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# Future sludge management from a sustainability perspective

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# Abstract

The aim with this project is to investigate the impact of leading the produced waterworks sludge (WWS) from Norrvattens drinking water treatment plant (DWTP), Görvälnverket, over to Käppalaverkets wastewater treatment plant (WWTP) as a step in a more sustainable sludge management. This alternative is compared to a future sludge management at Görvälnverket. The study, investigating the feasibility of leading the WWS over to Käppalaverket, is based on four main aspects, water treatment, operation, cost, and environmental impact. A literature study was performed to evaluate the effect of WWS on Käppalaverket. A life cycle assessment (LCA) analysis was performed to evaluate the environmental impact of leading the WWS over to Käppalaverket. The feasibility was evaluated using a multi-criteria decision analysis (MCDA), where the technical, environmental, and economic aspects were considered.

The study shows that the future sludge management is more favourable than leading the WWS over to Käppalaverket from a technical and economic aspect. The main drawback with leading the WWS over to Käppalaverket is that the WWS will likely impact the dewatering of the sewage sludge, resulting in a higher polymer consumption and an increased hydraulic load on centrifuges and digesters. However, the addition of WWS at Käppalaverket is not assumed to negatively impact the quality of the treatment at Käppalaverket. Leading the WWS over to Käppalaverket results in a lower environmental impact regarding chemical emissions but results in a higher environmental impact regarding transportation and energy consumption.

Leading the WWS over to Käppalaverket was found to be feasible, although the future sludge management at Görvälnverket was found to be more favourably in this study. A more in depth study on the feasibility of leading the WWS over to Käppalaverkets is required to fully assess this aspect. A trial where the WWS is added to Käppalaverket is recommended to further evaluate the impact of the WWS.

# Sammanfattning

Syftet med projektet är att undersöka effekten av att leda över vattenverksslam från Norrvattens vattenverk, Görvälnverket, till Käppalaverkets reningsverk som ett steg i en mer hållbar slamhantering. Detta slamhanterings alternativ jämförs med en framtida lokal slamhantering vid Görvälnverket. Studien undersöker möjligheten att leda vattenverksslam över till Käppalaverket utifrån fyra huvudaspekter, vattenrening, drift, kostnad och miljöpåverkan. En litteraturstudie genomfördes med syfte att utvärdera hur vattenverksslammet kan påverka reningsprocesserna vid Käppalaverket. En Livscykelanalys genomfördes med syfte att utvärdera miljöpåverkan av att leda över vattenverksslam till Käppalaverket. Genomförbarheten utvärderades med hjälp av en multikriterieanalys, där tekniska, miljömässiga och ekonomiska aspekter utvärderades.

Resultat från studien visade att den framtida lokala slamhanteringen är mer fördelaktig från ett tekniskt och ekonomiskt perspektiv, än överledning av vattenverksslammet till Käppalaverket. En nackdel med överledning av vattenverksslam till Käppalaverket är att vattenverksslammet sannolikt kommer påverka avvattningen av avloppsslammet, vilket resulterar i en högre polymerförbrukning och en ökad hydraulisk belastning på centrifuger och rötkammare. Överledningen av vattenverksslam antas däremot inte ha en negativ påverka på kvaliteten av reningen vid Käppalaverket. Att leda vattenverksslam över till Käppalaverket ger en lägre miljöpåverkan med avseende på kemikalieutsläpp till vattenmiljön men en högre miljöpåverkan med avseende på transporter och energiförbrukning.

Överledning av vattenverksslam till Käppalaverket bedöms som genomförbart, men denna studie visar att den framtida lokala slamhanteringen vid Görvälnverket är ett mer fördelaktigt alternativ. Om överledning av vattenverksslam till Käppalaverket fortsatt är ett aktuellt alternativ rekommenderas det att en mer djupgående studie utförs, där vattenverksslammet tillsätts till Käppalaverket för att utvärdera dess påverkan.

## Abbreviations

| | |
|---|---|
| BOD | Biological oxygen demand |
| COD | Chemical oxygen demand |
| DM | Dry mater |
| DWT | Drinking water treatment |
| DWTP | Drinking water treatment plant |
| PFAS | Per- and polyfluoroalkyl substances |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| MBBR | Moving bed biofilm reactor |
| MCDA | Multi-criteria decision analysis |
| WISER | Water Investments for Sustainability Enhancement and Reliability |
| WWS | Waterworks sludge |
| WWTP | Wastewater treatment plant |

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# 1 Introduction

Waterworks sludge (WWS) is an inescapable by-product of the drinking water treatment (DWT) [1]. The content of the WWS mainly depends on the quality of the raw water, but also which chemical are used in the treatment process [2]. For the removal of suspended particles from the raw water, metal salts are often used to initiate a coagulation process [3], [4].

The sludge produced during the DWT is seen as a clean by-product in comparison to wastewater. On the whole WWS is generally not ecotoxic, since the WWS contains mainly natural substances from the raw water source [1],[5]. However, chemicals added in the water treatment and in the sludge management will end up in the produced WWS, if these chemicals are not removed. The continued work towards an improved sludge management is therefore a crucial part in the sustainable development of the drinking water sector.

Norrvatten is a local federation that produce drinking water at their drinking water treatment plant (DWTP), Görvälnverket. Görvälnverket produces approximately 50 million $m^3$ of drinking water annually, supplying water to around 700 000 people in the northern part of Stockholm, Sweden [6]. The raw water comes from lake Mälaren and is treated primarily with chemical precipitation. The WWS produced during the DWT is managed on site at Görvälnverket. The sludge management consists of two steps, thickening with lamella sedimentation and dewatering with centrifuges. The final dewatered WWS will be disposed of by an external actor and used as landfill coverage. The reject water from the centrifuges is lead back to the lamella sedimentation and the clear phase water from the lamella sedimentation is released back to lake Mälaren [7].

Norrvatten has the aim to not emit substances that can have a negative impact on the aquatic environment in lake Mälaren. Polyacrylamide is currently added during the sludge management [8]. The added polyacrylamide will contain traces of unpolymerized acrylamide from the production of the polyacrylamide. Acrylamide is a genotoxic substance [9]. Norrvatten has identified acrylamide in the clear phase water released into lake Mälaren [8].

The emission of acrylamide is currently not regulated in Sweden. To reach Norrvattens aim of not emitting substances that can have a negative impact on the aquatic environment in lake Mälaren, Norrvatten has though decided that the clear phase water released to lake Mälaren should not exceed 0.1 µg acrylamide per liter water [8]. Besides the addition of acrylamide, the current sludge management could lead to an up concentration of per- and polyfluoroalkyl substances (PFAS) and heavy metals.

Norrvatten is planning to improve the current sludge management as a step in a more sustainable sludge management. One alternative, to accomplish this, is leading the produced WWS over to Käppalaverket wastewater treatment plant (WWTP) to treat the WWS together with the wastewater.

## 1.1 Objectives

The aim with this project is to investigate the impact of leading the produced WWS from Görvälnverket over to Käppalaverkets WWTP as a step in a more sustainable sludge management. This proposal for the sludge management will be compared to a future alternative for a local sludge management at Görvälnverket. The future sludge management is based on the current sludge management at Görvälnverket, but a treatment step for acrylamide removal is added. The study aims to evaluate the feasibility of the proposal to lead the WWS over to Käppalaverket.

The study is based on four main aspects to evaluate the main objective:

- **Water treatment**: Can a reduction of emissions be reached by leading the WWS over the Käppalaverket?
- **Operation**: How can the WWS affect the processes at Käppalaverket? This includes the different wastewater treatment steps as well as the sludge management. In addition, identify how the waterworks sludge will affect the properties of the sewage sludge.

- **Cost**: Identify the main cost barriers associated with leading the WWs over to Käppalaverket.
- **Environmental impact**: What environmental impact entails the sludge management alternative to lead the WWS over to Käppalaverket, in comparison to the alternative for the future sludge management at Görvälnverket?

This is an initial study of the feasibility for potential future sludge management. Norrvatten has provided support and input for this study, but Norrvatten is not responsible for the analysis and conclusions made in this report.

## 1.2 Methodology

A literature study is performed to evaluate the impact of WWS on WWTPs. A life cycle assessment (LCA) is performed to evaluate the environmental impact of leading the WWS from Görvälnverket over to Käppalaverket. The feasibility of leading the WWS from Görvälnverket over to Käppalaverket is evaluated in a multi-criteria decision analysis (MCDA). The aspects considered in the MCDA are technical, environmental, and economic.

# 2 Background

The treatment processes used at Norrvatten and Käppalaförbundet are described in more detail in the background. In addition, theoretical background to polyacrylamide is also presented as well as the impact of WWS on WWTPs.

## 2.1 Norrvatten

Norrvatten is a local federation that produces drinking water at the DWTP, Görvälnverket. Görvälnverket produces approximately 50 million $m^3$ of drinking water annually, supplying water to around 700 000 people in the northern part of Stockholm, Sweden [6]. The raw water comes from lake Mälaren and is treated at Görvälnverket with chemical precipitation, where the water first passes a flocculation tank followed by a sedimentation basin. The water is further treated with sand filtration, granulated carbon filtration, and UV disinfection before the finished drinking water leaves the facility [10]. The WWS produced during the water treatment is currently managed on site at Görvälnverket. The sludge management consists of two steps, thickening with lamella sedimentation and dewatering with centrifuges. The final dewatered WWS will be disposed of by an external actor and used as landfill coverage. The reject water from the centrifuges is lead back to the lamella sedimentation and the clear phase water from lamella sedimentation is then released back to lake Mälaren [7].

To meet the future drinking water needs as well as possible stricter emission regulations, Norrvatten is planning a major reconstruction of Görvälnverket. The reconstruction will be performed in different phases and is expected to be finished in year 2050 [11].

## 2.2 Käppalaförbundet

Käppalaförbundet is a local federation that treats wastewater at their WWTP, Käppalaverket. Käppalaverket treats around 50 million $m^3$ of wastewater every year from the northern and east part of Stockholm, Sweden [12]. Making Käppalaverket one of the largest WWTPs in Sweden [13]. The main part of the wastewater is transported to Käppalaverket through their own tunnel system [14].

The first steps of Käppalaverket wastewater treatment is pre-treatment, consisting of inlet screens and grit chambers. During the pre-treatment debris and sand is removed from the wastewater. The pre-treatment is followed by a primary sedimentation and then biological treatment with an active sludge process [13]. A chemical coagulant, ferrous sulphate, is added during the biological treatment, mainly for phosphorus removal. The next step is secondary clarification followed by sand filtration. Ferrous sulphate is also added before the sand filtration. Sand filtration is the final treatment step, and the water is then released to the Baltic Sea [15]. The primary sludge retrieved from the primary sedimentation and the excess sludge from the biological treatment is then managed together, in two steps. The first step in the sludge management is mesophile anaerobic digestion. This stabilizes the sludge and reduces the sludge volume. Käppalaverket has three digestion chambers, two parallel pre-digesters and one post-digester. The digestion chambers are heated by either the digestate leaving the digestion chambers or by the treated wastewater. The biogas produced in the digestion is then upgraded to vehicle gas [16].

After the digestion the remining sludge is dewatered with centrifuges. In the dewatering process a polymer is added to obtain a higher dry mater (DM) content in the sludge. The reject water from the centrifuges is lead back to the WWT and the dewatered sludge, is removed by an external actor. The sewage sludge from Käppalaverket is Revaq-certified and are used to spread on arable land [17].

New emission conditions will take effect in year 2026, effecting the emission of phosphorus, nitrogen, and organic compounds at Käppalaverket [18]. To meet the new emission conditions in addition to an increase in wastewater flow as the population grows, Käppalaverket will introduce a new treatment process. A moving bed biofilm reactor (MBBR) will be added to some of the basins in the biological treatment. In a MBBR the microorganisms will grow on suspended carriers instead of building flocs. This promotes the microbial growth. In addition, a carbon source will be added to the biological treatment to further stimulate the microbial growth and to increase the removal of nitrogen. Chemical coagulant will also be added to the secondary clarifier to increase the removal of phosphorus [19].

## 2.3 Polyacrylamide

Polyacrylamide is a polymer usually used for thickening and dewatering of sludge in both the DWT and the wastewater treatment. Polyacrylamide will agglomerate the sludge particles which then facilitates the removal of water from the sludge. Polyacrylamide is produced by free-radical polymerization of the monomer acrylamide, which is a neurotoxic substance that is likely to be carcinogenic in humans [9]. Animal studies have also indicated that acrylamide can have a negative impact on reproduction. The degree of toxicity for aquatic organisms varies though between different studies [8].

The produced polyacrylamide will contain some non-polymerized residue of acrylamide. Acrylamide is water-soluble, therefore the acrylamide added during the sludge management will mainly end up in the water phase of the sludge. At WWTPs the reject water is often led back to the biological treatment, where acrylamide can be broken down. On the contrary, at DWTPs the reject water is often released to the aquatic environment without any removal step for acrylamide. Acrylamide is biodegradable by some bacteria, often present in the natural aquatic environment [20], [21]. However, the degradation rate for acrylamide varies between different studies. A degradation rate between 17 hours and 42 days in natural waters have been demonstrated in previous studies [8]. Studies have also identified that the chemical and mechanical degradation of polyacrylamide does not result in acrylamide [21].

## 2.4 The Impact of Waterworks Sludge in Wastewater Treatment Plants

Treating WWS at WWTP is a common approach of sludge management [5],[22]. This is beneficial since no local sludge management at the DWTP is needed. The composition and characteristics of WWS however, deviates from that of domestic wastewater [3]. This is mainly due to the high content of either aluminium or ferric salt from the chemical precipitation [2]. From now on, only WWS containing the chemical coagulant aluminium will be considered, since this is the chemical coagulant currently used at Görvälnverket. The WWS will contain high amount of aluminium hydroxides, giving the WWS a peculiar composition in comparison to the domestic wastewater. As a consequence, the addition of WWS will impact the wastewater treatment. The impacts can be both favourable and unfavourable for the wastewater treatment [3].

One of the main documented advantages is that the WWS will increase the removal of phosphorus during the sedimentation [23],[24]. It is assumed that the aluminium hydroxide absorbs the phosphorus, leading to an increased phosphorus reduction [24]. An increased removal of organic substances in the sedimentation has also been observed when WWS is added. As a result, less chemical coagulant needs to be added in the sedimentation when WWS is present, to still obtain the same removal of phosphorus and organic substances. This will also result in a reduced cost of chemical coagulant for the WWTP. The addition of WWS could also be seen as a way of reusing the aluminium in the WWS [22].

The addition of WWS will increase the total load on the WWTP. The magnitude of the increase will however depend on the treatment methods at the WWTP and the ratio between the WWS and wastewater [25]. If the WWTP is load limited, the addition of WWS will have a negative impact. If the sewage sludge is digested, the WWS will have an impact in the load of the digester. WWS does not directly contribute to biogas production because of the low content of organic substances. WWS will therefore mainly take up capacity in the digester without giving rise to additional biogas production. If the digester load is a limiting factor, the hydraulic retention time will be decreased, as well as the biogas production [26],[23],[27]. A lower biogas production gives a loss in revenue to the WWTP if the biogas is sold to an external actor.

The distribution of the WWS through the WWTP is somewhat uncertain, though indications show that the majority of the WWS is separated in the primary sedimentation [5]. A master thesis performed together with Chalmers University of Technology, Gryaab AB and Kretslopp och Vatten, Göteborg Stad, investigated the distribution of WWS at Ryaverket WWTP. Observations from this study indicated that the WWS distribution is similar to that of wastewater, but potentially higher levels of sedimentation in the primary sedimentation [2].

Further, no direct effect on the microorganisms in the biological treatment step have been observed connected to the addition of WWS [24]. Regarding biological oxygen demand (BOD) and chemical oxygen demand (COD) no significant change has been observed [23]. Regarding the nitrification process, no significant impacts due to the WWS have been observed [23],[22].

One of the main drawbacks of treating WWS at a WWTP is problems with sludge settling [22]. Problems with sludge settling will in turn lead to a negative impact on thickening and dewatering of the sewage sludge. The reduced performance in thickening and dewatering gives rise to a variety of problems, for example increased hydraulic load in digesters and longer operating time for centrifuges. This in turn leads to higher operating cost [23].

Besides an increased hydraulic load for centrifuges, higher amount polymer has to be used to obtain desired DM content for the dewatered sewage sludge. The increased polymer usage will also lead to an increased operating cost. Despite a higher use of polymer and increased centrifuge operating time, it is often not possible to reach as the same DM content in the final dewatered sludge, as is possible without the addition of WWS. The lower DM content in the dewaters sludge will also result in a higher cost for the disposal of the dewatered sludge. The final dewatered sewage sludge will contain a higher level of aluminium but also other metals depending on the composition of the raw water [23].

### 2.4.1 Studies from Sweden

Borgs DWTP in Norrköping is currently facing a similar decision as Norrvatten. Borgs DWTP has previously released the WWS from the DWT directly into Motala river without prior treatment. Due to new regulations, this is no longer permitted. So, Borgs DWTP is now faced with the two alternatives, either leading the WWS over to Slottshagens WWTP or invest in a local sludge management. To evaluate the advantages and disadvantages regarding leading the WWS over to Slottshagens WWTP, Nodra has conducted a study where the WWS from Borgs DWTP is lead over to Slottshagens WWTP. The study was performed during a period of approximately 7 months [28].

The results from the study showed that the main drawback of the WWS was connected to dewatering of the sewage sludge. When the WWS was lead over to Slottshagens WWTP, the MD content in the dewatered sewage sludge decreased. This resulted in both a higher polymer consumption and an increased centrifuge operating time. Despite the increase in polymer usage and centrifuge operating time, it was not possible to obtain as high a DM content in the dewatered sludge as when the WWS was not lead to Slottshagens WWTP. The DM content in the dewatered sludge decreased by approximately 3 %. The polymer consumption was increased by approximately 30 %. Both the increased polymer consumption and centrifuge operating time resulted in higher operating cost [28].

The results also showed that the amount of added chemical coagulant during the sedimentation could be reduced without seeing a reduction in suspended matter and total phosphorus. Nodra was able to reduce the usage of chemical coagulant in the sedimentation with approximately 30 %. This in turn resulted in a reduced operating cost, however, not enough to compensate for the increased operating costs linked to the dewatering [28].

