adjusts the pH through adding acid is a cheaper technique than using carbon dioxide as in the other treatment systems. Flocculation is a relatively expensive solution but is needed to remove smaller dissolved pollutants. Ion exchange and filters can also be used for dissolved pollutants, but will probably not be cheaper (Pettersson, 2024). Parallel sediment containers will sediment the flocculated pollutants and particles and the silt curtains will further control the retention time and remove suspended materials.

4.3.2 Aspects and criteria

The aspects and criteria for the MCDA are shown in Table 4, and the description of each criterion is further described in Table 5.

Table 4 Aspects and criteria for weighting

Aspects	Criteria
Environmental	Waste generation
	Pollutant removal efficiency
	Energy and fuel consumption
	Chemical consumption
Technical	Flow rate and volume capacity
	Reliability
	Maintenance and control system
	Space
Economic	Initial implementation costs
	Operational and maintenance costs
Social	Health and safety risks

Table 5 Description of criteria for weighting

Criteria	Description
Waste generation	What type of waste is generated and how much?
Pollutant removal efficiency	At what rate are the pollutants that the solution is supposed to reduce removed?
Energy and fuel consumption	How much energy and fuel are used to operate and maintain the solution?
Chemical consumption	What type of chemicals are used and how much?
Flow rate and volume capacity	How much water can flow through the solution and still be treated efficiently?
Reliability	What is the probability of the solution failing during construction? How likely is the solution to malfunction?
Maintenance and control system	What maintenance is needed to operate the solution? How frequent is the maintenance?
Space	How much space does the solution take up? Will it cause problems for production?
Initial implementation costs	How much is the cost to implement the solution?
Operational and maintenance costs	How much is the cost to operate and maintain the solution?
Health and safety risks	How dangerous is it for workers to operate with or close to the solution? Potential hazards?

For the economic aspects, the viewpoint of the scoring and weighting should be as a lump-sum contract, which means that the lowest total price possible for all expenses is preferable. This will differ from the contract in the case study of Vasastan where the contract is a Cost-plus contract, which means that the contractor gets paid for all their expenses and additional percentage (Ellis, 2023). To further specify the financial costs. The implementation costs will be purchasing costs and not rental costs. This will leave the operational and maintenance costs to only operational and maintenance costs. The maintenance and operation costs should be regarded as a cost for about 6 more years.

4.3.3 Weighting

For the weighing, experts from Veidekke with expertise in each of the different aspects, as well as experts from the Swedish Transportation Administration, were invited. The weighting was done in groups with the experts from different aspects areas separately. First, the experts filled in the questionnaire sheet individually, and the results were shown to the group and after a discussion, the group came up with a combined group weighting. The group weighting was then compared with the other groups, and a median weighting was calculated. The dividing was as follows:

Environmental experts (Veidekke)

Titti Johansson, Pia Hildesson, Maja Fredman

Technical experts (Veidekke)

Gay Plato, Martin Holmstedt, Robin Johanesson

Economic experts (Veidekke)

Petter Rignell, Andreas Olander

Social experts (Veidekke)

Erik Hellhager, Lina Grunden

Swedish Transportation Administration experts

Andreas Werme, Daniel Östling

The scoring sheet that was presented for the weighting is shown in Appendix I.

5 Results and discussion

5.1 Water and sediment sampling results

One of the main goals of this thesis was to understand the current level of pollutants during the whole water cycle in the tunnel construction and how the different treatment techniques affect the pollutant removal efficiency in the water treatment procedures in the tunnel. To accomplish this goal, water and sediment samples were taken during sampling campaigns. This section shows and discusses the results obtained in the sample campaigns and how this information was implemented to the final results and conclusions.

5.1.1 Laboratory water samples

The sampling campaign on 2024-04-09 was performed in different locations of the construction site, coinciding with the time when blasting and drilling were executed. For the laboratory analysis, three water samples were taken: at the tunnel face where the construction wastewater was generated, before and after the tunneling wastewater treatment facility. The results of these three analyses are shown in Table 6.

Table 6. Results from the laboratory analysis of water samples.

Parameter	Limit value	Tunnel face	After sedimentation	Outgoing water from treatment facility
pH	6.5<pH<10	>11	10	7.5
Conductivity (mS/m)	500	270	62	91
Ammonium (mg/L)	60	0.63	8.7	11
Suspended solids (mg/L)	150	3300	41	11
Lead (mg/L)	0.05	0.16	0.00075	<0.00050
Cadmium m (mg/L) g/L	0.0005	0.0034	<0.00010	<0.00010
Copper (mg/L)	0.2	0.21	0.0098	0.0065
Chromium (mg/L)	0.05	0.26	0.026	0.0044
Chromium VI (mg/L)	0.007	0.058	0.024	<0.00020

Nickel (mg/L)	0.05	0.2	0.0039	0.0027
Zinc (mg/L)	0.2	1.4	0.012	0.003
Oil index (mg/L)	5	3.5	0.34	<0.11

As shown in Table 6, drilling, blasting, and concrete activities at the tunnel face make all the measured values considerably high. Out of the 12 restricted parameters, 8 were above the limit admissible values (shown with red marking) at this sector of the construction site. But as expected, after the sedimentation procedures such as sediment containers and ditches, it is clear how the different measured values decrease. This gives the opportunity to highlight the fact that sedimentation techniques are one of the most efficient ways to separate pollutants from construction wastewater. However, sedimentation was not enough, and there were still high pollutant concentrations that had to be lowered. The results after the treatment facility showed that the treatment procedures in the facility were crucial to reaching the target values.

Taking a deeper look into the laboratory analysis, the wastewater generated at the tunnel face was extremely polluted and alkaline caused by drilling, blasting, and shotcreting. After the water passes through ditches and sedimentation containers, the suspended particles have time to settle, which also reduces the concentration of the pollutants and toxic metals in the water. Nevertheless, other characteristics of the water, such as pH or chromium VI were not sufficiently reduced. They barely made the limit value, while the strict limit value for chromium VI was not upheld.

The last sample taken at the outlet showed that the treatment facility was efficient in dealing with those parameters that sedimentation could not afford. The critical pH value and chromium VI were sufficiently reduced. However, the conductivity increased while passing through the treatment facility which is a consequence of ions released by flocculants.

5.1.2 In-situ water samples

For tunneling wastewater treatment, two principal factors are relevant: pH and total suspended solids in the wastewater. Eight strategic places were spotted in the water chain inside the tunnel to evaluate the variation of the water properties during the entire water cycle. Turbidity and pH levels were measured at each point to check the effectiveness of each technique. This section shows the results of each measurement point, in Table 7, and the discussions about them.

Table 7. Results of in-situ measurements of water samples after all treatment steps.

Measurement point	pH	Turbidity (FNU)
First sedimentation container	10.4	167
Second sedimentation container	10.4	121
Final sediment pound containers	10.2	85.2
First container in the treatment facility	10.2	76.1
pH adjustment container	9.0	69.8
After hydrobox in the lamella	7.9	38.2
Last container in the treatment facility	7.9	20.0

The results from the measurement campaign are consistent with the expected values. As shown in Figure 26, at the beginning of the water cycle in the tunnel, and where the wastewater is generated, the pH of the tunneling wastewater had the highest value (>11) characterized as highly alkaline water. Then, after the water passes through the ditches, the measurements in the sedimentation and collection containers do not vary since at these points no technique was implemented to adjust the pH. Only after the pH adjustment container does the pH values vary from alkaline to more neutral. Sedimentation techniques do not affect the pH in the water, but CO_2 added in the pH adjustment container greatly decreased the pH in the wastewater. Moreover, the hydrobox also affects the pH due to the chemicals that are added to the water, flocculants separate the dissolved substances from the water, decreasing the pH into a more basic water solution. The measured values obtained in the lamella after the hydrobox (flocculation) show how the dissolved pollutants also affect the pH in the water. Finally, since both values from the lamella and the last container are the same, this coincides with the idea that the total suspended material does not influence the pH of the water.