Furthermore, no impact on biogas production was observed during the study. However, Nodra stated that evaluation of the biogas production was difficult to perform, since large variations in biogas production are seen during normal operation. Regarding the impact on the content of the sewage sludge, no changes in the metal content impacting the sewage sludge quality was observed when the WWS was added. Even though the incoming WWS did not fulfil the Revaq requirements [28].

In a study from 1999 performed in collaboration with Stockholm Vatten, SYVAB and Botkyrka municipality, WWS from Norsborgs DWTP was led over to Himelfjärdsverket WWTP. One main objective with the study was to investigate the impact that the WWS had on the wastewater treatment and the following sludge management at Himelfjärdsverket. Results from the study were similar to Nodras study demonstrating that the DM content in the dewatered sewage sludge decreased with approximately 3 % when WWS with was added. The study could also identify a higher requirement of polymer in the dewatering process. In addition, a slightly lower biogas production could be observed during the study period [29].

Inconclusive results were found in older documented studies, regarding the impact of WWS on the dosage of chemical coagulant in sedimentation. The study from 1999, performed by Stockholm Vatten, SYVAB and Botkyrka municipality, could not observe any changes in dosage of chemical coagulant in the sedimentation. Observations from Uddevallas WWTP, showed that a reduction of chemical coagulant in the sedimentation was possible when WWS was added to the WWTP. On the other hand, there was also observations from the Uddevallas WWTP that indicated that the introduction of WWS sometime gave rise to problems in the sedimentation. This problem results in an increased use of chemical coagulant. A WWTP in Finspång stated that the addition of WWS also resulted in an increased dosage of chemical coagulant in the sedimentation. Further, Karlshamns municipality reported that they could not determine whether a change in phosphorus could be observed when adding WWS to their WWTP [29]. Newer studies have showed a more consistent result, that the addition of WWS results in a reduction that a decreased dosage of chemical coagulant in sedimentation could be used, without decreasing the precipitation of suspended matter and total phosphorus [28].

A higher precipitation of phosphorus when WWS is added has also been observed from Kungsängens WWTP in Västerås. When the WWS was led from Hässlö DWTP over to Kungsängens WWTP, two main observations were made. One observation being that they obtained a higher reduction of phosphorus, despite a reduction in the usage if ferrous sulphate in the sedimentation. The other main observation was that a higher produced sludge volume was seen, when the WWS was added. This is in part due to the increased incoming flow and in part also due to a lower DM content in the dewatered sewage sludge [30].

# 3 Scenarios for the Sludge Management

Norrvatten is planning a major reconstruction of Görvälnverket. This project is based on the planned reconstructed DWTP for year 2050 and not the current DWTP operating today. The planned facility could change with updates being made after this work is carried out.

The flow of WWS used in this study corresponds to 2.5 % of the expected average intake of raw water in year 2050. Based on this, the considered average daily flow of WWS is 5100 $m^3$/day, with a DM content of 0.1 %. The average daily flow of WWS consists of both the sludge from chemical precipitation and backwash water from ultrafilters [31]. The sludge from the chemical precipitation accounts for 3 % of the total daily flow of WWS, with a DM content of 1.5 %. The sludge from backwashing accounts for 97 % of the total daily flow of WWS, with a DM content of 0.05 % [31]. The considered daily WWS flow is likely an overestimation, as it is possible that the water from backwashing would not be treated with the rest of the WWS. In this case, the amount of WWS needed to be treated would be greatly reduced.

The WWS will mainly contain natural substances from lake Mälaren and aluminium hydroxide from the chemical precipitation. In addition, the WWS will also contain low levels of non-polymerized residue of acrylamide. The WWS will presumably contain PFAS from lake Mälaren. The levels of PFAS in the WWS are uncertain. The amount of PFAS present in the WWS will mainly depend on the treatment steps at the DWT. Studies have shown that chemical coagulation and sedimentation does not remove PFAS from water. However, flotation has been shown to separate some PFAS from water. There is still some uncertainty regarding which phase of the sludge PFAS accumulates in, but there are indications that strongly suggest that PFAS accumulates in the water phase of the sludge. This can then be an explanation to the poor separation of PFAS during sedimentation [32]. In the current DWT, PFAS will be removed with flotation. Flotation, to reduce PFAS from the drinking water, will be used in the current DWTP as long as possible until the reconstructed DWTP is finished. As a result of this, significant amounts of PFAS will be accumulated in the WWS. For the planned reconstructed DWT, a carbon filter will be added that can absorb PFAS [11]. In this case no significant levels of PFAS would likely be seen in the WWS.

The proposed sludge management alternative to lead the WWS over to Käppalaverket is compared to an alternative for a future sludge management at Görvälnverket. Some comparisons will also be made against the current sludge management at Görvälnverket.

## 3.1 The Current Sludge Management

This scenario represents the current sludge management at Görvälnverket. Where the sludge treatment consists of two steps, thickening with lamella sedimentation and dewatering with centrifuges. The clear water phase from the lamella sedimentation is released back to lake Mälaren and the dewatered sludge is disposed of by an external actor [7].

## 3.2 Leading the WWS Over to Käppalaverket

This scenario represents the option where the WWS is lead over to Käppalaverket. The WWS is then treated at Käppalaverket together with the wastewater. The treated water will be released to the Baltic Sea and the dewatered sewage sludge is disposed of by an external actor [14].

The WWS is assumed to be led to Käppalaverket by Käppalaförbundets own wastewater tunnel. A connecting pipeline between Görvälnverket and Käppalaförbundets wastewater tunnel is required. The connecting pipeline can be drawn in lake Mälaren and is assumed to be around 5 km long. For this alternative, no local sludge management at Görvälnverket is used.

## 3.3 A Future Sludge Management at Görvälnverket

This scenario represents an option for a continued local sludge management at Görvälnverket, where the current sludge management is supplemented with two additional treatment steps. The additional treatment steps are applied to the clear phase water from the lamella sedimentation. The first additional treatment step is ozonation. The main purpose with the ozonation step is the removal of acrylamide. The second treatment step is biofiltration. The main purpose with the biofiltration is to remove by-products from the ozonation. After the biofiltration the clear phase water is released back to lake Mälaren [31].

This alternative requires building of a new sludge management building since the sludge management building standing at Görvälnverket today will be torn down to make room for the new DWT facility.

The design considered for the local sludge management at Görvälnverket, in this report, was the most current process design at the time that this work was conducted. It is possible that changes in the design will occur with updates being made after this work is carried out. For example, a potential addition of a treatment step for the removal of PFAS in the WWS is a likely update in the design.

# 4 Life Cycle Assessment

The LCA study have been performed using the education version (9.2.1.68) of the software GaBi. GaBi is a widely used LCA software for evaluating the environmental impact for different products, processes, or services. GaBi has an internal database as well as allowing other external databases such as Ecoinvent [33]. The theoretical background for the LCA methodology is provided in Appendix 1.

## 4.1 Goal and Scope Definition

Norrvatten is planning a major reconstruction of Görvälnverket in order to meet the future drinking water needs, as well as stricter regulations on DWT. One part of the reconstruction aims to improve the sludge treatment, to obtain a more sustainable sludge management [31]. The goal with this attributional LCA study is to investigate the difference in environmental impact related to two alternatives for a more sustainable sludge management. The first alternative is to lead the WWS over to Käppalaverket. The second alternative is a future sludge management at Görvälnverket, where the current sludge management is supplemented with ozonation and biofiltration. These two proposed alternatives will also be compared and evaluated against the environmental impact of the current sludge management at Görvälnverket. An attributional LCA is selected since the alternatives are investigated at a specific point in time. Additionally, attributional LCA is a common approach within the water sector [34]. This means that marginal data is used for modelling the background system.

Norrvatten is the main stakeholder for this LCA study. The results obtained from this study will provide Norrvatten with an initial evaluation of the environmental impact related to the two sludge management alternatives. This study can aid in the initial decision-making process for a more sustainable sludge management.

### 4.1.1 Functional Unit

The functional unit used in this study is 1 $m^3$ produced WWS from the DWT at Görvälnverket. The definition of produced WWS accounts for sludge retrieved from both chemical precipitation and backwash of ultrafilters [31]. The functional unit, 1 $m^3$ produced WWS, was selected since this is the dimensioning input coming in through the system boundary.

### 4.1.2 System Boundaries

The system boundaries are defined to specify which life cycle stages are included in the analysis, as well as which in- and outflows are accounted for. The system boundaries for this LCA study are defined in the following sections 4.1.2.1 to 4.1.2.4.

#### *4.1.2.1 Processes*

The system boundary is limited to the operational phase of the sludge management. The system does not include the DWT at Görvälnverket, production of chemicals used in the system or the disposal process of the dewatered sludge by an external actor. The study is therefore a gate-to-gate LCA since only parts of the sludge life stage are included. The initial flowchart illustrating the systems processes and boundaries are presented in figure 1.

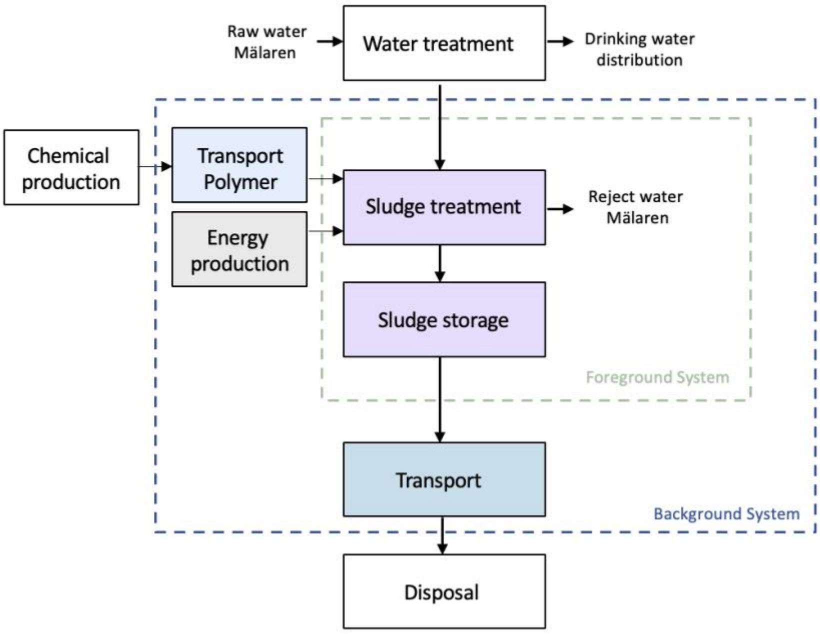

*Figure 1. Initial flowchart over the system.*

The system is divided into a foreground and background system. The foreground system includes the process steps that the decision-makers have influence over. These being the sludge treatment and the sludge storage. On the contrary the background system includes the process steps that the decision-makers have no influence over. These are transportation of chemicals used in the system, transportation of dewatered sludge for disposal, and electricity production.

#### *4.1.2.2 Geographical Boundaries*

The studied system for the current sludge management and the two alternatives for the future sludge management are within the geographical area of Stockholm, Sweden. Transportation of the dewatered sludge will also take place within the geographical area of Stockholm, Sweden. Transportation of chemicals will be transported from outside of Stockholm, as well as outside of Sweden.

Ideally, the datasets used would be specific for the geographical area. This is not always possible, and a more geographically broad dataset must then be used. Due to the absence of available site-specific datasets, data for transportation was obtained for the European market and data for electricity was obtained for the general Swedish market.

It is difficult to estimate the geographical scope of emissions and the resulting environmental impact of the emissions. Since the environmental impact of emissions can take place both globally and locally depending on the nature of the emission. As a result of this, the environmental effects linked to the emissions has been analysed at both a local and global level.

#### *4.1.2.3 Time Horizon*

This LCA study is intended to cover the proposed DWTP at Görvälnverket that will be operational in year 2050. The applicable time period for this LCA is for year 2050 and onwards. Consequently, any changes in the planned technology or chemicals used could result in changes to the environmental impact. Besides any technical changes that can cause unpredictability on temporal validity, uncertainties regarding changes in water quality in lake Mälaren may also contribute to temporal validity.

#### *4.1.2.4 Cut-off Criteria*

Parts from the product system that are excluded in this LCA study are presented below.

- The emission of chemicals added in the system are excluded from the analysis, due to lack of data for chemicals in the used database.
- Only fuel consumption is considered for transportation and not any other consumables. Since this is the data provided in the used database.
- Transportation of employees to the facility at Görvälnverket and Käppalaverket are excluded from this study.

### 4.1.3 Assumption and Limitations

Assumptions made and limitations of this LCA study are presented below.

- For this study it is assumed that the two alternatives for the future sludge management are up-and-running facilities. This means that the environmental impact due to the construction is excluded. As a consequence of this assumption, the study cannot conclude on which alternative is favourable form a construction point of view.
- The energy and chemical consumption used for Käppalaverket are estimations for year 2040, presented by Käppalaförbundet. The estimated energy and chemical consumption at Käppalaverket are not assumed to change appreciably between the years 2040 and 2050.
- For the transportation of dewatered sludge and chemicals, transportation with EURO-5 standard trucks is assumed to be used, since EURO-6 trucks are not available in the used education version of GaBi.
- The transportation distance for the dewatered sludge and chemicals are estimated using google maps.
- The electricity used is assumed to be the general electricity mix in Sweden for 2020.
- Käppalaförbundets wastewater tunnel is assumed to be able to receive the flow of the WWS from Görvälnverket. The dimensions of the pipeline that will connect the WWS from Görvälnverket to Käppalaförbundets wastewater tunnel is estimated.

## 4.2 Life Cycle Inventory Analysis

This chapter presents all the inventory data collected and used for the three system. This includes data for energy consumption and transportation to and from the system.

### 4.2.1 Energy

The energy consumption used for the current sludge management at Görvälnverket, has been based on the observed energy consumption for the current sludge management [35]. Regarding the future alternative for the sludge management at Görvälnverket, the current energy consumption has also been used in addition to the calculated energy consumption for ozone treatment and biofiltration. The calculations are presented in Appendix 4.

For the alternative, to lead the WWS over to Käppalaverket, an estimated energy consumption for Käppalaverket in 2040 has been used. This includes energy consumption for the wastewater treatment, anaerobic digestor, sewage sludge treatment, and Käppalaförbundets wastewater tunnel. The estimated energy consumption was provided by Käppalaförbundet [36]. The estimated energy consumption at Käppalaverket is not assumed to change appreciably between the years 2040 to 2050. Therefore, the 2040 energy consumption value is assumed to be apply for 2050. In addition, the energy consumption for pumping the sludge from Görvälnverket to Käppalaförbundets wastewater tunnel has been calculated. The calculations are presented in Appendix 4.

The electricity used at Görvälnverket comes from 33 % wind power and 67 % hydropower. The wind power is produced by Norrvattens own wind turbines located in Fallåsberget in Ockelbo municipality, Sweden and the hydropower is purchased from Vattenfall, Sweden [35]. The electricity used at Görvälnverket and Käppalaverket comes from different sources. For the purpose of this LCA study, the electricity is assumed to come from the same source, the general Swedish electrical mix.

The electrical mix used in GaBi was, *SE: Electricity grid mix* from 2020. This was the most current dataset available in the education version of GaBi [33].

### 4.2.2 Transportation

The transportation included in this LCA study is the transportation of dewatered sludge for disposal and the transportation of chemicals used in the system. The chemicals used in the alternative, leading the WWS over to Käppalaverket, are ferrous sulphate, methanol, and a polymer [36]. The methanol used in the biological treatment step at Käppalaverket is used to increase nitrogen removal [19]. Since the WWS contains very low levels of nitrogen, it is assumed that no additional methanol is required for treating the WWS and therefore no methanol is accounted for in this LCA. Observations from previous studies have shown that a lower dosage of chemical coagulant and higher dosage of polymer are needed for the treatment of WWS. For this LCA an adjusted value of 70 % of the ferrous sulphate and 133 % of the polymer used at Käppalaverket are considered. These adjusted chemical usages are based on a report provided by Nodra [28].

The chemicals considered for the alternative, future sludge management at Görvälnverket, are a polymer and polyaluminum chloride. The chemicals considered for the reference alternative is only a polymer [31].

Two truck sizes have been used, a lighter truck for the removal of dewatered sludge and a heavier truck for the transportation of chemicals. The light truck was chosen as the dewatered sludge is transported locally. The heavy truck was chosen as the chemicals are transported long distances. The transport distance for the dewatered sludge is based on round-trip travels, since the truck is assumed to drive empty to the facility to pick up the dewatered sludge. The total transport distance for the chemicals is based on one-way travel, since the long-distance trucks is assumed to transport a different cargo on the return trip. The transport distance was determined with the use of google maps. The shortest distance for the transportation was used for all cases. The specific information regarding transportations for each LCA setup can be found in Appendix 5.

EURO-5 trucks were used for this LCA study, since datasets for EURO-6 trucks were not available in the education version of GaBi. The trucks used from the datasets in GaBi was *Euro 5, 14 - 20t gross weight / 11.4t payload capacity* for the lighter truck and the *Euro 5, 26 - 28t gross weight / 18.4t payload capacity* for the heavier truck. The fuel for both trucks is assumed to be diesel. The diesel used from the datasets in GaBi was *EU-28: Diesel mix at refinery ts* [33].

### 4.2.3 Sensitivity Analysis for Life Cycle Inventory

The addition of WWS to the WW will change the composition of the incoming flow for Käppalaverket. For example, the WWS contains aluminium residues from the addition of chemical coagulant at Görvälnverket. The aluminium in the WWS will aid in the chemical precipitation process at Käppalaverket. It could therefore be more representative to assume that no additional chemical coagulant would need to be added for treatment of the WWS at Käppalaverket.

For the purpose of the sensitivity analysis, the chemical usage of the chemical coagulant ferrous sulphate is neglected. No transportation of ferrous sulphate is then needed. The actual chemical usage will be somewhere in between the chemical usage presented in section 4.2.2, Transportation, and for no ferric chloride usage.

A sensitivity analysis was also performed for the energy consumption at Käppalaverket. The two process steps considered are the biological treatment and the sludge management. The energy consumption for the biological treatment is mainly used for the removal of nitrogen. The WWS will have a low nitrogen content, the energy consumption for the biological treatment could therefore be considered lower [37]. The energy consumption for the sludge treatment would likely increase when WWS is added, mainly due to a higher centrifuge load [28]. The energy consumption for the sludge management could therefore be considered higher.