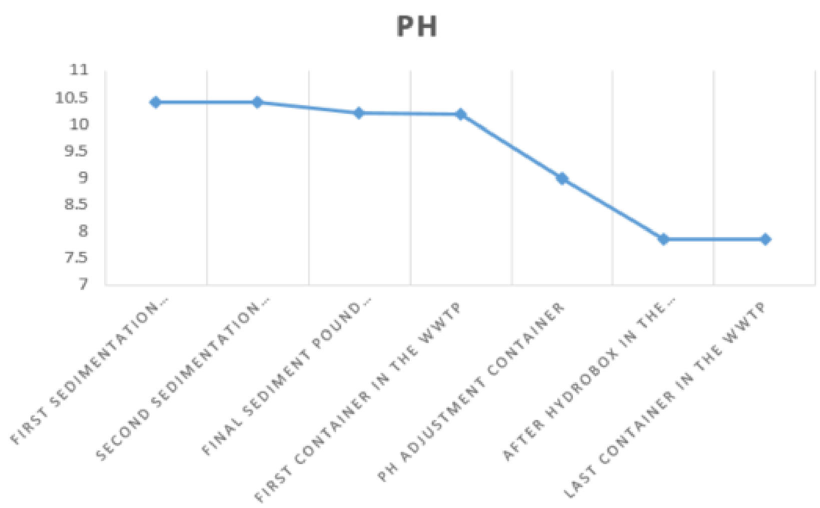


Figure 26. pH values for in-situ water samples taken after the different treatment steps.

At the same time turbidity, which starts considerably high at the wastewater point of origin, as seen in Figure 27, tends to decrease by the time the water passes through the different treatment techniques and compartments. The idea behind taking turbidity samples was to check the removal efficiency after each treatment step. In the first place, the purpose of the sedimentation containers is to decrease the suspended material as much as possible before the water enters the treatment facility. The lack of space and the capacity of the ditches and sedimentation containers limit the sedimentation rate of the tunneling wastewater. After the pH adjustment container, the water is separated from the suspended solids and the hydrobox flocculates the dissolved substances, putting the water in the final stage of the lamella separator procedure. The lamella separator is the last technique that separates suspended materials from the water, disposing the water in the storage container at the end of the treatment facility.

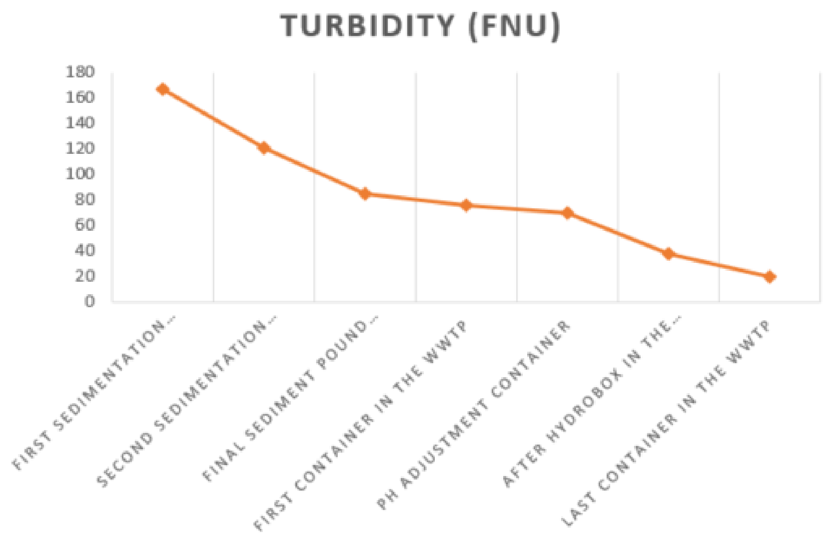


Figure 27. Turbidity values for in-situ water samples taken after each treatment step.

5.1.3 Sediment samples

Two sediment samples were taken in the ditches during water tunneling production and sent to the laboratory for analysis. One of them had more water content than the other. In order to differentiate them, One is going to be called as a "Consolidated sample" and the other one is a "saturated sample". The consolidated sample is the one that has less water content compared with the other sample. The characteristics of these samples were one consolidated sample with a mass percentage of 59.6% and the other was unconsolidated material immersed in water (saturated sample) with a mass percentage of 11.8%; both samples were taken 20 centimeters below the sediment surface. Different parameters were evaluated and compared with the Swedish Environmental Protection Agency's general guideline values for contaminated lands (NV 5976). Sensitive land use (KM) and less sensitive land use (MKM) guideline values were taken into consideration to evaluate the content of the samples. More than 60 parameters were measured for both samples and most of them were below the minimum value for quantification reported by the laboratory.

For the saturated sample, the results for the values above the minimum value of quantification are presented in Figure 28. Organic pollutants such as aliphatic hydrocarbon compounds were found in the sediment. The minimum accepted value for C_{12}-C_{16} and C_{16}-C_{35} in the sediment for KM is 100 mg/Kg DS. Both parameters had considerably high values, exceeding the minimum accepted value for sensitive land use KM. On the other hand, elements such as chromium, zinc and barium were also found in the sample, but these parameters were below the guideline values for both KM and MKM.

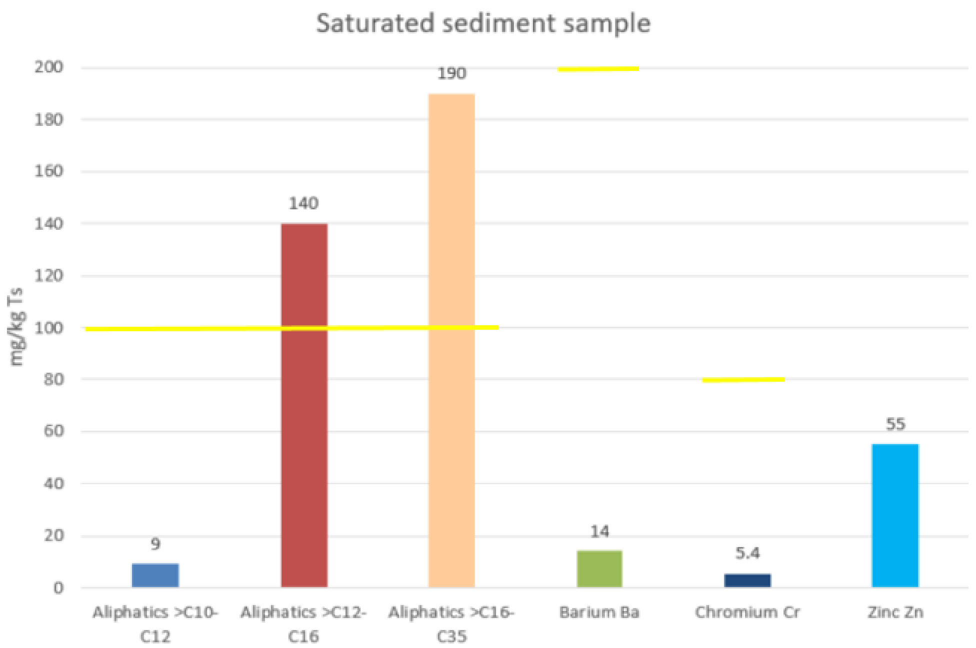


Figure 28. Concentrations of aliphatic hydrocarbons and other compounds in the sediment in the saturated sediment sample.

The results for the consolidated sediment sample are illustrated in Figure 29. As expected for the consolidated sample, the results showed higher values of toxic metals in the sediment. Chromium, copper, and zinc were metals measured under the guideline limits, but they were still considered as “less than low risk”, meaning these metals were relatively close to the limit values.

However, the guideline value for barium and cobalt for KM is 200 and 15 mg/Kg DS respectively, and both parameters had considerably high values in the sediment, exceeding the minimum accepted value for sensitive land use (KM). Other parameters such as aliphatic hydrocarbons were also found in the samples, but they were below the limit values.

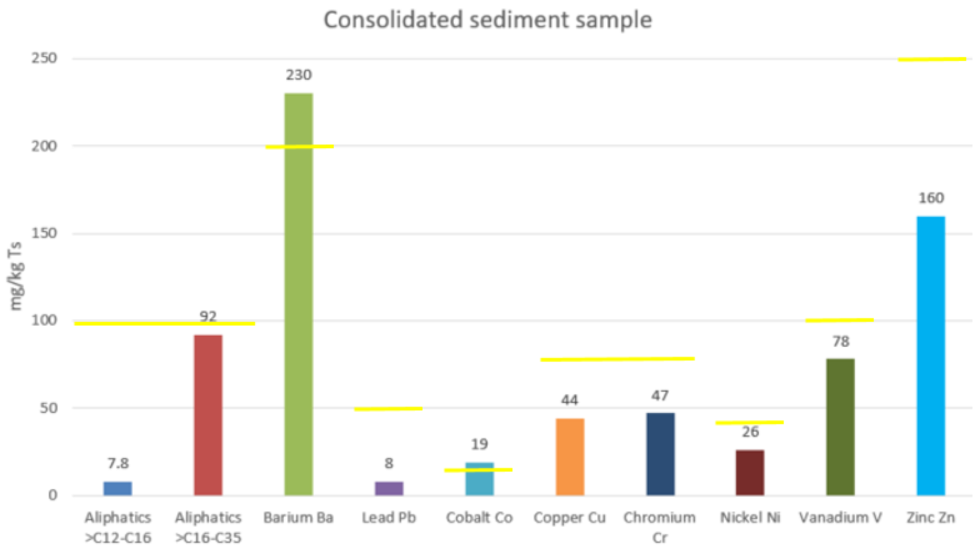


Figure 29. Concentrations of aliphatic hydrocarbons and other compounds in the sediment in the consolidated sediment sample.

From the results it is clear that most of the metals and other pollutants can easily be separated from the water using gravity as the working agent for sedimentation. The total suspended solids in polluted water usually have pollutants attached to the particles; this makes sedimentation a crucial step for the treatment procedures. In other words, when the suspended material is separated from the water, half of the work is already done. Therefore, sedimentation solutions are the most effective way of reducing the amount of polluted material that needs to be treated. Different techniques, such as ditches, sedimentation containers, and lamella structures, among others, provide possibilities of improvement in the existing facilities.

The sediment collected from the ditches and sediment containers is transported on trucks for special treatment procedures. There are not too many specifications about how the sediment is being treated and disposed, since the project only focuses on the water treatment. We only took sediment samples to have a realistic idea of the current state of the study area.

5.2 Scoring

For the scoring procedure, each criterion was individually evaluated for the different solutions. In this section, the different considerations and final scoring are presented.

Table 8. Scoring of the criteria for each alternative treatment solutions.

Criteria	1st alternative	2nd alternative	3rd alternative
Waste generation	2	3	3
Pollutant removal efficiency	3	3	4
Energy and fuel consumption	3	3	5
Chemical consumption	2	4	1
Flow rate and volume capacity	3	2	4
Reliability	3	2	4
Maintenance and control system	2	3	4
Space	4	4	5
Initial implementation costs	4	4	5
Operation and maintenance costs	3	1	4
Health and safety risks	4	5	1

5.2.1 Waste generation

For waste generation, the first alternative generates sediment throughout the tunnel in ditches, sedimentation containers, the sedimentation pond, and in the different steps of the wastewater treatment facility. The socks used in the hydrobox are biodegradable but still need to be changed daily, therefore the first gets a low score. The second alternative generates more or less the same amount of sediment throughout the tunnel, but there is no waste on a daily basis with socks. Instead, there are bio media filters and ion exchange matter that need to be changed but on a long-term basis. This results in a slightly higher score than the first alternative. The third alternative generates sediment in the sediment pond and the ditches throughout the tunnel as well as in the treatment facility. The issue restricting the third alternative from a high score is that the sediment will be spread out to a larger extent than the other systems in the large ditches.

5.2.2 Pollutant removal efficiency

For pollutant removal efficiency, the first alternative is relatively sufficient. However, during times with a flow > 20 m^3/h, the facility cannot sufficiently treat the water, and when pumps in sediment containers are set up incorrectly so that they are standing in the mud sediment will be pumped to the next treatment step exceeding the capacity of the wastewater treatment facility. There is no step for the removal of oil in the treatment facility, except at the workshop area. Therefore, whenever a spill of oil happens anywhere else in the tunnel except in the workshop sorbent material has to be used to stop the oil from spreading. There is no treatment of methylenedianiline (MDA) from chemical grouting which means that everything that leaks through the tarp laid out to collect the water means that MDA is not removed before released into the stormwater network. Other than that, the existing system is sufficient in pollutant removal efficiency. For the second alternative, the bio media filter removes oil spills and MDA from chemical grouting that affects the scoring for the existing system. However, the ion exchange is very effective in reducing inorganic ions, but there is no information on how it can reduce chromium VI, which might mean that a flocculant like RedOx is needed as well. Because of the uncertainties regarding chromium VI, the score will be the same as for the existing system. For the third alternative, the larger ditches will provide more sedimentation of sludge before entering the treatment facility, which will minimize the workload for the facility and result in more sufficient treatment. However, if the larger ditches are not sufficient enough to reduce the suspended materials, the treatment facility with the sedimentation containers with silt curtains is not as efficient as the lamella. This uncertainty restricts the third alternative from the highest scoring.

5.2.3 Energy and fuel consumption

For energy and fuel consumption, the first alternative uses electricity for the pumps in between all containers and treatment steps. Sludge cars are also needed approximately once a week at several locations and steps in the treatment system. The sediment in the ditches also needs to be excavated and transported away from the site by trucks. The second alternative has more or less the same energy and fuel consumption as the first alternative. However, the third alternative has fewer pumps, and the simple setup with sediment containers with silt curtains instead of a lamella further decreases the electricity consumption. This results in the highest score for the third alternative system.

5.2.4 Chemical consumption

For chemical consumption, the first alternative uses most of its chemicals in the hydrobox. PAX and RedOx which are two relatively environmentally friendly chemicals, are added in the hydrobox, but if they are overdosed, they can still be harmful. Chitosan socks have a short lifetime, and the two socks are changed every day. For the second alternative, there is no use of flocculation chemicals instead, it uses ion exchange, which reduces the polluted particles into something less harmful. The chemical consumption is lower for the second alternative and uses less harmful chemicals than the first alternative, so therefore it receives a higher score. The third alternative uses flocculants as well as acid for pH adjustment, which is a lot more harmful than using CO_2 as the other systems. The acid is also strong which can make a huge impact on the environment if it gets overdosed and released into the stormwater network. Therefore, the third alternative receives the lowest score.

5.2.5 Flow rate and volume capacity

For flow rate and volume capacity, the first alternative has a capacity of 20 cubic meters per hour, but the ditches in the tunnel cannot handle this volume and therefore require pumps and pipes to the sedimentation containers placed along the tunnel. This volume problem would be the same for the second alternative because it is composed of the same kind of ditches and sedimentation containers. However, the treatment facility itself is probably more restricted due to the ion exchange and bio media filter, which has a slightly lower volume capacity and therefore scores lower than the first alternative. The third alternative is composed of larger ditches, which hopefully are sufficient to have high volume capacity, but the sediment containers with silt curtains will restrict the system from getting the highest scoring.

5.2.6 Reliability

For reliability, the first alternative has several pumps with flotation sensors that often malfunction in various ways. However, the large sedimentation pond gives a buffer that is located later in the water treatment process, but for the pumps to the sediment containers before the sedimentation pond, there is no buffer for malfunctions. The buffer problem is the same for the second alternative, but it has a higher risk of clogging due to the ion exchange, sand filter, and bio media filter. Therefore, the score is lower for the second alternative. The third alternative requires fewer pumps that can malfunction and fewer treatment procedures, and the issue preventing it from getting the highest score is the risk of clogging the silt curtains.

5.2.7 Maintenance and control system

For the maintenance and control system, the first alternative requires a daily change of chitosan and almost daily emptying of sludge in the lamella. There are several different containers and treatment components located throughout the tunnel that require sludge cars at least every other week. The EXO probe gives continuous measurements on parameters and indicates whenever a parameter is exceeded. For the second alternative, the problem with sludge cars is the same as for the first alternative. However, the ion exchange and filters require less maintenance daily, and therefore, the second alternative system receives a higher score. For the third alternative, the use of sludge cars for regular maintenance is limited solely to the treatment facility. However, the larger ditches will produce more sludge that needs to be excavated out of the ditches. The ditches will not need to be emptied at the same interval as the ditches in the first alternative but will have more sludge whenever it is due. Although there are some issues with the large ditches, the third alternative system receives a higher score than both the first and second alternative.

5.2.8 Space

For space, the first alternative has a small and compact treatment facility and a sedimentation pond that is located in an area where it does not affect ongoing production. However, the ditches and sediment containers prevent the existing system from receiving the highest score. The second alternative requires the same amount of space as the first alternative except for a bio media filter and a sand filter that can fit into a container which is no big difference to give it the same score as the first alternative. For the third alternative, the treatment facility will be the same size as the third alternative system but will not have any containers located throughout the tunnel, and therefore, it receives the highest score.

5.2.9 Initial implementation costs

For the initial implementation cost, the first alternative is relatively cheap to implement. The cost comes with the hydrobox as well as the installation costs for the pipes to the sedimentation containers throughout the tunnel. For the second alternative, most of the costs are the same except that the ion exchange is cheaper than the hydrobox but that evens out with the bio media and sand filters, which gives the second alternative system the same scoring as the first alternative. For the third alternative, there is no installation of pipes for sedimentation containers throughout the tunnel which lowers the cost. The use of sedimentation containers with silt curtains in the treatment facility is cheaper than a lamella which lowers the cost even more. Therefore, the third alternative system receives the highest score.