For the purpose of this sensitivity analysis a higher energy consumption case is considered where the energy consumption for the sludge management is increased with 25 %. A lower energy consumption case is considered where the energy consumption for the biological treatment is decreased with 50 %.

## 4.3 Life Cycle Impact Assessment

The LCIA methodology selected in GaBi was ReCiPe *2016 v1.1 Midpoint (H)*. ReCiPe 2016 creates a set of endpoints categories based on the aggregate of multiple environmental concerns at midpoint level [38]. The selected midpoint impact categories are presented in table 1. The most relevant midpoint impact categories for this assessment were selected.

*Table 1. Selected midpoint impact categories, endpoint area of protection and damage pathways and measured.*

| **Midpoint impact category** | **Endpoint area of protection** | **Damage pathways** | **Measured unit** |
|---|---|---|---|
| Climate change | Human health and Ecosystem | Increase in malnutrition, damage to freshwater species and damage to terrestrial species | kg CO2-eq |
| Freshwater eutrophication | Ecosystem | Damage to freshwater species | kg P-eq |
| Freshwater ecotoxicity | Ecosystem | Damage to freshwater species | kg 1,4-DB |
| Marine eutrophication | Ecosystem | Damage to marine species | kg N-eq |
| Marine ecotoxicity | Ecosystem | Damage to marine species | kg 1,4-DB |
| Terrestrial acidification | Ecosystem | Damage to terrestrial species | kg $SO_2$-eq |
| Terrestrial ecotoxicity | Ecosystem | Damage to terrestrial species | kg 1,4-DB |
| Human carcinogenic toxicity | Human health | Increase in various types of cancer | kg 1,4-DB |
| Human non-carcinogenic toxicity | Human health | Increase in other diseases/causes | kg 1,4-DB |

# 5 Multi-Criteria Decision Analysis

The MCDA in this study has been performed using the WISER software. WISER is an Excel-based tool that has been developed for decision support within the Swedish drinking water sector. The aim with the tool is to provide support and guidance for decision-making where several different alternatives are compared and evaluated. WISER is developed to account for four different decision dimensions, technical, social, environmental, and economic [39]. Since WISER is specifically designed for decision making within the drinking water sector it is a valid tool for the analysis of the alternatives for the future sludge management. The theoretical background for WISER is provided in Appendix 2.

## 5.1 Alternatives

The MCDA is based on two different alternatives for a future sludge management developed by Norrvatten. The two alternatives are:

1. Leading the WWS from Görvälnverket over to Käppalaverket, where the WWS is treated together with the wastewater.
2. The future sludge management at Görvälnverket, where the sludge management consists of four steps, thickening, dewatering, ozonation and biofiltration.

The reference alternative is the current sludge management at Görvälnverket, where the sludge management consists of 2 steps, thickening and dewatering. The two alternatives for the future sludge management will be assessed against the reference alternative.

## 5.2 Criteria

The criteria used in this analysis are presented and described in table 2. The criteria consist both of criteria suggested by WISER, as well as specially adapted criteria relevant for Norrvattens future sludge management. The selected criteria have been determined in consultation with employees at Norrvatten.

*Table 2. Compilation of selected criteria, as well as description and indicators for each criterion.*

| **Criteria** | **Description of criteria** | **Indicators** |
|---|---|---|
| **Technical dimension** | | |
| Adaptability | The alternatives ability to perform satisfactorily during external changes | Increased flow of WWS or stricter emission regulations |
| Permission | The ability to obtain the necessary permits for the alternative | The probability of obtaining the necessary permits |
| Availability | Norrvattens ability to influence the system, i.e., to what extent is Norrvatten dependent on external actors | Influence over the system and potential conflicts of interest with other actors |
| Feasibility | The alternatives feasibility of implementation in relation to when the alternative needs to be in operation | Expected project time |

| | | |
|---|---|---|
| **Environmental dimension** | | |
| Quality of water resource | Effect of emissions on the quality of the raw water resource (lake Mälaren) | Estimated magnitude of unwanted substances released into the water resource that potentially could affect the quality of the water resource |
| Energy usage and greenhouse gas emissions | The alternatives energy consumption and greenhouse gas emissions | Energy consumption [kWh] and greenhouse gas emissions [kg $CO_2$-eq] |
| Land use | The alternatives claim to land | Estimated magnitude of land use |
| Chemical use | Amount of chemicals used in the system | Amount of chemicals [kg/$m^3$ WWS] |
| Local emissions | The alternatives effects on the aquatic ecosystem | Estimated magnitude of unwanted substances released that could have a negative impact on the aquatic ecosystem |
| **Economic dimension** | | |
| Investment costs | Capital expenses | Estimated magnitude of investment costs |
| Operation costs | The alternatives operation costs | Energy and chemical consumption |

This analysis is based on only three of the four dimensions, technical, environmental, and economic. The social dimension has been excluded from this analysis, following discussions with Norrvatten. The social dimension is assumed to have little influence on the decision making between the two alternatives. There are some social impacts from the two alternatives, but they are assumed to be small. The two alternatives will not have a direct effect on the produced drinking water.

For alternative 2, future sludge management at Görvälnverket, the new processes will be built on Norrvattens own land. This can contribute to some noise connected to construction, but since Görvälnverket will undergo a major reconstruction during this time, the noise from the future sludge management alternative is assumed not to have a direct impact. For alternative 1, leading the WWS over to Käppalaverket, a pipeline from Görvälnverket to Käppalaförbundets wastewater tunnel must be installed on the bottom of lake Mälaren. This will entail some social disturbance.

None of these alternatives are deemed to entail any new work environment risks when in operation. However, alternative 1, leading the WWS over to Käppalaverket, results in the termination of the local sludge management at Görvälnverket. This could potentially result in a decrease in job opportunities at Norrvatten.

## 5.3 Scoring

The scoring scale used, ranges from -10 to 10, were -10 is defined as least favourable and 10 is defined as most favourable [39]. The two sludge management alternatives were scored against the reference alternative. The scale used for the scoring is presented in table 3. For a more detailed description of the scoring se appendix 6. Assessment of the criteria has been based on scientific articles, reports, and expert knowledge from employees at Norrvatten.

*Table 3. Scale for scoring of the criteria.*

| **Score** | **Categorizing** |
|---|---|
| 6 to 10 | Significant improvement |
| 1 to 5 | Moderate improvement |
| 0 | No change |
| -1 to -5 | Moderate deterioration |
| -6 to -10 | Significant deterioration |

### 5.3.1 Adaptability

The alternatives ability to perform satisfactorily during sudden external changes, for instance increased flow of WWS or stricter emission requirements. An increased flow of WWS could be a consequence of an increase in drinking water production, deteriorated water source quality or additional process steps in the DWT. This criterion is assessed due to the alternatives adaptability to a higher WWS flow and stricter emission requirements. The scoring for the alternatives is presented in table 4.

The reference alternative is quite adaptable for changes in the flow of WWS. On the contrary, if stricter restrictions on emissions were established, the system may have to be supplemented with additional treatment steps. For example, as of now the reference alternative cannot remove acrylamide from the clear phase water released into lake Mälaren. In the case of regulations on acrylamide emission, the reference alternative might not be able to meet that requirement. It is also a possibility that PFAS removed in the DWTP (depending on process design of the DWTP) could contribute to WWS containing significant amounts of PFAS. If a major part of the PFAS is assumed be in the water phase of the sludge, significant emission of PFAS to lake Mälaren might be observed. In the case of stricter requirements on PFAS emissions, the reference alternative might not be able to meet the requirement.

Alternative 1 is more adaptable against stricter regulations on emissions than the reference alternative. Regarding the addition of polymer at Käppalaverket, the water is recirculated back to the biological treatment step where any traces of acrylamide can be broken down [40]. On the contrary, Käppalaverket has no treatment step for removal of PFAS [14]. This means that the case of stricter requirements on PFAS emissions, alternative 1 might not be able to meet the requirement. Regarding higher flow in WWS, Käppalaverket has a higher adaptability compared to the reference alternative.

Alternative 2, could remove the main part of acrylamide from the clear phase water, since ozonation is introduced. This makes alternative 2 more adaptable towards stricter regulations on the emission of acrylamide, compared to the reference alternative. Alternative 2 is also quite adaptable for changes in the flow of WWS. Regarding PFAS, alternative 2 is not assumed to reduce the emissions of PFAS. In the case of stricter regulations on PFAS emissions, alternative 2 might not be able to meet the requirements. However, it is likely that a treatment step for the removal of PFAS would be added to the potential future sludge management at Görvälnverket. In this case, the local sludge management would be able to reduce the emission of PFAS to lake Mälaren.

*Table 4. Scoring of the criterion adaptability.*

| **Alternative** | **Adaptability** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Adaptable to moderately higher WWS volumes, relatively adaptable towards stricter emission regulations | 2 |
| 2. Future sludge management at Görvälnverket | Adaptable to slightly higher WWS volumes, relatively adaptable towards stricter emission regulations | 2 |
| Reference | Adaptable to slightly higher WWS volumes, not adaptable towards stricter emission regulations | - |

### 5.3.2 Permission

This criterion is assessed on the alternatives ability to obtain necessary permission for implementation of the system. The scoring for the alternatives is presented in table 5.

The reference alternative is an up and running facility, meaning that it does not require any implementation permission. For alternative 1, permission is required for drawing a pipeline in lake Mälaren that will connect Görvälnverket with Käppalaförbundets wastewater tunnel. This is considered to be obtained with moderate certainty.

For alternative 2, a new sludge management building will be built, which will require building permits. The new building will be built on Norrvattens land, so no new land is required. Necessary permission is assumed to be obtained with moderate certainty.

*Table 5. Scoring of the criterion permission.*

| **Alternative** | **Permission** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Permission required for laying a pipeline in lake Mälaren | 5 |
| 2. Future sludge management at Görvälnverket | Permission required for building new sludge management building | 4 |
| Reference | No implementation permission required | - |

### 5.3.3 Availability

This criterion evaluates Norrvattens ability to influence the system, i.e., to what extent Norrvatten is dependent on other actors for the alternatives. The assessment of this criterion is therefore based on the degree of influence Norrvatten has over the system and potential conflicts of interest with other actors. The scoring for the alternatives is presented in table 6.

For the reference alternative, Norrvatten is dependent on an external actor for disposal of the dewatered sludge. Norrvatten is also, to some extent, dependent on external actors for supplying the chemical used in the system.

In alternative 1, Norrvatten is no longer dependent on an external actor for disposal of the dewatered sludge. On the contrary, Norrvatten will be dependent on Käppalaförbundet to take care of the WWS. Both Norrvatten and Käppalaförbundet are public entities and have to some extent a common governing organization. As a result of this, there is an uncertainty in the scoring of Norrvattens influence over alternative 1. The maximal and minimal scoring point are presented in Appendix 7. The most likely score is though set to 0.

Alternative 2 will not change the composition or amount of dewatered sludge at Görvälnverket. Meaning that Norrvattens influence over the system is unchanged compared to the reference alternative. A chemical coagulant will be used in the thickening process in addition to the polymer used in the reference alternative. This will, to a lesser extent, make Norrvatten more depended on external actors for the supply of chemicals. The dependency on a chemical supplier is assumed not to be significant in comparison to the disposal of the dewatered sludge. Consequently, the additional dependency on a chemical supplier is neglectable.

*Table 6. Scoring of the criterion availability.*

| **Alternative** | **Availability** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Dependent on Käppalaverket for receiving the WWS | 0 |
| 2. Future sludge management at Görvälnverket | Dependent on external actor for disposal of the dewatered sludge | 0 |
| Reference | Dependent on external actor for disposal of the dewatered sludge | - |

### 5.3.4 Feasibility

This criterion describes the feasibility for the implementation of the alternatives in relation to when the alternatives need to be in operation. The assessment is based on expected project time. The scoring for the alternatives is presented in table 7.

The reference alternative is an already up and running facility. For alternative 1, it is assumed that the implementation could require more time in comparison to when the system needs to be in operation. This is mainly due to that an agreement between Norrvatten and Käppalaförbundet must be established. The implementation of alternative 2 should be able to be finished close to when the alternative needs to be in operation.

*Table 7. Scoring of the criterion feasibility.*

| **Alternative** | **Feasibility** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Possible delays due establishing an agreement between partners | -3 |
| 2. Future sludge management at Görvälnverket | Assumed to be implemented in close proximity to when the alternative needs to be in operation | -1 |
| Reference | Already an up and running facility | - |

### 5.3.5 Quality of Water Resource

The aim with this criterion is to analyse how the water resource quality in lake Mälaren will be affected by the different alternatives. The assessment is based on the estimated magnitude of emissions released to the water resource, that could affect the water quality in lake Mälaren. The scoring for the alternatives is presented in table 8.

The reference alternative will emit acrylamide into the water resource, due to this alternative having no step for acrylamide removal. There are some uncertainties regarding how fast the acrylamide is biodegraded in lake Mälaren [8]. This means that there is a risk that the released acrylamide will be taken up again with the intake water. Based on this, there is a potential risk that the reference alternative negatively effects the water recourse quality, concerning acrylamide. The reference alternative will also contribute to a up concentration of PFAS in lake Mälaren, which also could contribute to a lower water resource quality. A minor emission of heavy metals to lake Mälaren could also occur.

Alternative 1, will result in a significant improvement in water resource quality since the clear phase water will no longer be discharged into lake Mälaren. All emissions to lake Mälaren linked to the clear phase water will then cease.

The release of acrylamide to lake Mälaren will, to a great extent, cease if alternative 2 is put into operation, because a treatment step for acrylamide is then incorporated. This will improve the water resource quality concerning acrylamide. Although emissions of PFAS and heavy metals would not be reduced with alternative 2. However, it is likely that a treatment step for the removal of PFAS would be added to the potential future sludge management at Görvälnverket. In this case, the local sludge management would be able to reduce the emission of PFAS to lake Mälaren.

*Table 8. Scoring of the criterion quality of water resource.*

| **Alternative** | **Quality of water resources** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Significant improvement of the raw water resource quality | 9 |
| 2. Future sludge management at Görvälnverket | Improvement of raw water resource quality | 5 |
| Reference | Presumed to have a negative impact in the raw water resource quality | - |

### 5.3.6 Energy Usage and Greenhouse Gas Emissions

This criterion includes both the energy consumption and the greenhouse gas emissions linked to the alternatives. Energy consumption is measured in kWh and accounts for the facilities energy consumption for treating 1 $m^3$ produced WWS. The greenhouse gas emissions are measured in kg $CO_2$-eq and includes both the emissions associated to the facilities energy usage, the transportation of used chemicals and the removal of dewatered sludge. Energy consumption is the driving factor for greenhouse gas emissions and the transportation of chemicals has a minor effect on greenhouse gas emissions.

The alternatives are scored based on how much higher the energy consumption and greenhouse gas emission are compared to the reference alternative. The scoring for the alternatives is presented in table 9.

Alternative 1 entails an increase energy consumption compared to the reference alternative. The WWS will go through more treatment steps at Käppalaverket which leads to a higher energy consumption. In addition, the WWS also needs to be transported to Käppalaverket. Alternative 1 also has a higher greenhouse gas emission than the reference alternative.

Alternative 2 will also have a higher energy consumption and greenhouse gas emission than the reference alternative as this system includes two additional treatment steps.

*Table 9. Scoring for the criterion energy usage and greenhouse gas emissions.*

| **Alternative** | **Energy consumption [kWh]** | **Greenhouse gas emissions [$CO_2$-eq]** | **Score** |
|---|---|---|---|
| 1. Leading the WWS over to Käppalaverket | 0.53 | 0.032 | -4 |
| 2. Future sludge management at Görvälnverket | 0.39 | 0.024 | -2 |
| Reference | 0.30 | 0.020 | - |

### 5.3.7 Land Use

This criterion is assessed on the alternatives claim to land. The scoring for the alternatives is presented in table 10.

The reference alternative entails no additional claim to land. Alternative 1 will require laying a pipeline in lake Mälaren. This alternative will have to claim some land outside Norrvatten area, but the land used is underwater and therefore assumed not to hinder the continued use of this land by others.

Alternative 2 will not require any additional land outside Norrvattens current premises. This in turn will increase the land needs within the Norrvatten site. Norrvattens land is limited and alternative 2 will increase the land required.

*Table 10. Scoring of the criterion land use.*

| **Alternative** | **Land use** | **Score** |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | The measure entails no direct increase in land use | 0 |
| 2. Future sludge management at Görvälnverket | The measure entails a moderate increase in land use | -3 |
| Reference | No additional claim to land | - |

### 5.3.8 Chemical Use

This criterion is assessed according to the expected to change in chemical consumption as a result of the two sludge management alternatives compared to the reference alternative. The estimated chemical consumption is provided in kg/m$^3$ WWS. The scoring for the alternatives is presented in table 11.

The reference alternative requires polymer in the sludge management. Alternative 1 has a higher usage of chemicals compared to the reference alternative, if both polymer and the chemical precipitant, ferrous sulphate, are accounted for. The chemical usage would be lower than the reference alternative if the chemical precipitant, ferrous sulphate, is assumed to not have to be added to the WWS.

Alternative 2 will not give rise to a higher polymer consumption compared to the reference alternative. On the contrary, alternative 2 includes an additional chemical coagulant. This contributes to a to a slightly higher chemicals consumption compared to the reference alternative.

*Table 11. Scoring of the criterion chemical use.*

| Alternative | Chemical use [kg/m$^3$] | Score |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | 0.069 | -2 |
| 2. Future sludge management at Görvälnverket | 0.044 | -2 |
| Reference | 0.011 | - |

### 5.3.9 Local Emissions

This criterion analysis the alternatives effect on the aquatic ecosystem. The scoring is based on the estimated magnitude of substances released into the aquatic environment, that could have a negative impact on the aquatic ecosystem. The scoring for the alternatives is presented in table 12.

The reference alternative will emit acrylamide to lake Mälaren since this alternative have no step for acrylamide removal. Acrylamide is genotoxic and can therefore have a negative impact on the aquatic ecosystem [8]. The reference alternative will also contribute to an up concentration of heavy metals and PFAS (depending on process design of the DWTP) in lake Mälaren, which also could contribute to a negative impact on the aquatic ecosystem.