5.2.10 Operation and maintenance costs

For operation and maintenance costs, the first alternative has a relatively high cost for chemicals and a similar cost for service technicians for Swedish hydro solutions. The cost of sludge cars is higher than the cost of chemicals and technician services but that one is difficult to lower. For the second alternative, the cost of chemicals could be cheaper due to the lower cost for ion exchange matter than flocculants but the cost for service technicians and maintenance will increase due to the sand filter and bio media filter. The long-term cost of the filters and the ion exchange is relatively high. This gives the second alternative a lower score than the existing system. For the third alternative, the cost of maintaining the ditches might increase somewhat but it could store more sludge before it needs to be excavated compared to the other system’s ditches, which means that the interval between the maintenance would be longer. Acid is also cheaper than the CO_2 used in the other systems. The need for service technicians will also be lower due to less complicated treatment steps that can be maintained by tunnel workers. This gives the third alternative system a higher score than the other systems.

5.2.11 Health and safety risks

For the health and safety risks, the first alternative has one critical risk when changing the flocculants because PAX and RedOx are harmful to get in contact with. Otherwise, the risks are related to the “open” treatment steps where the water can be contaminated and easy to get in contact with or if the worker falls or drives into a ditch. For the second alternative, the only critical risk is the same with the “open” treatment steps as in the first alternative. Otherwise, there are no critical risks of getting in contact with any chemicals or other risk factors. Therefore, the second alternative system receives the highest score. For the third alternative, the risk related to the “open” treatment steps is greater due to the larger ditches. There are also risks when changing flocculants, but the highest risk would be the acid used for pH adjustment, which is very harmful and not recommended to use. Therefore, the third alternative system receives the lowest score.

5.3 Weighting

The weighting gave each department with involved personnel a chance to supply their thoughts and priorities. Their weighting, comments, and suggestions reflected their line of work and useful information was provided to the report.

The following sections show the expert’s weighting, the average weighting, and the comments and suggestions from the meetings.

5.3.1 Weighting by environmental experts

As expected, the environmental experts put the environmental aspect as the most important aspect with pollutant removal efficiency as the highest rated criterion. The technical aspect followed with a high weighting, where reliability was put the highest. That might be due to the risk of discharge of water with water parameters over the restriction limits to the stormwater network if a solution to the tunneling wastewater treatment system (WWTS) were to malfunction or if the load of water were to be too high.

The environmental experts are also involved in maintaining the treatment facility, and therefore, the high weighting on operation and maintenance costs can be described.

Table 9. Environmental experts weighting sheet

Department
Environment

Name (voluntary)
Titti Johansson, Pia Hildesson & Maja Fredman

Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	35	Waste generation	8
		Pollutant removal efficiency	13
		Energy and fuel consumption	7
		Chemical consumption	7
Technical	28	Flow rate and volume capacity	7
		Reliability	10
		Maintenance and control system	5
		Space	6
Economical	20	Initial implementation costs	7
		Operation and maintenance costs	13
Social	17	Health and safety risks	17
	100%		100%

5.3.2 Weighting by technical experts

The technical experts prioritized the technical aspects and the criteria that impacted them the most with the highest percentages. Fuel consumption is something relatable to them as well as the impact of reliability. Reliability impacts their daily work as any interruption affects their schedule and they have to fix the problem before continuing or at least reorganize the workers to fix the problem. A notable criterion is space. They set the space weighting very low even though they are the ones most affected by it. They argued that it is more important to have a sufficient water treatment system than the extra square meters they might get.

Further comments they made regarding the weighting were the importance of buffer basins before and after the wastewater treatment facility. With buffer basins before the facility, a steady flow to the facility could be possible and the water would have time to sediment. The buffer basin after the treatment facility would help when no water is allowed to be released into the stormwater network.

These basins of treated water could also be used for the recirculation of water for the machines. If the water is clean enough, machines like drilling rigs do not have to use fresh water but treated tunneling water instead which would lead to less water in the tunnel’s water cycle. It would also further lengthen the detention time of water in the tunnel when no water is allowed to be released to the stormwater network.

Table 10. Technical experts weighting sheet

Department
Technical

Name (voluntary)
Gay Plato, Martin Holmstedt & Robin Johannesson

Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	30	Waste generation	10
		Pollutant removal efficiency	5
		Energy and fuel consumption	10
		Chemical consumption	5
Technical	33	Flow rate and volume capacity	10
		Reliability	15
		Maintenance and control system	6
		Space	2
Economical	17	Initial implementation costs	5
		Operation and maintenance costs	12
Social	20	Health and safety risks	20
	100		100

5.3.3 Weighting by economic expert

The economic experts had a similar weighting as the technical experts except a few percent moved from the social to the economic aspects.

They had one comment on the weighting and that was the possibility of demolishing the wastewater treatment system and reinstalling it at the next construction site. The wastewater treatment components have a longer life expectancy than the five years that have been set as an assumption for weighting and therefore a criterion such as space and initial implementation costs can be influenced if it is possible to use the facility at other construction sites when the current construction site is finished.

Table 11. Economic experts weighting sheet

Department
Economical

Name (voluntary)
Petter Rignell & Andreas Olander

Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	30	Waste generation	8
		Pollutant removal efficiency	10
		Energy and fuel consumption	5
		Chemical consumption	7
Technical	35	Flow rate and volume capacity	10
		Reliability	11
		Maintenance and control system	9
		Space	5
Economical	20	Initial implementation costs	8
		Operation and maintenance costs	12
Social	15	Health and safety risks	15
	100		100

5.3.4 Weighting by social experts

The weighting of the social experts clearly shows that they think health and safety is the most important criterion taking up more than ⅓ of the total percentage of the 11 criteria. A reason for this could be that they wanted the social aspect to be shown as the most important aspect out of the four.

The social experts had two comments on the weighting. The first one concerns the risk of anchoring. The weighting sheet includes examples of how the experts could weigh the different aspects and criteria. This could potentially lead to a false value due to anchoring. The example might influence the expert’s values if they see that it weighed a specific criterion differently than their first impression.

The other comment was on the lack of consistency in the number of criteria per aspect. This could potentially lead to false values when the aspects with more criteria get a higher percentage and the aspect with fewer criteria gets a lower value than the other aspects.

Table 12. Social experts weighting sheet

Department	
Health & Safety	

Name (voluntary)	
Erik Hellhager & Lina Grunden	

Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	31	Waste generation	7
		Pollutant removal efficiency	10
		Energy and fuel consumption	5
		Chemical consumption	9
Technical	22	Flow rate and volume capacity	4
		Reliability	7
		Maintenance and control system	4
		Space	7
Economical	11	Initial implementation costs	6
		Operation and maintenance costs	5
Social	36	Health and safety risks	36
	100%		100%

5.3.5 Weighing by the Swedish Transport Administration

The experts from the Swedish Transport Administration prioritized the environmental and technical aspects over the economic and social aspects. Whereas the difference in weighting between the criterion was the lowest.

Table 13. Swedish Transport Administration weighting sheet

Department	
Trafikverket	

Name (voluntary)	
Andreas Werme & Daniel Östlund	

Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	33	Waste generation	8
		Pollutant removal efficiency	10
		Energy and fuel consumption	10
		Chemical consumption	5
Technical	32	Flow rate and volume capacity	10
		Reliability	9
		Maintenance and control system	8
		Space	5
Economical	20	Initial implementation costs	7
		Operation and maintenance costs	13
Social	15	Health and safety risks	15
	100		100

5.3.6 Average weighting

The average weighting was made by calculating the mean value of the different criteria values set by the weighting groups and then calculating the corresponding aspect value. The average weighting is shown in Table 14 and Figure 30.

Table 14. Average weighting sheet

Average weighting			
Aspects	Aspect weighting	Criteria	Criteria weighting
Environmental	32	Waste generation	8
		Pollutant removal efficiency	10
		Energy and fuel consumption	7
		Chemical consumption	7
Technical	29	Flow rate and volume capacity	8
		Reliability	10
		Maintenance and control system	6
		Space	5
Economical	18	Initial implementation costs	7
		Operation and maintenance costs	11
Social	21	Health and safety risks	21
	100		100

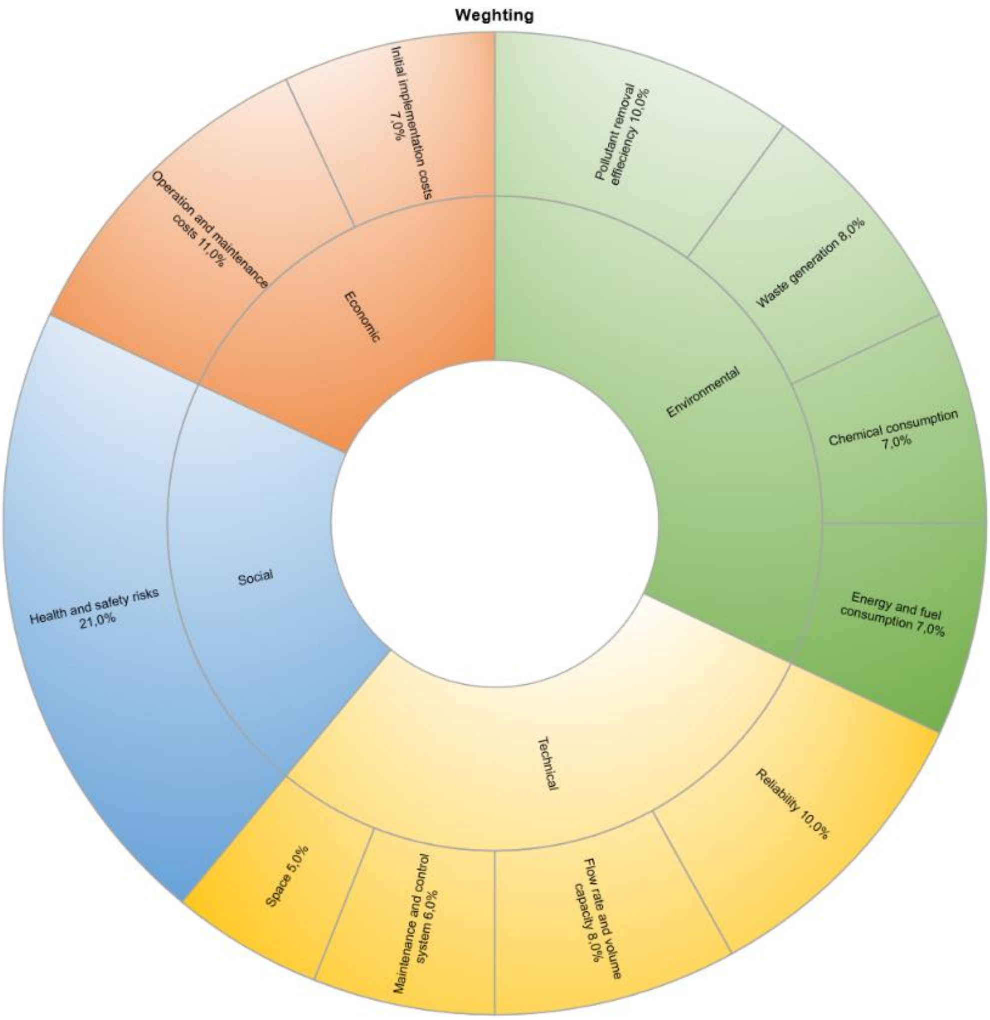


Figure 30. Weighting graph. Distribution in percentage of the different criteria.

The average weighting shows that the environmental and technical aspects are prioritized with pollutant removal efficiency and reliability as the most important criteria. For the economic aspects, the operation and maintenance costs are prioritized, probably because of the assumption that all the treatment procedures are bought and not rented to a hypothetical project that lasts for at least five years. The social aspect with health and safety risks as its only criterion is ranked almost twice as high as the second most prioritized criterion, showing that a water treatment system lacking health and safety implementation is not an option. Space is the lowest-ranked criterion, even though this is a common concern at most tunnel construction sites. This reason for it being a common concern might be because this is the criterion that gets marginalized due to the importance of everything else and therefore the most notifiable as a problem.

The comments gathered during the weighting meeting were the following:

- Recirculation of water to minimize the need for new freshwater entering the

tunnel and lengthening the detention time for the water in the tunnel when no water is allowed to be released into the stormwater network
- The importance of having a large buffer basin before and after the water treatment facility to be able to handle events like maintenance, releasing restrictions, and incomplete treatment of water
- The possibility to demolish the facility and install it on a new construction site when the current construction site is finished
- Anchoring - by showing examples in the weighting sheet, the participants might get influenced by the example values and change their mind
- The fact that it is different amounts of criteria for each aspect might influence the participants to put a lower value on the aspects with fewer criteria connected to it

The individual weighting by each expert can be found in Appendix II.

5.4 MCDA result

The following diagrams were produced by using the linear additive model described in section 2.5.5 Final Evaluations, the following diagrams were produced. Staple 1 represents the first alternative (existing water treatment system), staple 2 represents the second alternative, and staple 3 represents the third alternative.

In Figure 31, the MCDA results for the environmental criteria are shown. A notable result is that the third alternative scores higher than the second alternative for the environmental criteria. This is due to the high result for pollutant removal efficiency and energy and fuel consumption. However, the acid used for pH adjustments results in a low score for chemical consumption.

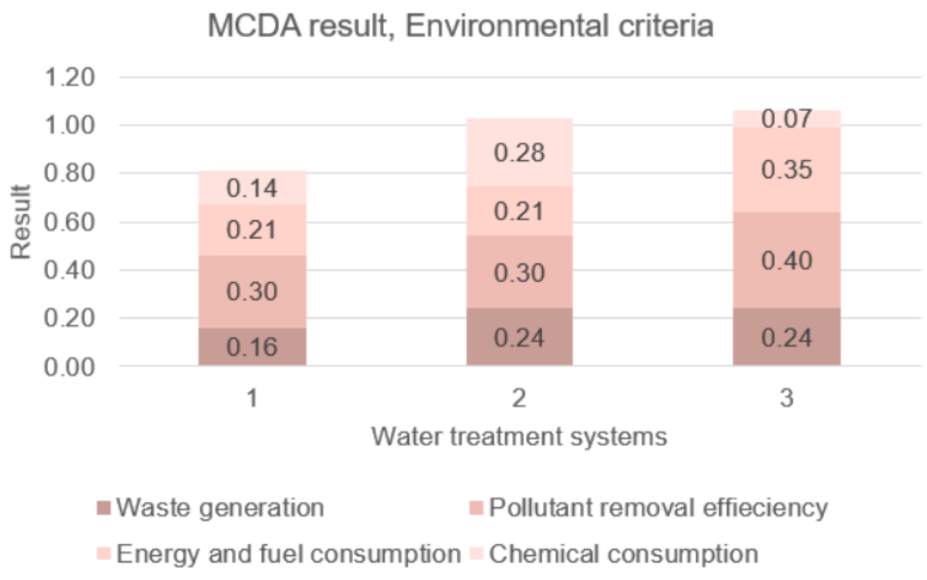


Figure 31. Environmental criteria, MCDA result for each of the wastewater treatment alternatives

In Figure 32, the MCDA results for the technical criteria are shown. The third alternative system scores high throughout the technical criteria with reliability contributing the most.

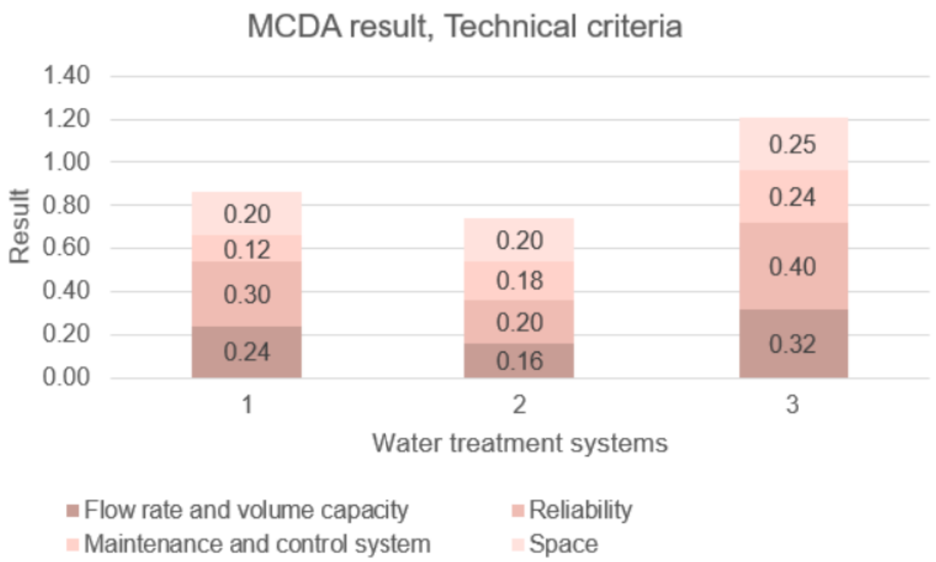


Figure 32. Technical criteria, MCDA result for each of the wastewater treatment alternatives

In Figure 33, the MCDA results for the economic criteria are shown. The third alternative scores the highest, followed by the first alternative, and the second alternative scores the lowest. The second alternative is impacted by the high cost of operation and maintenance.