Alternative 1, could lower the negative impact on the aquatic ecosystem since acrylamide is no longer emitted. On the contrary, PFAS cannot be removed and negative impact on the aquatic ecosystem regarding PFAS will still be observed. A slightly lower emission of heavy metals can be reached with alternative 1, resulting in a lower impact in the aquatic ecosystem. Although the emission of PFAS and heavy metals will be moved from lake Mälaren to the Baltic Sea.

The release of acrylamide to lake Mälaren will to a great extent cease if alternative 2 is put into operation. This will contribute to a less negative impact on the aquatic ecosystem. On the contrary, alternative 2 will not contribute to a reduction of PFAS and heavy metals. However, it is likely that a treatment step for the removal of PFAS would be added to the potential future sludge management at Görvälnverket. In this case, the local sludge management would be able to reduce the emission of PFAS to lake Mälaren.

*Table 12. Scoring of the criterion local emissions.*

| Alternative | Local emissions | Score |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | No emission of acrylamide, reduced emission of heavy metals, but still emission of PFAS | 5 |
| 2. Future sludge management at Görvälnverket | No emission of acrylamide, but emission of PFAS | 3 |
| Reference | Emission of acrylamide, PFAS and heavy metals | - |

### 5.3.10 Operation Costs

This criterion is assessed according to the magnitude of the operational cost. The operational cost is estimated based on electricity demand and chemical usage. The scoring for the alternatives is presented in table 13.

Both alternative 1 and 2 will require a higher operational cost than the reference alternative, as both alternatives have a higher energy consumption and a higher chemical usage.

*Table 13. Scoring of the criterion operation costs.*

| Alternative | Operation cost | Score |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Entails higher energy consumption and chemical usage | 2 |
| 2. Future sludge management at Görvälnverket | Entails higher energy consumption and chemical usage | 1 |
| Reference | - | - |

It should be noted that WISER uses an inverted scale for operating costs. A lower operation cost will result in a lower score (more favourable) and a higher operating cost will result in a higher score (less favourable).

### 5.3.11 Investment Cost

This criterion is assessed based to the magnitude of the investment cost linked to the alternatives. The scoring for the alternatives is presented in table 14.

At this stage, the investment cost for alternatives 1 and 2 is only roughly estimated. This contributes to a large uncertainty regarding the actual investment cost. Based on the current estimated investment cost however, the investment cost for both alternative 1 and 2 on the same order of magnitude.

*Table 14. Scoring of the criterion investment cost.*

| Alternative | Investment cost | Score |
|---|---|---|
| 1. Leading the WWS over to Käppalaverket | Entails a moderate investment cost | 2 |
| 2. Future sludge management at Görvälnverket | Entails a moderate investment cost | 2 |
| Reference | - | - |

It should be noted that WISER uses an inverted scale for investment cost. A lower investment cost will result in a lower score (more favourable) and a higher investment cost will result in a higher score (less favourable).

## 5.4 Weighting

Next step in WISER is weighting the criteria and dimensions. The weighting was performed in consultation with employees at Norrvatten. First, the criteria within each dimension were weighted against each other. By assigning every criterion a number between 0 to 10. Where 0 representing no importance and 10 representing highest importance [39]. The weighting scores for the criteria are presented in figure 2. The dimensions were then weighted against each other to illustrate which dimension is most important for Norrvatten in the decision-making process. The same scale for weighting was used. The weighting of the dimensions is presented in figure 3.

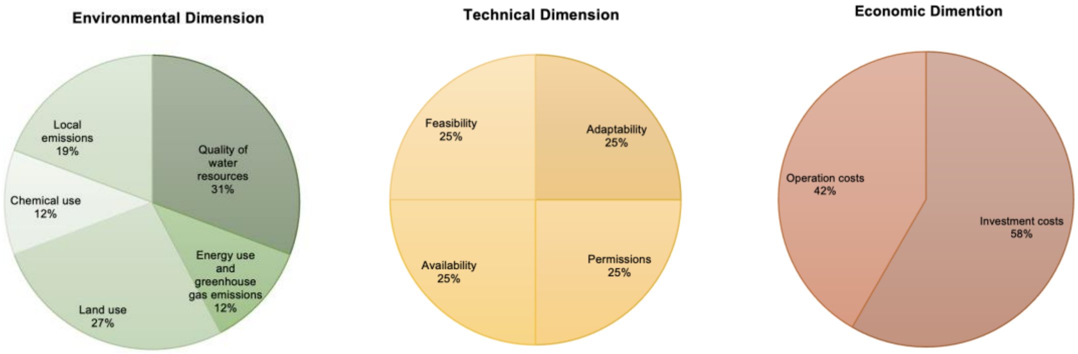

*Figure 2. The weighted scores for the criteria in each dimension. The green pie chart represents the environmental dimension, the yellow pie chart represents the technical dimension, and the red pie chart represents the economic dimension.*

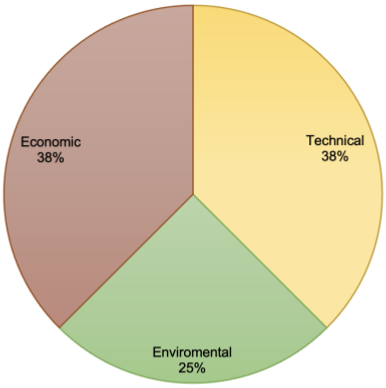

*Figure 3. Weighting of the dimensions.*

WISER then combines both the weighting of the criteria and the dimensions, which is presented in a solar chart figure 4. The outer part of the chart represents the criteria, and the inner part of the chart represents the dimensions.

*Figure 4. A solar chart that combines the weighting of the criteria and the dimensions.*

## 5.5 Sensitivity analysis

As of now the plug-in software @Risk (version 8) is needed to run the sensitivity analysis in WISER [39]. It was not possible to obtain the @Risk software for this project. Since this software was not available, the @Risk supported sensitivity analysis built into WISER was not performed. Instead, a manual sensitivity analysis was performed.

A variation analysis was first performed. The calculation from WISER was recalculated using the minimum and the maximum scores for each dimension respectively to obtain the uncertainty range for the results from WISER. The minimum and maximum scores assigned for each criterion are provided in Appendix 7.

A sensitivity analysis was also preformed where the economic dimension was excluded to evaluate which alternative would be favourably if Norrvatten was not limited economically. This was performed by giving the economic dimension a weight of 0 while the weights were kept constant for the technical and environmental dimensions.

# 6 Results

Result from the LCA study is presented under the heading 6.1 and the result from the MCDA is presented under heading 6.2.

## 6.1 Result for Life Cycle Assessment

The LCA study was performed on three cases, alternative 1 (leading the WWS over to Käppalaverket), alternative 2, (future sludge management at Görvälnverket) and the reference alternative (representing the current sludge management at Görvälnverket). The environmental impact for each impact category was scaled to the functional unit of 1 m$^3$ produced WWS.

The results for alternative 1, leading the WWS over to Käppalaverket, are presented in figure 5. The results show that the energy consumption is the aspect that has the largest contribution to all the impact categories. The energy consumption has the largest percentage of impact on human carcinogenic toxicity (97 %), marine eutrophication (96 %), and terrestrial ecotoxicity (94 %) and the lowest percentage of impact on terrestrial acidification (66 %), climate change (63 %), and human non-carcinogenic toxicity (59 %).

The transportation of sludge and the transportation of chemicals mainly affects the impact categories climate change (23 % and 9 % respectively) and terrestrial acidification (19 % and 7 % respectively). The transportation of sludge and chemicals has further no impact on the freshwater and marine eutrophication. Regarding the other impact categories, transportation of sludge and chemicals has only an impact of less than 1%.

The use of diesel for the transportation of sludge and chemicals is the second largest impact aspect for all impact categories except from climate changes (5 %) and terrestrial acidification (8 %).

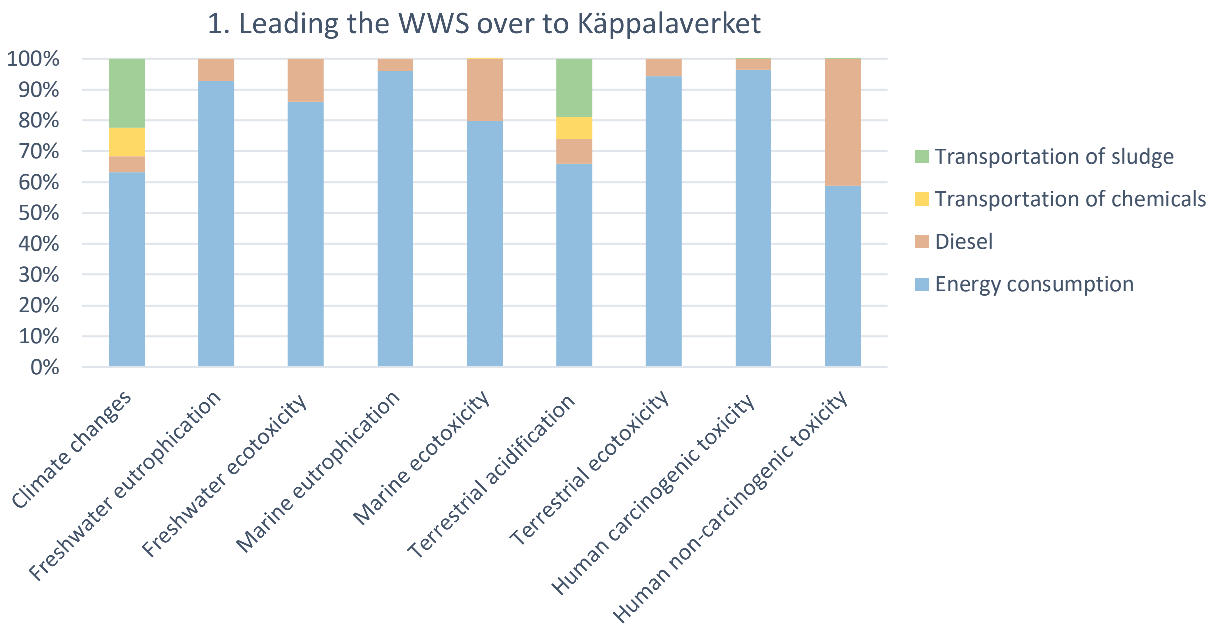

*Figure 5. The environmental impact on the selected impact categories linked to the energy consumption, diesel, transportation of sludge and chemicals for alternative 1, leading the WWS over to Käppalaverket.*

The results for the alternative 2, the future sludge management at Görvälnverket, are presented in figure 6. The results shows that the energy consumption is once again the aspect that has the largest contribution to all the impact categories. The energy consumption has the largest percentage impact on human carcinogenic toxicity (96 %), marine eutrophication (95 %), and terrestrial ecotoxicity (93 %) and the lowest impact on climate change (77 %), marine ecotoxicity (76 %) and human non-carcinogenic toxicity (53 %).

The transportation of sludge and the transportation of chemicals mainly affects the impact categories climate change (7 % and 9 % respectively) and terrestrial acidification (5 % and 7 % respectively). The transportation of sludge and chemicals has further no impact on the freshwater and marine eutrophication. Regarding the other impact categories, transportation of the sludge and chemicals has only an impact on less than 1%.

The use of diesel for the transportation of sludge and chemicals is the second largest impact aspect for all impact categories except from climate changes (8 %) and terrestrial acidification (12 %).

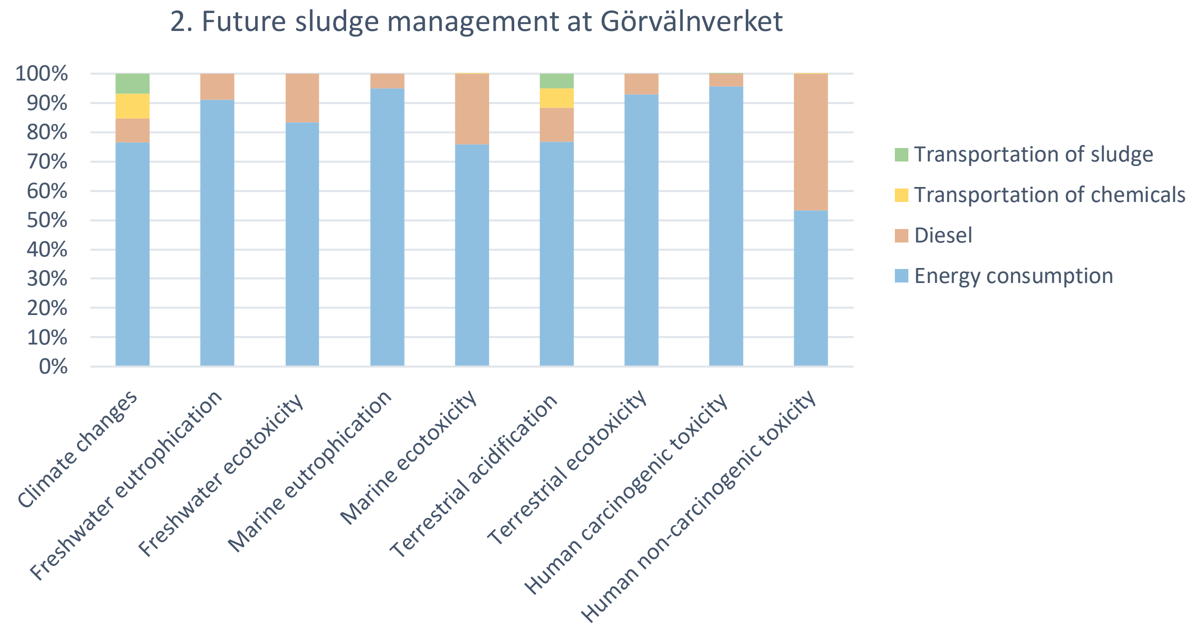

*Figure 6. The environmental impact on the selected impact categories linked to the energy consumption, diesel, transportation of sludge and chemicals for alternative 2, future sludge management at Görvälnverket.*

The results for the reference alternative are presented in figure 7. The results shows that the energy consumption is once again the aspect that has the largest contribution to all the impact categories. The energy consumption has the largest percentage impact on human carcinogenic toxicity (95 %), marine eutrophication (94 %), and terrestrial ecotoxicity (92 %) and the lowest impact on terrestrial acidification (58 %), climate change (55 %), and human non-carcinogenic toxicity (50 %).

The transportation of sludge and the transportation of chemicals mainly affects the impact categories climate change (34 % and 5 % respectively) and terrestrial acidification (29 % and 4 % respectively). The transportation of sludge and chemicals has further no impact on the freshwater and marine eutrophication. Regarding the other impact categories, transportation of the sludge and chemicals has only an impact of less than 1%.

The use of diesel for the transportation of sludge and chemicals is the second largest impact aspect for all impact categories except from climate changes (6 %) and terrestrial acidification (10 %).

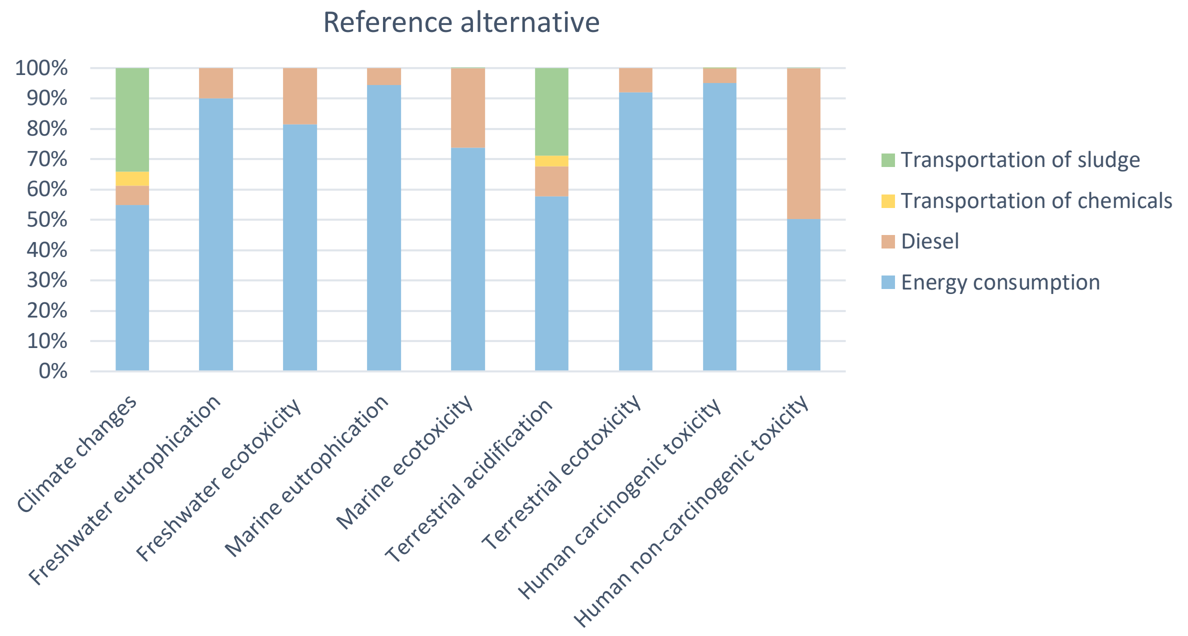

*Figure 7. The environmental impact on the selected impact categories linked to the energy consumption, diesel, transportation of sludge and chemicals for the reference alternative.*

To be able to compare the alternatives, the total environmental impact for each impact category is presented in figure 8. The results shows that the reference alternative has the lowest environmental impact on all the impact categories. Further it can be seen that alternative 1 has a higher environmental impact than alternative 2 for the impact categories.