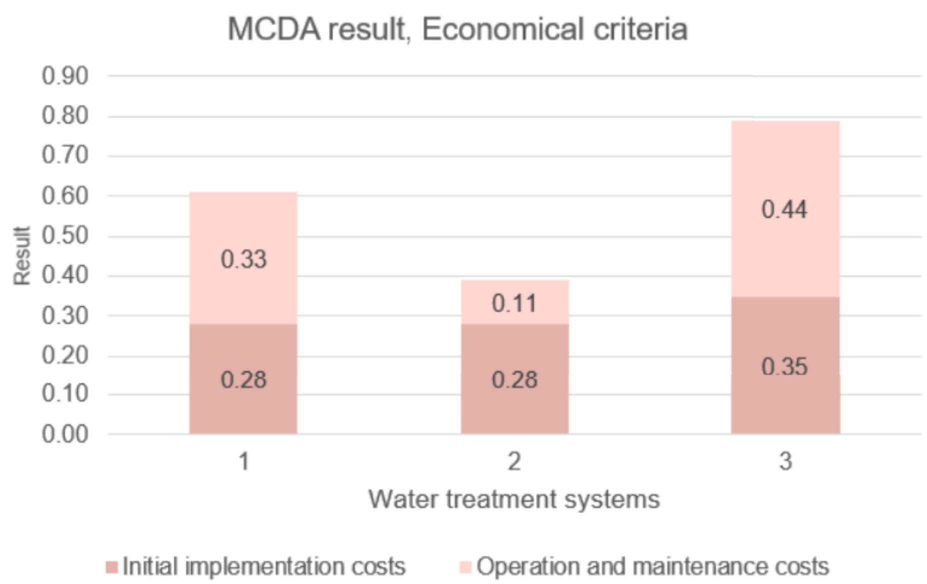


Figure 33. Economic criteria, MCDA result for each of the wastewater treatment alternatives

In Figure 34, the MCDA results for the social criterion are shown. The staples consist of solely the health and safety risks and the second alternative system scores the highest, closely followed by the existing system. The third alternative system scores low due to the use of acid for pH regulation.

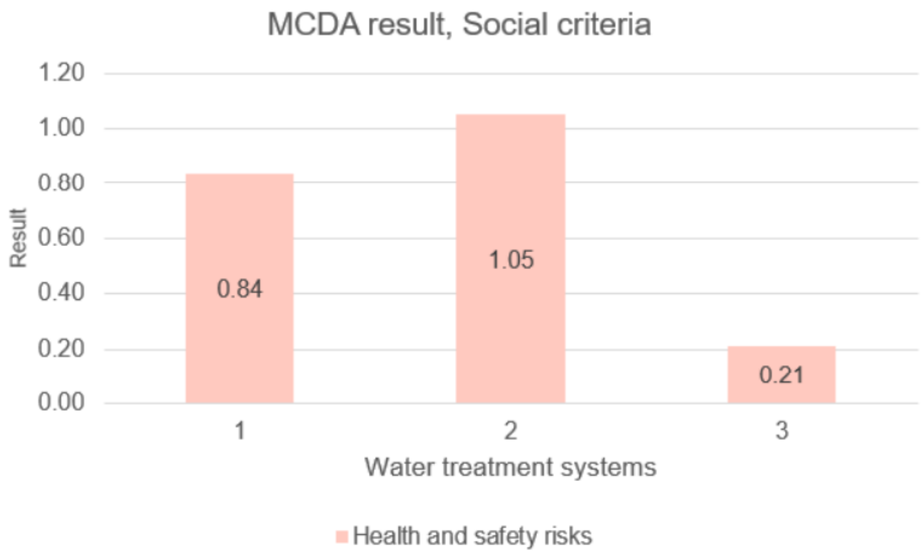


Figure 34. Social criteria, MCDA result for each of the wastewater treatment alternatives

In Figure 35, the final MCDA results are shown. The results for the first alternative are 3.12 with the score spread evenly among the four aspects. The results for the second alternative system are slightly higher with 3.21. The limiting factor is the low economic criterion due to the operation and maintenance costs. The results for the third alternative are the highest with a score of 3.27. The limiting factor for the third alternative is the health and safety risks due to the acid for pH regulation.

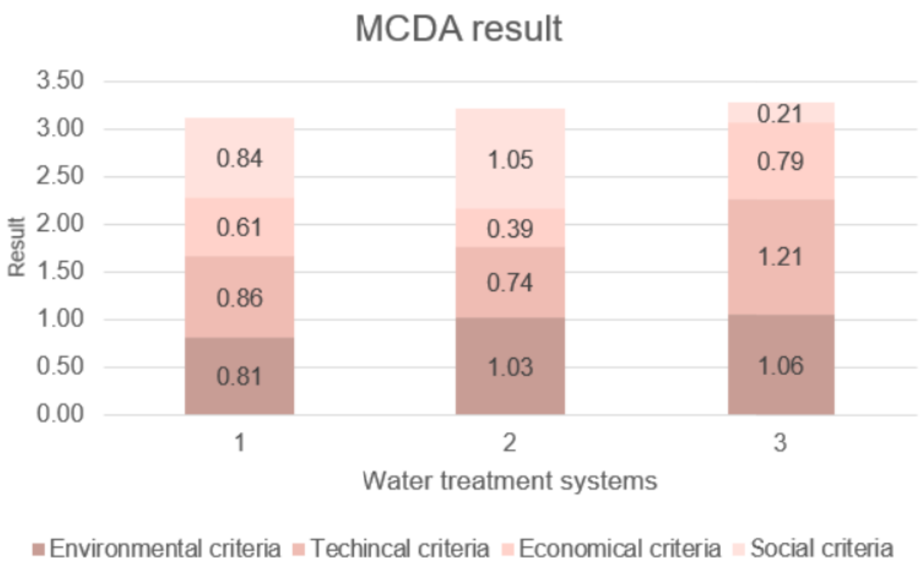


Figure 35. MCDA result for each of the wastewater treatment alternatives

The full table of calculations can be found in Appendix III.

5.5 Further improvements of the treatment system

By interviewing Gay Plato (2024), who is the site manager at the Vasastan tunnel, two further improvements were identified. The first one is the recirculation of water for the drilling rig. Epirock, the manufacturer of the drilling rig, mentioned that the drilling rig can use treated water from the wastewater treatment facility for cooling when drilling without damaging the rig's water system. This would save money compared to today when freshwater is used for all drilling, and it would also reduce the water volume passing through the wastewater treatment system. The water can instead be recirculated, and the same water can be used during the next drilling session. For example, when drilling for explosive insertion around 25-30 m^3 of water is used. With recirculation, this number can be reduced considerably.

Another improvement that usually is something to strive for, at least in construction sites with less of a buffer to hold water as in the Vasastan tunnel, parallel setups of water treatment solutions are preferable. This leads to the possibility of running the water treatment even if maintenance is ongoing. It allows redirecting the water to the parallel solution that is not undergoing maintenance at the time, and the production is not affected. Due to the high cost of parallel setup, this is often used only for filters and sedimentation containers.

A third improvement would be to get the sediment dewatered before transporting it to Ragn-Sells. Dry sediment is cheaper to transport as well as dispose of. To achieve this a filter press could be installed at the facility or sediment basins, and the same as used as at Varbergstunneln could be added to dry the sediment (Johansson, 2024).

A fourth aspect that will have a huge impact on the efficiency of treatment is the way the pumps are set up. A pump placed at the bottom of a container or ditch will pump large amounts of sediments to the next step of treatment, making the previous steps of decreasing the turbidity by particle settling of no use. For an efficient treatment the pumps need to be placed in free-flowing water at a reasonable distance from the settled particles (Johansson, 2024).

5.6 Sensitivity analysis

For this thesis, water samples were taken once, and there is a risk that the results for different parameters are not representative for a longer time period. To achieve a more representative result, multiple samples must be gathered to present an average value for each parameter. There is also a risk that the flow through the facility was not equal to the flow of water at the tunnel face. There is a delayed water cycle as the sedimentation containers and ditches are filled, which means that when the samples were taken, the water was not going at a full flow rate in the container where the "after sedimentation"-samples were taken.