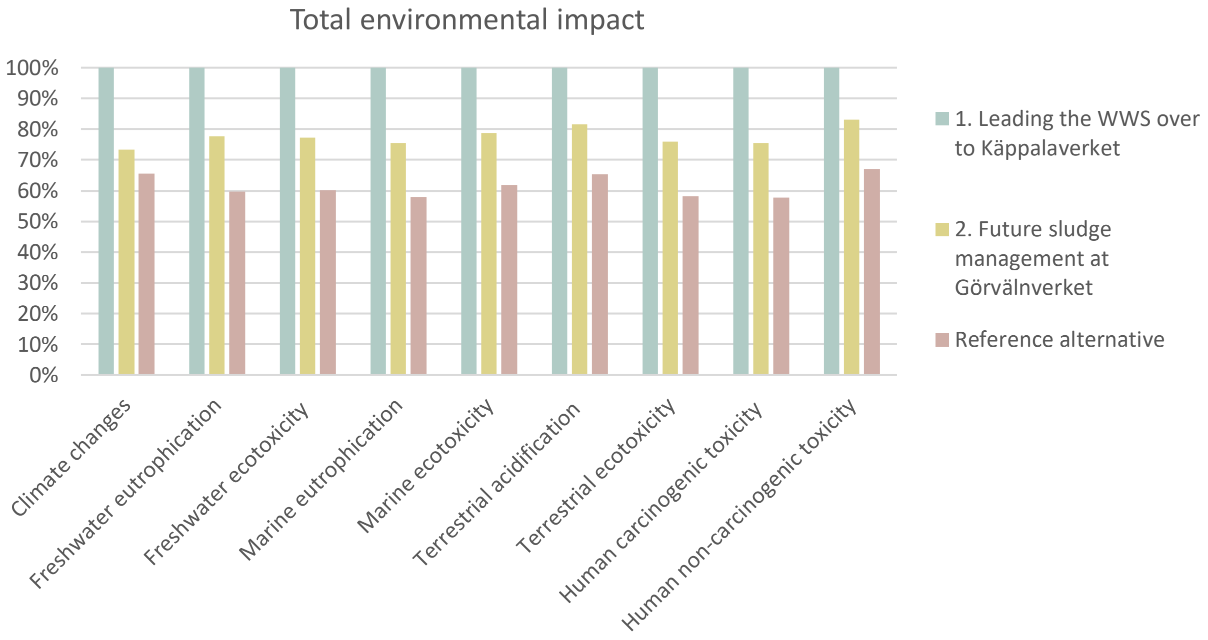

*Figure 8. The total environmental impact on the impact categories for each alternative.*

### 6.1.1 Sensitivity Analysis

The results from the sensitivity analysis for ferrous sulphate usage can be seen in figure 9. The decreased usage of chemicals results in a decrease for all impact categories. It can be seen that some impact categories have a large sensitivity to a change in chemical usage. The impact categories most sensitive are climate change, human non-carcinogenic toxicity, and terrestrial acidification, with a decrease range around 10 %. Other impact categories see a decrease of 2 % to 6 %.

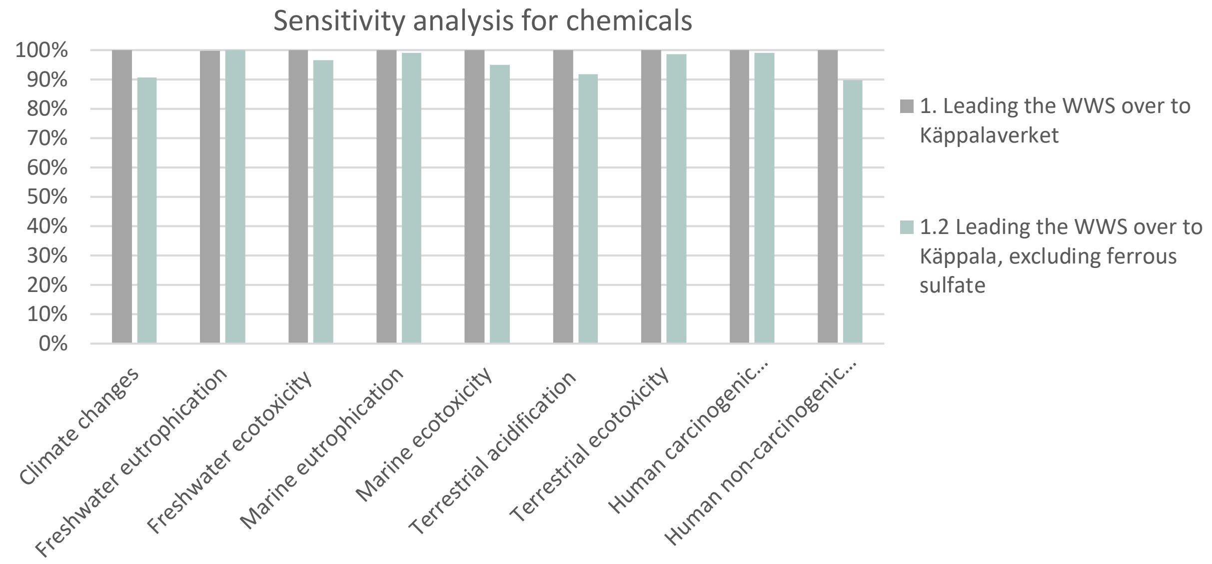

*Figure 9. The total environmental impact for two different chemical usage for the alternative to lead the WWS over to Käppalaverket. 1. including ferrous sulphate and 1.2 excluding ferrous sulphate.*

In figure 10 the relative environmental impact is presented for alternative 1, leading the WWS over to Käppalaverket, alternative 1.2 leading the WWS over to Käppalaverket where ferrous sulphate is not accounted for, alternative 2, future sludge management at Görvälnverket and the reference alternative. In general, the difference in environmental impact for alternative 1 and 1.2 is small. Both alternative 1 and 1.2 have a lower environmental impact than alternative 2. Leading the WWS over to Käppalaverket has a lower environmental impact than the future local sludge management irrespective of the sensitivity to ferrous sulphate.

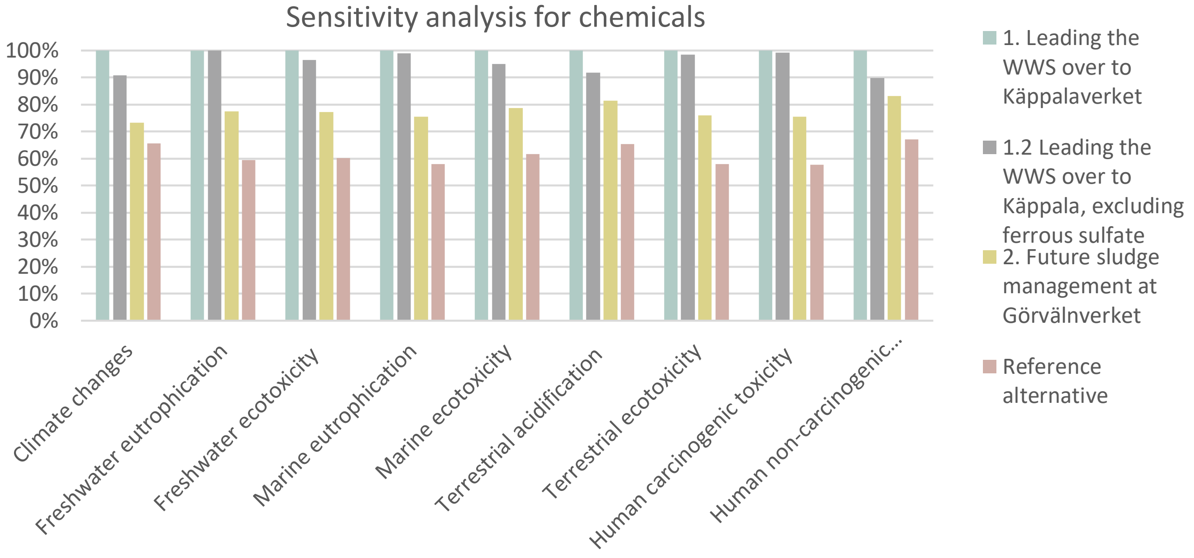

*Figure 10. The total environmental impact for alternative 1, leading the WWS over to Käppalaverket, alternative 1.2 leading the WWS over to Käppalaverket excluding ferrous sulphate, alternative 2, future sludge management at Görvälnverket and the reference alternative.*

The results of the sensitivity analysis for energy consumption at Käppalaverket are presented in figure 11. Here it can be seen that, 1.4 increased energy consumption for the sludge management will result in a slightly higher environmental impact. The lower limit for energy consumption at Käppalaverket, 1.3

decreased energy consumption in the biological treatment, results in a lower environmental impact. The influence of the biological treatment is considerably larger than the influence from the sludge management. This does not change the order of environmental impact for the alternatives, leading the WWS over to Käppalaverket, future sludge management at Görvälnverket and the reference alternative.

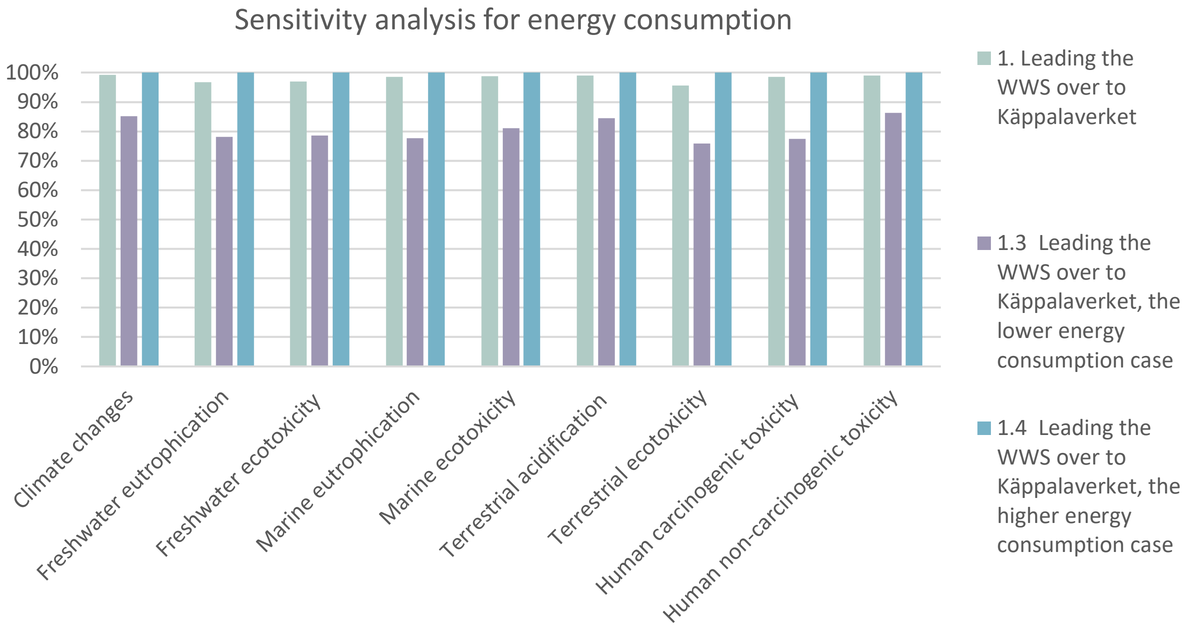

*Figure 11. The total environmental impact for 1. leading the WWS over to Käppalaverket, 1.3 leading the WWS over to Käppalaverket for the lower energy consumption case and 1.4 leading the WWS over to Käppalaverket for the higher energy consumption case.*

## 6.2 Result for Multi-Criteria Decision Analysis

The results from the MCDA using WISER are presented under heading 6.2.1 and 6.2.3.

### 6.2.1 Dimension Index

The dimension index for the three dimensions, technical, environmental, and economic are presented in figure 12. For the technical dimension the result show that both alternative 1 and 2 are beneficial compared to the reference alternative. Where alternative 2 is the most advantageous (1.3) compared to alternative 1 (1.0). Both alternatives 1 and 2 are also beneficial compared to the reference alternative, regarding the environmental dimension, but here alternative 2 (3.0) is more advantageous than alternative 1 (0.8). For the economic dimension, both alternatives are less advantageous than the reference alternative. Alternative 1 has an economic index on -10 and alternative 2 have an economic index on -7.9.

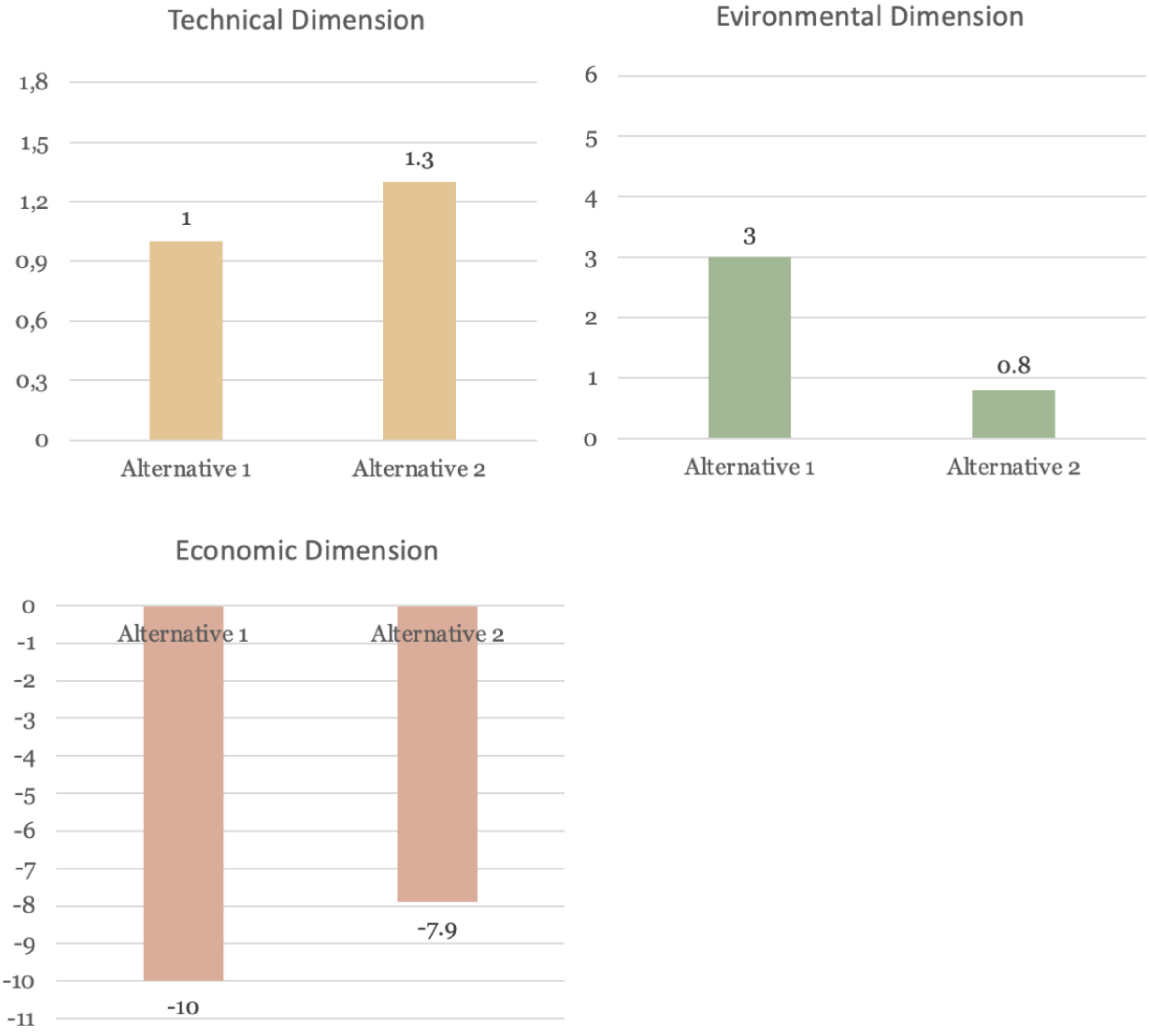

*Figure 12. Results from the calculated dimension index. Technical index is illustrated with yellow bars, environmental index is illustrated with green bars and economic index is illustrated with red bars.*

### 6.2.2 Weighted Index

The weighted index for alternative 1 and 2 are presented in figure 13. The weighted index shows that alternative 2, future sludge management at Görvälnverket (-2.3) is more favourable than alternative 1, leading the WWS over to Käppalaverket (-2.6). Although the difference is small between the two alternatives.

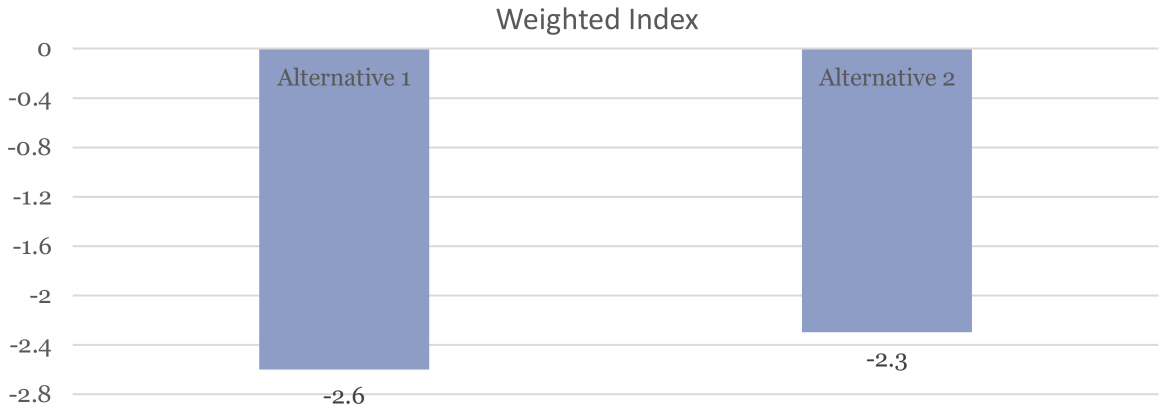

*Figure 13. The total weighted index for alternative 1 and 2.*

Figure 14. shows the percentage distribution of the dimensions that make up the total weighting index. In this figure it can been seen that the economic dimension accounts for the main part of both alternative 1 and 2. The technical dimension makes up a larger percentage share for alternative 2 compared to alternative 1. On the contrary, the environmental dimension constitutes a larger percentage share for alternative 1 than for alternative 2.

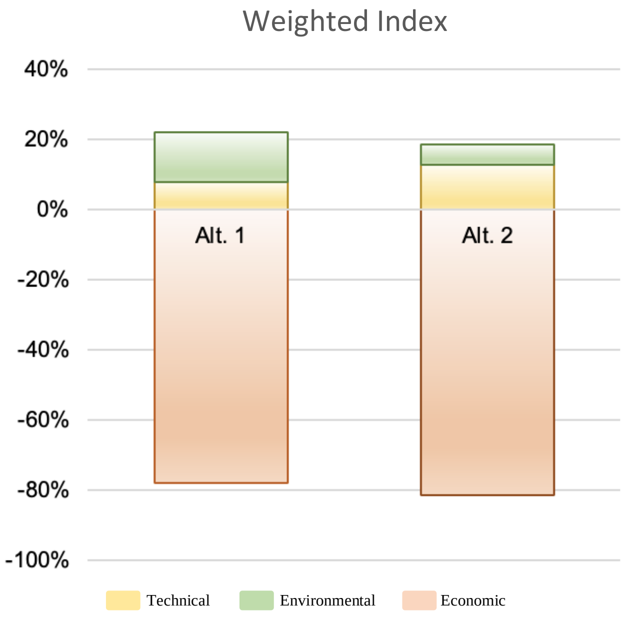

*Figure 14. The percentage distribution of each dimension that constitutes the weighted index.*

### 6.2.3 Sensitivity Analysis

In figure 15 the results from the variation analysis are presented. If a minimum score for the technical dimension is assumed alternative 2 is still the most favourable alternative. On the contrary alternative 2 is most favourable regarding the technical dimension if the maximum score is assumed. For the environmental dimension and the economic dimension, alternative 1 is still the most favourable alternative for both the minimum and the maximum score. The only dimension that changes favourability is the technical dimension when the maximum scores are used.

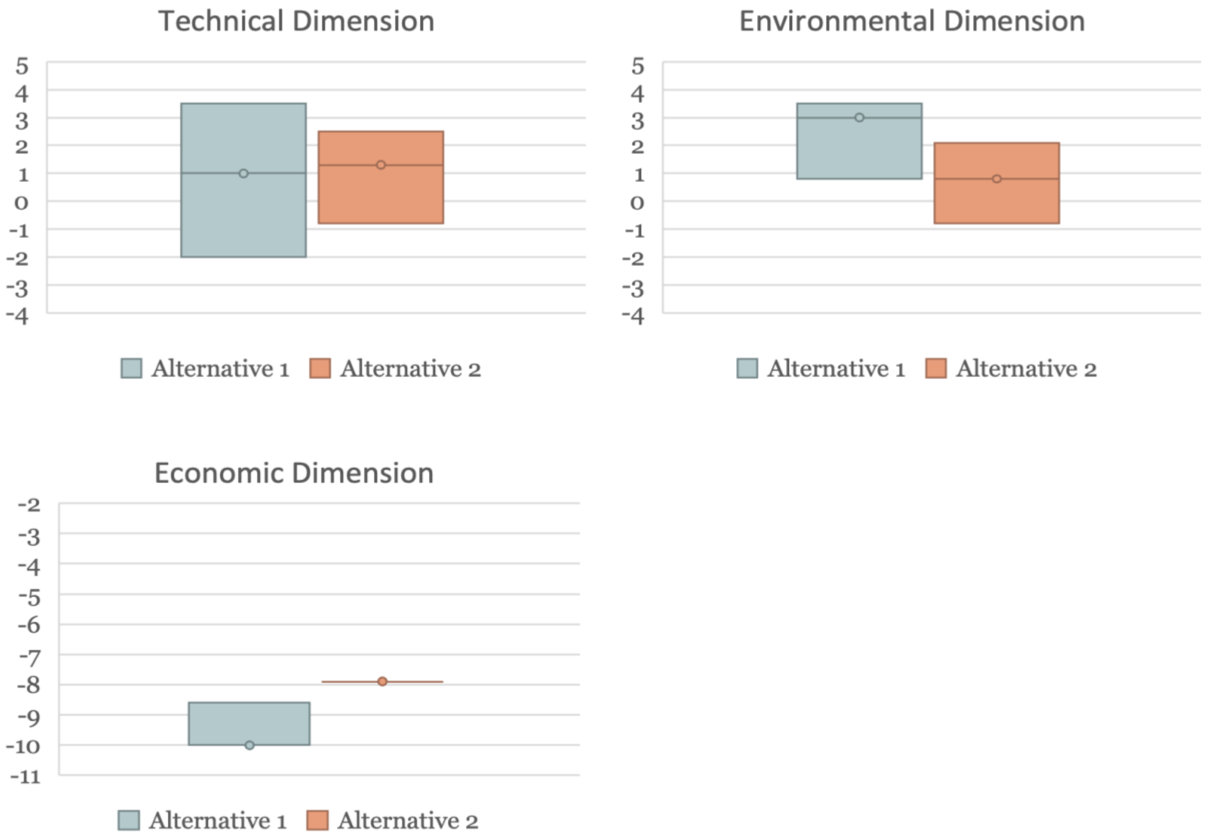

*Figure 15. Result from the variation analysis that show the uncertainty ranges for each dimension, technical, environmental, and economic. The first diagram in the top row represents the technical dimension, the second diagram in the top row represents the environmental dimension and the first diagram in the second row represents the economic dimension.*

The uncertainty range affects the total weighted index for the two considered alternatives. If the minimum scores are used alternative 2, future sludge management at Görvälnverket, is the most favourably alternative. This is consistent with the result when the most likely scores are used. On the contrary, if the maximum scores are used alternative 1, leading the WWS over to Käppalaverket, is the most favourably alternative as seen in figure 16. The total uncertainty range for alternative 1 is larger than for alternative 2.

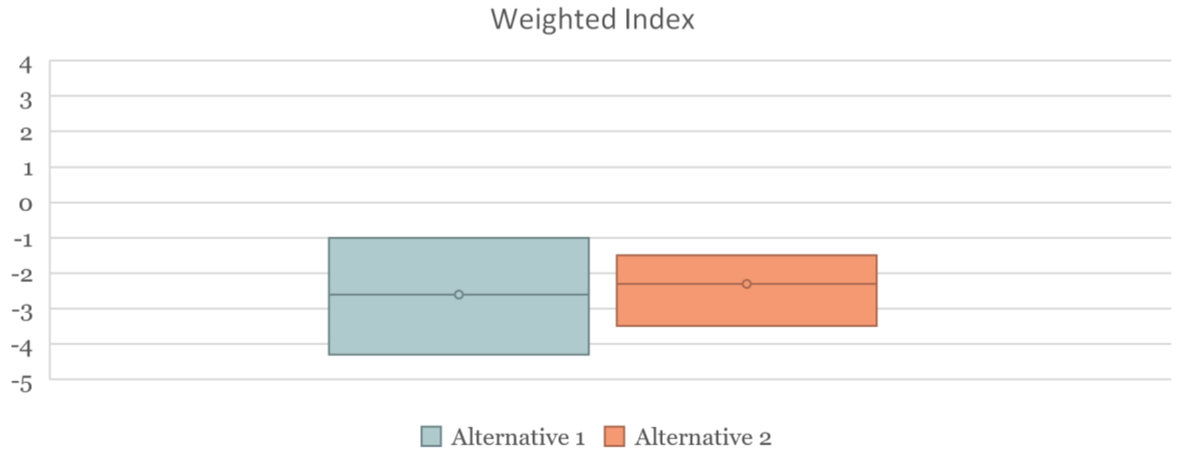

*Figure 16. Results for the variation analysis showing the probability distributions for the weighted Index.*

If Norrvatten was not depended on the economic aspect in the decision-making prosses for the future sludge management, alternative 1, leading the WWS over to Käppalaverket, would be the most favourably alternative as seen in figure 17.

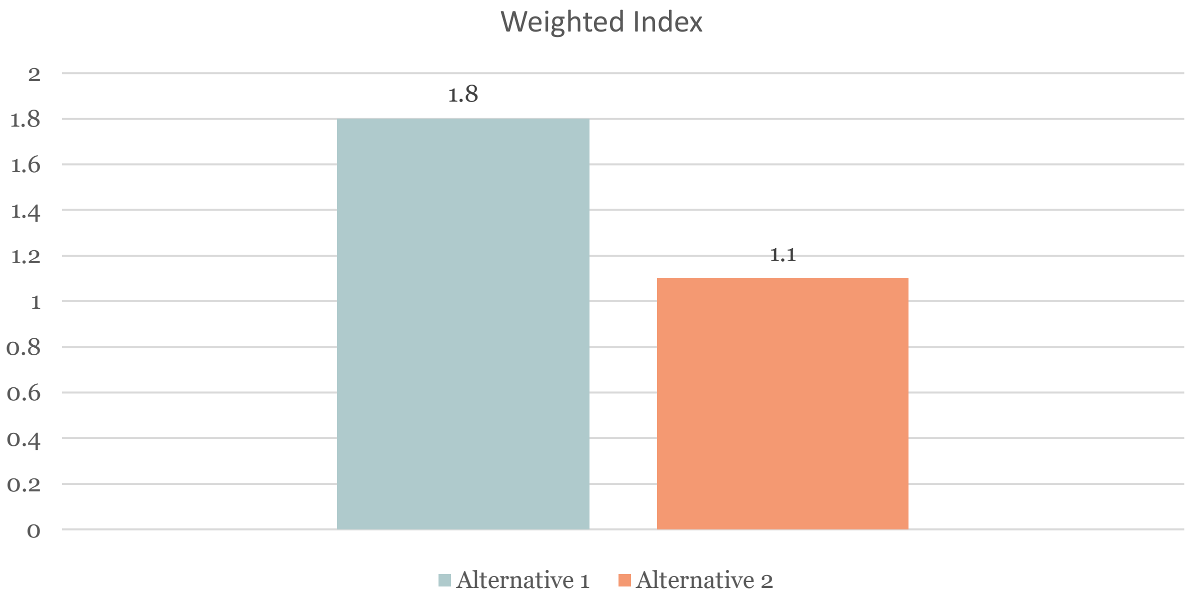

*Figure 17.The results from the sensitivity analysis where the economic dimension is excluded.*

# 7 Discussion

Norrvatten has the aim to not emit substances that can have a negative impact on the aquatic environment in lake Mälaren. By leading the WWS from Görvälnverket over to Käppalaverket, will Norrvattens emission of acrylamide to lake Mälaren cease. No local sludge management at Görvälnverket is then needed. However, polymer is added during the sludge management process at Käppalaverket, here the reject water from the centrifuges is lead back to the biological treatment step. Acrylamide from the added polymer will then, to a great extent, be broken down [9]. On the other hand, the addition of WWS to the wastewater will make the dewatering process less effective and more polymer will therefore have to be used in the dewatering process. This could possibly increase the emission of acrylamide to the Baltic Sea.

This alternative for the future sludge management will make it possible for Norrvatten to fulfil their set goal to not release clear phase water into lake Mälaren that exceeds 0.1 μg acrylamide per liter water. The risk of lowering the raw water source quality regarding acrylamide will also cease. In addition, the up concentration of PFAS and heavy metals in lake Mälaren will also cease. Leading the WWS over to Käppalaverket could therefore potentially increase the raw water quality and the aquatic environment in lake Mälaren.

The flow of WWS constitutes around 3 % of the wastewater flow into Käppalaverket. The additional inflow of WWS does not equate to a significant increase in load on the wastewater treatment. The WWS is assumed to not have any direct impact on the load at Käppalaverkets [14]. The considered daily flow of WWS in this study is an upper estimation. As the sludge from both the chemical precipitation and backwash water are considered in the total WWS. It is possible that the backwash water would not be transported to Käppalaverket. In this case the amount of WWS lead to Käppalaverket would be greatly reduced.

Previous studies show both advantages and disadvantages with treating WWS at WWTPs. The WWS contains chemical coagulant that will change the composition of the incoming wastewater, even if the WWS constitutes small percentages of the entire inflow of wastewater to the treatment plant. The main drawback with adding the WWS to Käppalaverket is that the addition of WWS will likely impact the dewatering of the sewage sludge, resulting in a higher polymer consumption and an increased hydraulic load on the centrifuges and the digesters. Since the WWS has such a low content of organic substances, the WWS will only increase the load in the digestors without give rise to any biogas production. The digester space at Käppalaverket is a limiting factor, the addition of WWS would likely result in a decreased biogas production. Despite a higher polymer usage and increased centrifuge operating time, it is often not possible to reach the same DM content in the final dewatered sludge, as is possible without the addition of WWS. A lower DM content in Käppalaverkets sewage sludge is therefore expected with the addition of WWS. On the contrary, a reduced chemical coagulate usage at Käppalaverket could likely be obtained if the WWS is added as a result of the aluminium content in the WWS. No reduction in efficiency on the wastewater treatment is expected.

Identified cost aspects linked to leading the WWS over to the Käppalaverket indicate a higher operating cost. A higher polymer consumption, increased centrifuge operating time and larger volumes of sewage sludge (due to a lower DM content) will likely increase the operating costs at Käppalaverket. If biogas production decreases when WWS is added, Käppalaförbundets revenue will decrease. The decrease in operating cost for a potential lower usage of chemical coagulant will not compensate for an increase in operating cost due to the higher energy consumption and polymer usage in the dewatering process. Observations from the study presented by Nodra, show that operating costs increased due to the higher polymer usage and increases centrifuge operational time [28].

The impact of WWS on the quality of the sewage sludge is uncertain. The metal content in the sewage sludge is not assumed to increase significantly. A study performed by Nodra observed that the addition of WWS showed no significant changes in the metal content of the sewage sludge, even though sampling on the metal content in the incoming WWS showed that the WWS hade a higher metal content [28].

The results from the LCA study showed that leading the WWS over to Käppalaverket has a higher environmental impact than the future sludge management at Görvälnverket. The higher environmental impact is mainly due to a higher energy consumption. The sensitivity analysis showed that the environmental impact for the transportations of chemicals to Käppalaverket does not have an influence on the final result. However, both the alternative to lead the WWS over to Käppalaverket and the future local sludge management have a higher environmental impact than the current local sludge management. The environmental impact considered in the LCA includes only transportations and energy consumption and not chemical emissions. The sensitivity analysis of the energy consumption at Käppalaverket found that the results are mainly dependent on the energy consumption of the biological treatment.

An increased energy consumption would be seen if a treatment step for the removal of PFAS is added to the considered design for the future sludge management at Görvälnverket. This would increase the environmental impact for the future sludge management due to the higher energy consumption. It is not concluded if the increased environmental impact will result in that the future sludge management at Görvälnverket will have a higher environmental impact than leading the WWS over to Käppalaverket.

The results from the MCDA show that a future sludge management at Görvälnverket is most favorable based on the weighted score for the technical, environmental, and economic dimensions. The difference in the results for the two alternatives was though small. The alternative to lead the WWS over to Käppalaverket is the most favorable, if only the environmental dimension is considered. However, the future local sludge management is most favorable for both the technical and economic dimensions. The results from the sensitivity analysis showed that the only dimension that changes favourability when the minimum and maximum score is assumed, is the technical dimension when the maximum scores are used. The sensitivity analysis also showed that the range of uncertainty is greater for the alternative to lead the WWS over to Käppalaverket compared with the alternative for a future sludge management at Käppalaverket. In addition, the sensitivity analysis showed that if Norrvatten was not depended on the economic aspect in the decision-making prosses for the future sludge management, leading the WWS over to Käppalaverket would be the most favourably alternative.

## 7.1 Future Work

If the alternative to lead the WWS over to Käppalaverket is to be pursued further, a more in depth study on the feasibility of leading the WWS over to Käppalaverkets should be conducted to fully evaluate this alternative. A trial where the WWS is added to Käppalaverket is also recommended to evaluate the impact of the WWS at Käppalaverket.

This study does not go into depth for the construction of the transport pipeline connecting Görvälnverket to Käppalaverkets wastewater tunnel. This is an aspect that should be considered thoroughly. Also, how the cooperation between Norrvatten and Käppalaförbundet should look like should be established to further evaluate the feasibility of Käppalaverket treating the WWS.

# 8 Conclusion

WWS is generally seen as a clean bioproduct in comparison to wastewater. The treatment needed for WWS is in comparison is less demanding than for wastewater. Treating WWS at a WWTP will entail a much more intensive treatment process than is needed to treat the WWS. As the energy consumption for treating the WWS at Käppalaverket is assumed to be higher than the local sludge management, an unnecessary energy consumption would be used in order to treat the WWS. The WWS would be displacing the treatment capacity of the WWTP, which is critical for society and environmental protection. For these reasons, a local sludge management is seen as favorable. The local sludge management is also favorable from a technical and economic perspective. However, the addition of WWS at Käppalaverket is not assumed to negatively impact on the treatment quality at Käppalaverket. Although the WWS is expected to impact the dewatering of the sewage sludge, resulting in a higher polymer consumption and an increased hydraulic load on centrifuges and digesters. Despite a higher polymer usage and increased centrifuge operating time, it is often not possible to reach the same DM in the final dewatered sludge, as is possible without the addition of WWS. A lower DM content in Käppalaverkets sewage sludge is therefore expected with the addition of WWS. A higher polymer consumption, increased centrifuge operating time and larger volumes of sewage sludge, due to lower DM content will increase the operating costs at Käppalaverket.

The environmental impact from chemical emissions and the environmental impact from transportation and energy consumption are evaluated separately. Leading the WWS over to Käppalaverket results in a lower environmental impact regarding chemical emissions but results in a higher environmental impact regarding transportation and energy consumption.

Leading the WWS over to Käppalaverket was found to be feasible, although the future local sludge management at Görvälnverket was found to be more favourably in this study. A more in depth study on the feasibility of leading the WWS over to Käppalaverkets is required to fully assess this aspect. A trial where the WWS is added to Käppalaverket is recommended to further evaluate the impact of the WWS.

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# Appendix 1: Background for Life Cycle Assessment

LCA is a methodology used to identify and quantify potential impact on environmental aspects throughout the lifetime of a product, a process, or a service. A LCA can be applied to either a products entire life cycle, called cradle-to-grave LCA, or only parts of a products life cycle, called gate-to-gate LCA [41].

The general framework and principles for conducting LCA studies has been specified with two ISO standards (ISO 14040, 2006 and ISO 14044, 2006) [41]. Regarding LCA studies within the water sector there is no comprehensive specific guidance, besides the general guidelines [34]. The LCA framework developed in ISO 14040 divides the LCA study into four different phases, goal and scope definition, inventory analysis, impact assessment and interpretation [42]. The four different phases of the LCA study are illustrated in figure 18.