There are two obvious limiting factors for the alternative wastewater treatment systems. The second alternative was limited by the uncertainty of sufficient treatment for chromium VI and the third alternative was limited by the risks to workers involving handling of acid for pH adjustment. To evaluate the impact of these limiting factors the scoring and MCDA were redone with an added flocculant such as RedOx, which treats chromium VI for the second alternative, and the acid used for pH adjustment was changed to CO_2 for the third alternative. The results of these changes are shown in Tables 15 and 16.

Table 15. Scoring after corrections

Criteria	1st alternative	2nd alternative	3rd alternative
Waste generation	2	3	3
Pollutant removal efficiency	3	4 (up 1)	4
Energy and fuel consumption	3	3	5
Chemical consumption	2	3 (down 1)	3 (up 2)
Flow rate and volume capacity	3	3 (up 1)	4
Reliability	3	3 (up 1)	4
Maintenance and control system	2	3	3 (down 1)
Space	4	4	5
Initial implementation costs	4	3 (down 1)	5
Operation and maintenance costs	3	1	3 (down 1)
Health and safety risks	4	4 (down 1)	4 (up 3)

Table 16. MCDA result after corrections

WWTS	1st alternative	2nd alternative	3rd alternative
Old MCDA result	3.12	3.21	3.27
New MCDA result	3.12	3.14	3.87

As seen in Table 16, the second alternative had a lower result when adding the flocculant to make it sufficient in treating all parameters. This is due to the additional costs, maintenance, and so on that an extra step in the treatment causes. As for the third alternative, the change of acid to CO_2 has a small negative impact on the maintenance and its cost but it has a large positive impact on chemical consumption and health and safety risks which increases the MCDA result significantly and makes the third alternative stand out as the best option.

Water from different tunnels has different characteristics, and therefore, even with several water samples, sediment samples, and calculations conducted before the implementation of a new wastewater treatment system, there is no assurance that the facility is sufficient in treating the wastewater. It is more of a trial-and-error methodology to achieve the best result. Therefore, the conclusions of this thesis have to be tested and evaluated practically.

6 Conclusion and recommendations

This master thesis was based on four research questions. The answers to each question were found taking into account the literature review, visits to other construction sites, interviews & MCDA method, and all the information about the case study area Vasastan tunnel at Västlänken Station Haga. The answers were focused on general tunneling wastewater management and its implementation on the case study. Research question number two is not added to this chapter since it is explicitly answered in section 2.4.

Research question 1: What are the different pollutants that can occur in wastewater from tunnel construction, and which can be found in the case study? What is the current level of contaminants and different pollutants in the study area?

The specific levels of particles and pollutants in tunneling wastewater can vary widely depending on factors such as the type of tunneling method used, the geological conditions of the area being tunneled through, and the construction materials involved. In general, tunnel construction can introduce various pollutants into wastewater including sediment, suspended solids, toxic metals, hydrocarbons, and chemicals used in construction processes. In the case study, the sampling campaigns confirmed that all of the pollutants previously mentioned were present. The wastewater generated in the study area does not fulfill the municipal (Trafikverket) quality guidelines and needs to be treated. Specifically:

- At the wastewater source, the levels of toxic metals such as lead, copper, chromium, nickel and zinc are higher than the limit values, combined with high levels of suspended material.
- The alkaline tunneling wastewater has a pH higher than 11.
- Special attention to and treatment of chromium VI and MDA is required since they are harmful and cancerogenous substances that have a specific behavior and are hard to remove compared to other harmful substances immerse in the water

Research question 3: What are the pollutant removal efficiency, costs, advantages/disadvantages, and maintenance requirements for water treatment techniques implemented at tunnel construction sites?

There are multiple factors that influence the effectiveness of wastewater treatment in tunnel construction. In general, sedimentation is crucial to separate pollutants sorbed to particles from the tunneling wastewater. By reducing the suspended materials, the stress on the facility will decrease and the costs and maintenance will be lower. The disadvantages of performing proper sedimentation are that it requires a lot of space and a low flow rate to be accomplished. Another problem is the large volume of wastewater generated when drilling. It is important to have a buffer system that can handle a temporary high flow rate and keep the water entering the facility at a constant rate. A buffer after the facility is also preferred for two reasons, to recirculate water to the drilling rigs will minimize the total water volume

used in the tunnel and be able to store water whenever the project is restricted to release water.
For all components to run efficiently, the pump setup is crucial. A pump installed with the intake at the bottom, i.e. in the sediment, and not with the intake near the surface where the water is free from particles will erase the benefit of the sedimentation treatment step.

Research question 4: Which is the most sustainable and suitable solution for wastewater treatment at Vasastan, Station Haga?
There is not a perfect treatment solution for the Vasastan project. However, if the results of the MCDA are meticulously followed, the best solution for the site would be to implement the third alternative with the Ion exchange, sand filter and biochar. Even though the ion exchange is a good eco-friendly option that reduces costs and maintenance expenses, as a long-term solution this particular technique may be complex and with multiple factors that could malfunction. Aspects such as dosing, backwashing, contaminant concentration in the water, among others, make this technique propensity to collapse. Ion exchange must be constantly monitored to avoid malfunction. On the other hand, the implementation of biochar in the treatment process assures the reduction of chromium VI, MDA and some other substances that are difficult to eliminate from the tunneling wastewater. Biochar is an ecological innovative solution that can efficiently eliminate the pollutants in the tunneling wastewater, which does not need too much maintenance or monitoring. Both solutions, Ion exchange and biochar, generate waste that must be treated. If the target is to reduce emissions and have the most sustainable solution, waste generation and disposal also need to be considered. The lack of space at the site forces the constructors to optimize their space. Larger ditches in combination with wider sedimentation tanks/containers is also a good idea to increase the sedimentation flow time in the settling solutions and increase the settlement rate of the suspended particles in tunneling wastewater. The combination of these techniques can provide discharged concentration below the limit values in a more environmentally friendly treatment process but would demand intense monitoring and maintenance.

In conclusion, when it comes to tunneling wastewater treatment, the ideal scenario involves the simplest possible setup. This minimizes possible malfunction, maintenance, and costs in the different components of the tunneling wastewater management system at the construction site. The specific characteristics of the water and the construction site determine the best approach that can fulfill the treatment requirements. For the case study, cramped space is a challenge and makes sedimentation a limiting factor.

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Appendix I - Sheets for weighting

Department

Names (voluntary)

Which are the most important aspects and criteria for water treatment solutions in your opinion?
- 11 different water treatment solutions for tunnel construction have been evaluated based on the criteria to the right. The evalualuation has resulted in a scoring from 1-5 for each criteria and to rank the solutions towards each other we need you to weight the aspects and criteria against each other.

First you weight the 4 aspects against each other and it must add up to 100%
Second you weight the 11 criteria against each other and it must also add up to 100%

Aspects	Example	Aspect weighting	Criteria	Example	Criteria weighting
Environmental	25%		Waste generation	9%	
			Pollutant removal efficiency	9%	
			Energy and fuel consumption	9%	
			Chemical consumption	9%	
Technical	25%		Flow rate and volume capacity	9%	
			Reliability	9%	
			Maintenance and control system	9%	
			Space	9%	
Economical	25%		Initial implementation costs	9%	
			Operation and maintenance costs	9%	
Social	25%		Health and safety risks	10%	
	=100%	0		=100%	0

Are there any other criteria that you would like to include?

Criteria	Description
Waste generation	What type of waste is generated and how much?
Pollutant removal efficiency	At what rate are the pollutants that the solution is supposed to reduce removed?
Energy and fuel comsuption	How much energy and fuel is used to operate and maintain the solution?
Chemical comsumption	What type of chemicals are used and how much?
Flow rate and volume capacity	How much water can flow through the solution and still be treated efficiently?
Reliability	What is the probability of the solution to fail during construction? How likely is the solution to malfunction?
Maintainance and control system	What maintenance is needed to operate the solution? How frequent is the maintanence?
Space	How much space does the solution take up?
Initial implementaion costs	How much does it cost to implement the solution?
Operational and maintenance costs	How much does it cost to operate and maintain the solution?
Health and safety risks	How dangerous is it for workers to operate with or close to the solution? Potential hazards?