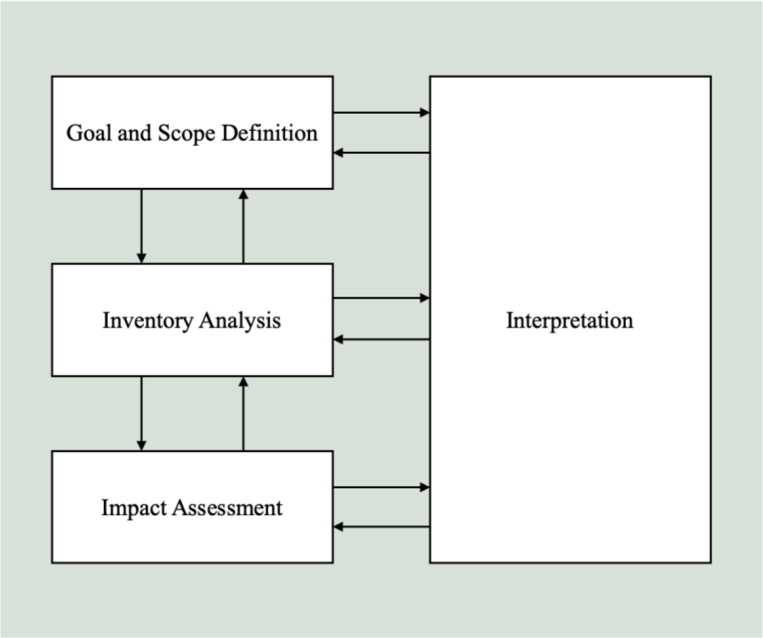

*Figure 18. Illustration of the 4 different phases in LCA studies.*

## Goal and Scope Definition

The first step in the LCA is to clearly define the goal of the study. This includes the aim of the study, and which questions the study should answer. The intended application of the results and stakeholders should also be defined within the goal of the study [42].

The next step in the LCA is to define the scope of the study. The aim of the scope is to clearly define which product systems are included and how the assessment is to be performed [42]. The functional unit for the product is also defined during this step. The functional unit should represent the action performed or the function of the system [34]. The definition of the functional unit plays thus an important role in the performance, results, and the interpretation of the LCA. It is therefore important to carefully define the functional unit, especially when a comparative LCA study is performed [42].

The system boundaries for the study are defined to account for which processes of the product system are included or excluded from the analysis. All parts of the process relevant to the aim of the study should be included within the system boundaries [34]. Relevant system boundaries are, technological, geographical, time horizon and cut-off criteria. Assumptions and limitations made in the study should also be accounted for in the scope definition.

The two main types of LCA studies are attributional and consequential, based on the goal and scope of the study. The aim with attributional LCA is to isolate the product system from the rest of the technosphere. The attributional methodology has the goal of evaluating the environmental impact of a product or process. An assumption made is that other life cycles are not affected by changes in the studied system. The consequential LCA study, on the other hand, aims to account for economic changes caused by the product system. The consequential methodology strives to evaluate the environmental impact connected to the consumption of a product [34]. Another difference between the two types of LCA studies are how the background system is modelled. For an attributional LCA, average data is used to model the background system, while marginal data is used to model the background system for a consequential LCA [42].

### Inventory Analysis

The data for the product system is collected using a so called life cycle inventory analysis (LCI). This includes data for both incoming and outgoing flows for the system. The functional unit is used as a basis to quantify the inventory data [42].

The studied system is divided into a foreground and background system, where different data is often used for the two different systems. The data collected for the foreground system often consists of data retrieved from measurements, suppliers, or design documents. Whereas, data for the background system often is retrieved from a LCI database [34].

### Impact Assessment

The aim with a LCIA is to increase the inventory data’s relevance and interpretability. Raw inventory data is translated into different chosen environmental impact categories [34], [42]. The impact categories should be chosen so that the environmental impact related to the studies product system is reflected [42]

The LCIA can either be based on midpoint impact indicators or endpoint impact indicators. Midpoint impact indicators are based on changes to the environment that can be related to resource usage and emissions. Midpoint impact indicators could be, for example, climate change, ecotoxicity, and human toxicity. Endpoint impact indicators, on the contrary, are based on measured damage or benefit to the environment that effect ecosystem quality, natural resources, and human health [42]. Today there are several LCIA methodologies existing in LCA software that evaluate both at a midpoint and at an endpoint level [34]. An example of one of these methodologies is ReCiPe. This method creates a set of endpoints categories based on the aggregate of multiple environment concerns at midpoint level [38]. ReCiPe is commonly used in Europe [43].

The impact assessment phase can be divided into three different steps. The first step is to select relevant impact categories for the study. The second step is to assign inventory data for the selected impact categories. In the last step, impacts are characterized by translated inventory data to impacts [34].

Normalisation and weighting are two additional steps in the impact assessment that are optional to perform according to the framework, ISO 14044:2006. The aim with the normalisation is to provide better understanding for the characterised results, which is done by relating the result to an external common reference. Characterisation is also useful for identifying errors that could contribute to normalised results being unreasonably high or low. Normalisation is performed by distributing indicator scores in a common metric for all chosen impact categories. Weighting is done by assigning weights to each of the impact category, based on the relative importance of the impact category. This makes the impact categories comparable, and also provides the possibility to calculate a total indicator score from the weighted impact scores. The total indicator score can then be used in decision-making where different product systems are compared [34].

### Interpretation

The final phase in the LCA study is interpretation, where the aim is to ensure transparency in the result of the study. The interpretation can be performed in three steps according to the provided guidelines from the ISO standard. The first step is identification of significant issues [34]. This is done by analysing the results from the previous phases in the LCA study to identify important issues that could contribute to changes in the final result. Next step is evaluation, where the results from the identification element are evaluated based on stability and reliability. The evaluation step can in turn be divided into three subparts, completeness check, sensitivity and uncertainty analysis, and consistency check. The completeness of available data for the processes and impacts is determined by a completeness check. A completeness check is carried out for both inventory and impact assessment. The purpose with the sensitivity and uncertainty analysis is to identify how collection of inventory data can be improved as well as identify improvements with the impact assessment. Finally, the consistency check aims to examine how well the goal and scope definition are consistent with the method, assumptions, and data collection in the study. The last step in the interpretation phase is to draw conclusions from the study, identify the study's limitations and finally present recommendations based in the applications of the results to the stakeholders [42].

# Appendix 2: Background for Multiple-Criteria Decision Analysis

MCDA is an approach to distinctly and systematically evaluate different and often conflicting criteria for decision-making. The term MCDA includes a variety of different developed systematic approaches for decision-making [44]. A common aspect to all MCDA is the view that by dividing the overall evaluation into different, often conflicting criteria, the decision-making process can be improved. However, the criteria chosen should be defined in such a way that it is measurable, either quantitative or qualitative [45].

The MCDA in this study has been performed using the program WISER. WISER is an abbreviation for water investments for sustainability enhancement and reliability and is an Excel-based tool that has been develops for decision support within the Swedish drinking water sector. The aim with the tool is to provide support and guidance for decision-making where several different action alternatives are compared and evaluated. WISER is developed to account for four different decision dimensions, technical, social, environmental, and economic [39].

The decision-making process in WISER starts with deciding which criteria will be included in evaluation of the different action alternatives. An action alternative is then assessed relative to a reference alternative (the design currently used), based on selected criteria. The criteria are weight based on importance. The results can be analysed and then a decision can be made. The decision-making process in WISER is illustrated in figure 19.

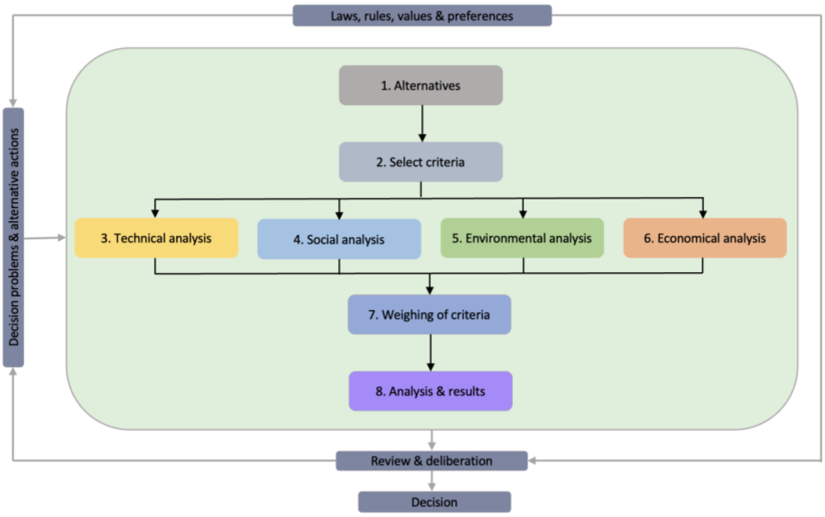

*Figure 19. The decision-making process in WISER* [39].

### Criteria

In WISER there are suggestions for different criteria that have been developed for decision making within the drinking water sector. It is possible to decide which of these criteria should be included or excluded from analysis. It is also possible to include other criteria that might be suitable for the analysis [39].

### Scoring

During the scoring step, the performance of each action alternative is assessed with respect to the included criteria, in relation to a reference alternative. The evaluation of each criterion is then translated into an interval scale so that the criteria are assessed on the same scale. The assessment scale in WISER consists of a scale from -10 to 10, where -10 is defined as the largest deterioration and 10 is defined as the largest improvement [39]. The scale used for the scoring is presented in table 15.

*Table 15. The different scores and description of the scores used in WISER.*

| **Score** | **Description** |
|---|---|
| **6 to 10** | Significant improvement |
| **1 to 5** | Moderate improvement |
| **0** | No change |
| **-1 to -5** | Moderate deterioration |
| **-6 to -10** | Significant deterioration |

### Weighing

The weighting is performed in two different levels. Frist, the criteria within a dimension are weighted against each other to illustrate their importance for the specific decision-making process. In the next step, the dimensions are weighed against each other to illustrate the importance of the dimension linked to the specific decision-making process. The weighting is done so that each criterion or dimension is assigned a score on a scale from 0 to 10. Where 0 means that the criteria or dimension is not of importance and 10 means that the criteria or dimension is of most importance. The assigned scores are then calculated to a weighting percentage, which is illustrated in a pie chart. The results from the weighting are then presented in a solar chart, which shows the importance between the criteria and dimensions [39].

### Balance of Weighting and Scores

The next step is to balance the weighting and the scores for each dimension. The purpose of this step is to show how the alternatives performs relative to the reference alternative within the dimension. This is a way of visualizing whether the alternative leads to an improvement or a deterioration within the dimension, in relation to the reference alternative. This is done by using a linear adaptive method to calculate an index that combines the scores and weights for each main criterion in relation to each alternative. The linear adaptive method used in WISER is presented in eq 1, where I represents the index, d represents the dimension, w represents the weigh, s represents the scores and k represents the criteria. The calculated index will obtain a value between -10 to 10, where -10 represents a case where the alternative shows a large deterioration compared to the reference alternative, 10 represent a case where the alternative shows a large improvement compared to the reference alternative and 0 represent a case where the alternative shows no change in performance compared to the reference alternative [39].

$$I_{d,a} = \sum_{c=1}^{C} w_k \, p_{a,c} \tag{1}$$

The next step is to rank the alternatives against each other, based on the dimension assessment. This is done by calculating an index that combines the dimension index to estimate the alternatives performance relative the reference alternative. The combined index is calculated in WISER using a leaner adaptive method according to eq 2, where S represents the combined index, a represents the alternative, d represents the dimension, Wd represents the dimensions relative weight and Id,a represents the alternatives calculated dimension index [39].

$$S_a = \sum_{d=1}^{D} W_d \, I_{d,a} \tag{2}$$

### Sensitivity Analysis

The impact of the uncertainty in the scoring can be evaluated by using the assigned minimum and maximum scores for each criterion to derive an uncertainty range. To calculate an uncertainty distribution in WISER, a separate plug-in software @Risk (version 8) is currently needed [39]. This plug-in software is compatible with Excel and enables Monte Carlo-simulations. The software @Risk is currently distributed by the company Lumivero [46].

# Appendix 3: Flowcharts for Life Cycle Assessment

The flowchart generated in GaBi for leading over the WWS to Käppalaverket is presented in figure 20.

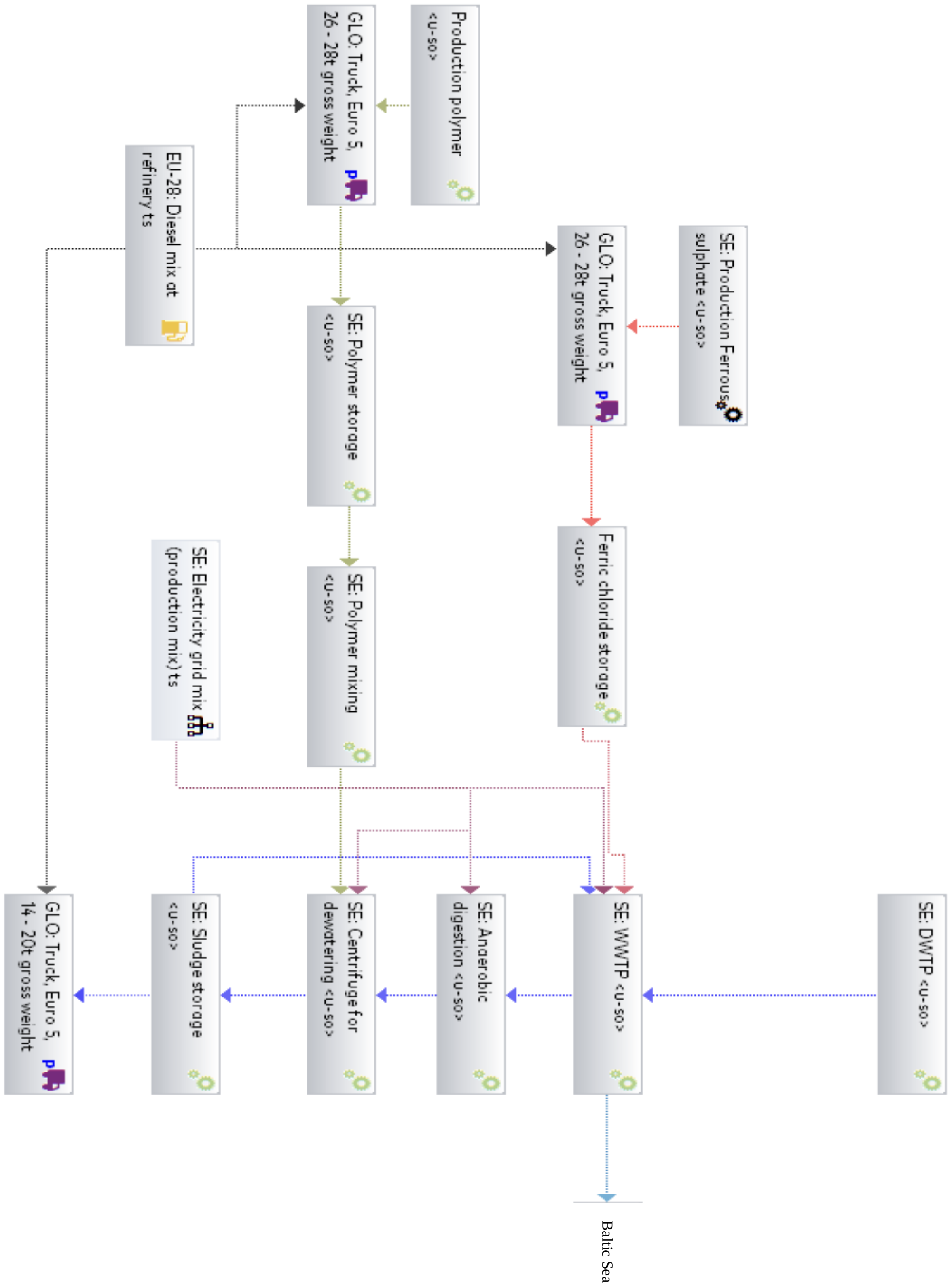

*Figure 20. Flowchart for leading over the WWS to Käppalaverket.*

The flowchart generated in GaBi for the future sludge management at Görvälnverket is presented in figure 21.

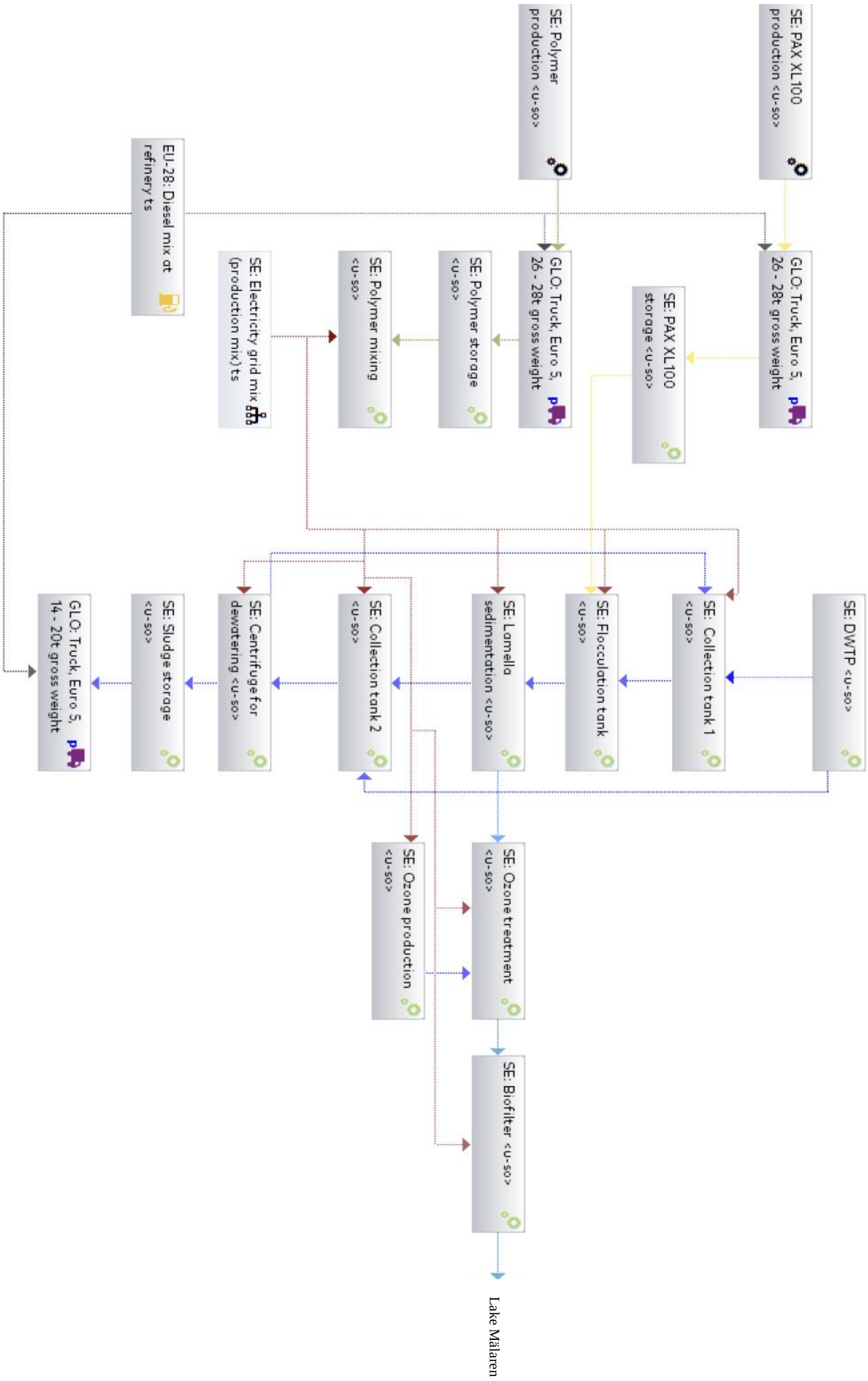

*Figure 21. Flowchart for the future sludge management at Görvälnverket.*

The flowchart generated in GaBi for the current sludge management at Görvälnverket is presented in figure 22.