Appendix II - Individual weighting results

Criteria	Erik	Lina	Titti	Pia	Maja	Robin	Gay	Martin	Andreas	Petter	Andreas	Daniel	
Department	Social	Social	Environmental	Environmental	Environmental	Technical	Technical	Technical	Economical	Economical	Trafikverket	Trafikverket	Average
Waste generation	8	7	10	5	10	6	10	5	10	8	8	10	8
Pollutant removal efficiency	17	5	15	13	10	6	5	5	10	11	10	10	10
Energy and fuel consumption	5	10	5	7	10	10	10	5	4	6	10	10	8
Chemical consumption	5	10	10	5	5	6	5	5	6	8	5	10	7
Flow rate and volume capacity	5	5	10	7	5	7	10	10	10	10	10	7	8
Reliability	8	5	10	9	10	10	12	20	12	10	9	8	10
Maintenance and control system	5	8	5	6	5	10	6	10	12	6	8	7	7
Space	2	10	5	3	10	5	2	5	6	4	5	8	5
Initial implementation costs	10	5	5	10	5	5	7	5	15	8	7	10	8
Operation and maintenance costs	5	5	10	15	15	15	18	10	5	12	13	10	11
Health and safety risks	30	30	15	20	15	20	15	20	10	17	15	10	18
													100

Appendix III - MCDA Calculations

MCA results

Scoring	Existing	Environmental	Economical	x	Weighting	=	Existing	Environmental	Economical
Waste generation	2	3	3		8%		0,16	0,24	0,24
Pollutant removal efficiency	3	3	4		10%		0,3	0,3	0,4
Energy and fuel consumption	3	3	5		7%		0,21	0,21	0,35
Chemical consumption	2	4	1		7%		0,14	0,28	0,07
							0,81	1,03	1,06
Flow rate and volume capacity	3	2	4		8%		0,24	0,16	0,32
Reliability	3	2	4		10%		0,3	0,2	0,4
Maintenance and control system	2	3	4		6%		0,12	0,18	0,24
Space	4	4	5		5%		0,2	0,2	0,25
							0,86	0,74	1,21
Initial implementation costs	4	4	5		7%		0,28	0,28	0,35
Operation and maintenance costs	3	1	4		11%		0,33	0,11	0,44
							0,61	0,39	0,79
Health and safety risks	4	5	1		21%		0,84	1,05	0,21
							0,84	1,05	0,21
						Total	3,12	3,21	3,27

Appendix IV - Site visit at Varberg tunnel, Implenia.

In order to expand our understanding of water treatment procedures in tunnel construction, a visit to the Varberg tunnel construction site was conducted. Since the Varberg Tunnel project is characterized by similar geology properties and the implementation of the same tunneling method (drilling and blasting), this was an interesting place that provided the opportunity for comparative analysis. The visit took place in the water treatment facility set up with the water treatment supervisor at Implenia, who showed and explained the water cycle in the facility. This chapter shows the description of the techniques, framework, solutions implemented, and more information and details about the Varberg tunnel project.

Project description

Approximately 9 kilometers of double-track railway construction is being created nowadays on the coast of Varberg. The Swedish Transportation Administration wants to expand the West Coast Railway with this mega project. Implenia is the company in charge of the planning and execution of this project that started in June 2018 and intends to finish in January 2025.

More in detail, this project has 2 phases which contemplate the construction of 2.8 kilometers of rock tunnel, a service & rescue tunnel alongside the mountain tunnel, and 300 meters of concrete tunnel, three new bridges, a new freight terminal, a new station with immersed platforms, level crossings, production of 900 meters of a concrete trough in a submerged area, completion of a landfill, and stormwater retention ponds.

Different challenges are present in this project. On first place, the sustainability of the project needs special attention In the north side of the construction site because it includes a nature and bird sanctuary, which is subject to strict environmental regulations related to limitations for noise emission, vibration, and structure-borne noise have to be observed, in particular within the urban area of Varberg, where the tunnel entrance has only a few meters of rock coverage. The project area has also heavily contaminated soils that requires safety measurements. On the other hand, another challenge is that the Railway traffic for passengers and freight must be maintained throughout the whole construction period which requires detailed planning of various traffic phases. In other words, all passenger and freight traffic on Västkustbanan is planned to be able to run throughout the construction (Implenia, 2024).

Water treatment overview

The construction water is pumped from the lower points of the construction site through pipes and a series of pump stations due to the long distance the water has to move. After that, the water is transported through a collection container to regulate the flow into the water treatment area, as can be seen in Figure 36.

Figure 36. Collection container before entering the water treatment system

The normal flow rate at the inlet is 50 m3/h. The first step of treatment is two sedimentation ponds. The sediment ponds are placed one after the other and can hold up to 150 m3 each and have a depth of 86 cm. The bottom and walls of the ponds are covered with rubber plates which makes them water sealed. The rubber plates also give the sediment ponds a smooth bottom surface which makes the process of cleaning out the sediment easier, where the sludge car can vacuum suck the sediment from the bottom by just dragging the hose along the bottom. Each sediment pond has a silt curtain across the pond in the middle to stop particles from continuing further along in the treatment process. The sedimentation ponds can be seen in Figure 37-39.

Figure 37. Sediment ponds from above

Figure 38 and 39. Sediment ponds

Instead of transporting the sediment away from the site with the sludge cars, the sludge gets moved to sediment basins and gets stored for a longer period of time. During this time the sludge separates from the water and the water gets emptied back into the sediment pond while the sludge gets dried out, excavated out, and placed in piles to get transported away on trucks. This saves money due to the large expense of transporting wet sludge masses. The basins and sediment piles can be seen in Figure 40 and 41.

Figure 40 and 41. Sediment basins and sediment piles

After the water has flowed through both sediment ponds the water reaches a bio-media filter set up by Swedish Hydro solution. Bio-media filter is an environmentally friendly treatment solution that reduces the amounts of toxic metals such as copper, lead, and zinc as well as organic coalitions based on oil or chloride. The bio media is a version of specially developed active carbon which according to Swedish Hydro Solutions has at least ten times more treatment efficiency than regular active carbon (Swedish Hydro Solutions, 2024) In Figure 42 it is shown how the bio-media filter is set up out of IBC containers with the filters inside.

Figure 42. Bio-media filters

The final step of water treatment is three water treatment wells where the water passes through three different filters: an oil filter, a sand filter, and a metal filter. When the water has passed through the filters the water is released into the city's separate stormwater network. Samples are taken on the outgoing water every week to ensure that the water quality meets the regulations for each parameter. In Figure 43 and 44 one of the wells as well as the sampling point is shown.


Figure 43 and 44. Treatment well and sampling point

Parameters that have been the most problematic during the construction so far have been trichloroethylene which has been found when excavating old industrial areas. Metals such as copper and zinc have been exceeding the regulations as well as suspended materials.

During the 4 years of construction, the water flow rate has been higher than it is today and during that time another treatment facility was in place. The flow rate was as high as 140 m3/h and Rewalbi had the responsibility for water treatment. They had four flocculation containers as a first step of treatment followed by a larger sediment pond of 4500 m3. After that, they had two additional sediment containers before the water reached the water treatment wells.

Further improvements to the treatment procedures as they are today, suggested by the supervisor, would be to add two sand containers set up parallel to each other with one running and the other for backup and cleaning. As well as a lamella structure in the sediment ponds to collect particles and break the water surface. The problem with the lamella solution would be the maintenance and cleaning. It would take much longer to clean each fold of the lamella and it wouldn’t be possible to be as thorough.

Appendix V - Site visit at Volvo Trucks Lundby

Veidekke are doing the groundwork for new offices and business premises at Volvo trucks in Lundby (Veidekke, 2023). For the open shafts during construction a water treatment plant was installed for treatment of certain parameters. The most problematic parameter was PFAS which is a collective name for around 10 000 different per- and polyfluorinated alkyl substances (Naturvårdsverket, 2024). A water treatment plant from Geoserve was installed containing the following treatment steps. First, two sedimentation containers seen in Figure 45.

Figure 45. Sedimentation containers

After that the water goes to a container with an activated carbon filter and a ion exchange filter set up after one another as seen in Figure 46.

Figure 46. Active carbon filter and ion exchange filter

The final step is a container with three separate filter socks seen in Figure 47 and 48. After the socks, the water gets released to the city's combined sewer system (Hildesson, 2024).


Figure 47. Three separate socks filter

Figure 48. A sock filter

The water treatment plant has had a few problems since it was installed. The first problem was that the activated carbon filter increased the arsenic in the water above the limit value which made them have to order sludge cars to get rid of the excess water. They still have not understood why the activated carbon filter increased the arsenic concentration in the water, but the value has dropped below the limit value at least. The second problem was that the ion exchange filter increased the pH above the limit value. This was due to not sufficient backwashing after charging the filter. First, hydrogen ions were added and after that sodium hydroxide was added but the excessive sodium hydroxide was not backwashed sufficiently which made the sodium hydroxide travel with the water through the rest of the treatment system. To resolve this situation, carbon dioxide dosing through cans was installed to lower the pH.