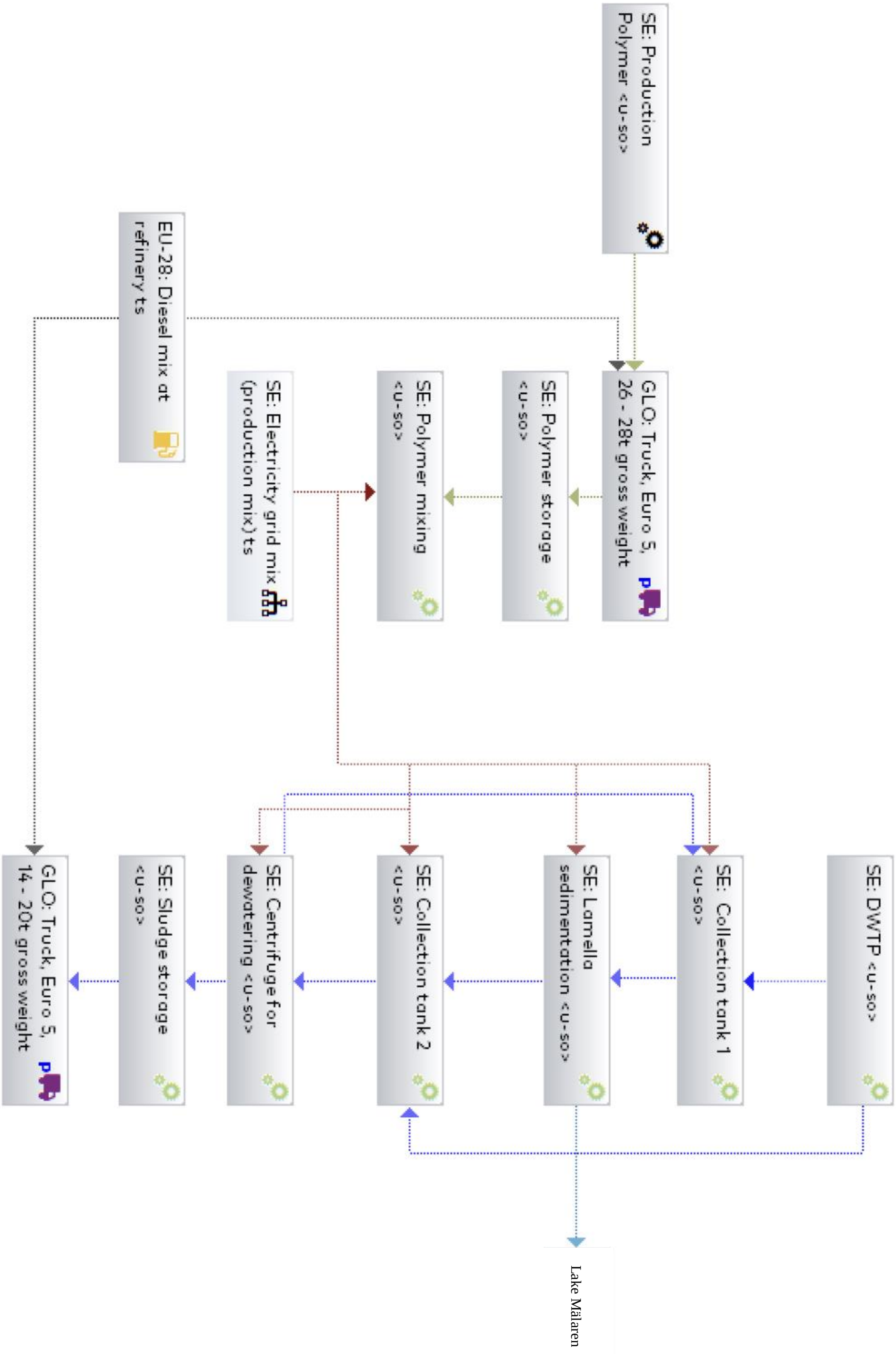

*Figure 22. Flowchart the current sludge management at Görväln*

# Appendix 4: Energy Consumption

The calculated energy consumption for the alternatives, leading the WWS over to Käppalaverket, the future sludge management at Görvälnverket and the current sludge management at Käppalaverket are presented in this appendix.

## Leading the WWS over to Käppalaverket

The energy consumption ws estimated by using Käppalaförbundets own estimations for the energy consumption for year 2040 and by calculating the energy consumption for pumping the WWS from Görvälnverket to Käppalaförbundets wastewater tunnel.

The estimated energy consumption for Käppalaverket in year 2040 are presented in table 16.

*Table 16. Estimation of the energy consumption for Käppalaverket in year 2040, provided by Käppalaförbundet* [36].

| | **Energy [GWh/year]** |
|---|---|
| Tunnel & inflow pumping | 7.9 |
| Biological treatment | 17 |
| Sludge management | 2.1 |
| Anaerobic digestion | 4.7 |
| Total | 31.7 |

The energy consumption for 1 m$^3$ of incoming wastewater to Käppalaverket is calculated:

Incoming wastewater in year 2040: $\dot{V}_{wastewater} = 72 \cdot 10^6\ [m^3/year][36]$

Total energy consumption $E_{wastewater} = 31.7\ [GWh/year]$

$$Energy\ conumption_{wastewater} = \frac{E_{wastewater}}{\dot{V}_{wastewater}} = \frac{31.7\ [GWh/year]}{72 \cdot 10^6\ [m^3/year]} = 0.44\ [kwh]$$

The energy consumption for treating 1 m$^3$ wastewater at Käppalaverket is 0.44 kWh.

The energy consumption for pumping 1 m$^3$ WWS from Görvälnverket over to Käppalaförbundets wastewater tunnel was calculated. The connecting pipeline between Görvälnverket and Käppalaförbundets wastewater tunnel was assumed to be 5 km and have a dimeter of 0.4 m. First the pipelines cross section is calculated:

Assumed pipe diameter $d_{pipe} = 0.4\ [m]$

$$Cross\ section_{pipe} = \pi \cdot \left(\frac{d_{pipe}}{2}\right)^2 = \pi \cdot \left(\frac{0.4\ [m]}{2}\right)^2 = 0.06\ [m^2]$$

The velocity for the WWS was then calculated:

Volume flow for the WWS $\dot{V}_{WWS} = 7115\ [m^3/d]\ = 0.08\ [m^3/s]$ [31]

$$v_{WWS} = \frac{\dot{V}_{WWS}}{Cross\ section_{pipe}} = \frac{0.08\ [m^3/s]}{0.06\ [m^2]} = 1.27\ [m/s]$$

The kinematic viscosity was then calculated:

Viscosity of water at 20 °C $\mu = 10.02 \cdot 10^{-4}\ [Pa\ s]$

Density of water at 20 °C $\rho = 998.3\ [kg/m^3]$

$$u = \frac{\mu}{\rho} = \frac{10.02 \cdot 10^{-4}\ [Pa\ s]}{998.3\ [kg/m^3]} = 1.00 \cdot 10^{-6}[m^2/s]$$

Reynolds number was then calculated:

$$Re_{pump}\ = \frac{v_{WWS} \cdot d_{pipe}}{u} = \frac{1.27\ [m/s]\ \cdot 0{,}4\ [m]}{1.00 \cdot 10^{-6}[m^2/s]} = 5.07 \cdot 10^5\ [-]$$

To calculate the friction loss, the friction factor must first be determined. To derive the friction factor, the pipe was assumed to be made of steel, which gives an absolute surface roughness of 0.00015 ft [47]. The relative surface roughness was then obtained by dividing the absolute surface roughness by the diameter of the pipe in unit feet:

Absolute surface roughness for steel $Ar_{steel} = 0.00015\ [ft]$

Assumed pipe diameter $d_{pipe} = 0.4\ [m] = 1.31\ [ft]$

$$Relative\ surface\ roughness = \frac{Ar_{steel}}{d_{pipe}} = \frac{0.00015\ [ft]}{1.31\ [ft]} = 1.14 \cdot 10^{-4}\ [-]$$

The friction factor can then be retrieved from a friction factor plot for circular pipes, using Reynolds number and the relative surface roughness. From the friction factor plot, a friction factor of $3.85 \cdot 10^{-3}$ was obtained [47].

The expansion coefficient ($K_e$) is 1 since $S_b$ are assumed to go against infinity in comparison to $S_a$ see equation 2.

$$K_e = \left(1 - \frac{S_a}{S_b}\right)^2 \tag{3}$$

The contraction coefficient ($K_c$) will have a value of 0,4 since $S_b$ can be assumed to go to infinity in comparison to $S_a$, see equation 4.

$$K_c = 0{,}4 \cdot \left(1 - \frac{S_b}{S_a}\right) \tag{4}$$

The loss coefficient is the loss that occurs when the pipe bends, a bend of 90° gives a loss coefficient of 0.75 and a bend of 180° gives a loss coefficient of 1.5 [47]. To calculate the loss coefficient, the assumption has been made that the pipe will be bent four times at 90°. Calculation of the loss coefficient:

$$K_f = 4 \cdot 90\ °C = 4 \cdot 0.75 = 3.00$$

The friction loss can then be calculated:

| | |
|---|---|
| Length of pipe | $L_{pip} = 5000\ [m]$ |
| Contraction coefficient | $K_C = 4.0\ [-]$ |
| Expansion coefficient | $K_e = 1\ [-]$ |
| Friction factor | $f = 3.85 \cdot 10^{-3}\ [-]$ |
| Loss coefficient | $K_f = 3.00\ [-]$ |

$$\text{Friction loss} = \left(4 \cdot \text{f} \cdot \frac{L_{pip}}{d_{pip}} + K_C + K_e + K_f\right) \cdot \frac{v_{WWS}^2}{2}$$

$$\text{Friction loss} = \left(4 \cdot 3.85 \cdot 10^{-3} \cdot \frac{5000\ [m]}{0.4\ [m]} + 4.0\ [-] + 1\ [-] + 3.00\ [-]\right) = 159.39\ [J/kg]$$

The theoretical effect was then calculated using the friction loss and mass flow:

| | |
|---|---|
| Mass flow of WWS | $\dot{m}_{WWS} = 82.20\ [kg/s]$ |

$$P_{teori} = \text{Friction loss} \cdot \dot{m}_{WWS} = 159.39\ [J/kg] \cdot 82.20\ [kg/s] = 13.10\ [kW]$$

The calculations to estimate the pump effect is simplified and in reality, the losses will be greater, which will result in the actual energy consumption being higher. In addition, a pump does not have an efficiency of 100 %, which will also lead to the real energy consumption being greater. Based on this, the assumption is made that the real energy consumption is 50 times greater than the calculated power:

| | |
|---|---|
| Increase power by 50 % | $\eta = 0.5$ |

$$P_{pump} = \frac{P_{teori}}{\eta} = \frac{13.10\ [kW]}{0.5} = 26.20\ [kW]$$

The energy consumption for pumping 1 m$^3$ WWS was then calculated:

$$\text{Energy consumption}_{pump} = \frac{P}{\dot{V}_{WWS}} = \frac{26.20\ [kW] \cdot 86400}{7115\ [m^3/d]} = 0.32\ [MJ/m^3] = 0.09\ [kWh]$$

The energy consumption for pumping 1 m$^3$ WWS is 0.09 kWh. The total energy requirement for the alternative to lead the WWS over to Käppalaverket was then calculate:

$$Total\ energy\ requirement = Energy\ conumption_{wastewater} + \text{Energy consumption}_{pump}$$

$$Total\ energy\ requirement = 0.44\ [kwh] + 0.09\ [kWh] = 0.53\ [kWh]$$

The total energy consumption for the alternative to lead the WWS over to Käppalaverket is 0.53 kWh per 1 m$^3$ of WWS.

### The current sludge management at Görvälnverket

The total energy requirement for the current sludge management is 0.30 kWh WWS [35].

## The alternative for the future sludge management at Görvälnverket

The energy consumption is determined by using energy consumption for the current sludge management and the calculated energy consumption for the ozonation, biofiltration, and the pumps, pumping the WWS between the ozone treatment and the biofiltration. The ozone generator, Wedeco SMOEVO 410 ozone system, from Xylem is assumed to be used [48].

First the ratio between the installed power and the power factor was calculated:

| | |
|---|---|
| Installed power [48] | $P_I = 18.2\ [kW]$ |
| Power factor [48] | $P_F = 0.95\ [-]$ |

$$Ratio = \frac{P_I}{P_F} = \frac{18.2\ [kW]}{0.95\ [-]} = 9.58\ [kWh]$$

The energy requirement for 1 m$^3$ WWS was then calculated:

| | |
|---|---|
| Desired ozone production | $Oz = 3.0 \cdot 10^{-3} [kg/m^3]$ |

$$E_{ozonation} = Oz \cdot Ratio = 3.0\ \cdot 10^{-3} [kg/m^3] \cdot 9.58\ [kWh] = 0.03\ [kwh]$$

The energy consumption for the ozonation is 0.03 kWh.

The energy conception for the biofiltration with leca was calculated by first calculate the pressure drop over the biofilter:

| | |
|---|---|
| Maximal surface load for biofilter | $\dot{V}_0 = 2.0 \cdot 10^{-3}\ [m/s]$ |
| Length of biofilter | $L = 5\ [m]$ |
| Sphericity of leca [47] | $\phi_s = 0.8\ [-]$ |
| Assumed diameter of leca | $d_l = 0.006\ [m]$ |
| Void fraction [47] | $\varepsilon = 0.05\ [-]$ |
| Viscosity of water at 20 °C | $\mu = 10.02 \cdot 10^{-4}\ [Pa\ s]$ |
| Density of water at 20 °C | $\rho = 998.3\ [kg/m^3]$ |

$$\Delta p = L \cdot \frac{150 \cdot \dot{V}_0 \cdot \mu}{\phi_s^2 \cdot d_l^2} \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75 \cdot \rho \cdot \dot{V}_0^2}{\phi_S \cdot d_l} \cdot \frac{1-\varepsilon}{\varepsilon^3}$$

$$\Delta p = 5\ [m] \cdot \frac{150 \cdot 2.0 \cdot 10^{-3} \left[\frac{m}{s}\right] \cdot 10.02 \cdot 10^{-4}\ [Pa\ s]}{0.8^2\ [-] \cdot 0.006^2\ [m]} \cdot \frac{(1 - 0.05\ [-])^2}{0.05^3 [-]}$$

$$+ \frac{1.75 \cdot 998.3\ [kg/m^3]\ \cdot 2.0 \cdot 10^{-3^2} [m/s]}{0.8\ [-] \cdot 0.006\ [m]} \cdot \frac{1 - 0.05\ [-]}{0.05^3 [-]} = 641{,}29 \approx 641\ [Pa]$$

The pressure drop over the biofilter is 641 Pa. Then the effect for the biofiltration was calculated:

Volume flow though the filter $\dot{V}_f = 0.08\ [m^3/s]$
Number of filters $f = 4$

$$P_f = \Delta p \cdot \dot{V}_f \cdot f = 641 \ \cdot 0.08 \ \cdot 4 = 211.24\ [W]$$

The energy consumption for 1 m$^3$ WWS was then calculated:

Volume flow for 1 m$^3$ WWS $\dot{V}_{WWS} = 1.40\ [m^3/s]$

$$E_{filter} = \frac{P_f}{\dot{V}_{WWS}} = \frac{211.24}{1.40} = 151.41 = 151\ [J] = 5.4 \cdot 10^{-5}\ [kWh]$$

The energy consumption for the biofiltration is $5.4 \cdot 10^{-5}$ kWh.

The energy consumption for the pump transporting the clear phase water between the ozone treatment and the biofiltration was estimated, by first calculate the cross section of the pipe:

Assumed diameter of the pipe $d_{pipe} = 0.2\ [m]$

$$Cross\ section_{pipe} = \pi \cdot \frac{d_{pipe}^2}{2} = \pi \cdot \frac{0.2^3 [m]}{2} = 0.02\ [m^2]$$

The velocity for the WWS was then calculated:

Volume flow for the WWS[31] $\dot{V}_{WWS} = 7115\ [m^3/d]\ = 0.08\ [m^3/s]$

$$v_{WWS} = \frac{\dot{V}_{WWS}}{Cross\ section_{pipe}} = \frac{0.08\ [m^3/s]}{0.02\ [m^2]} = 5.09\ [m/s]$$

Then the kinematic viscosity was calculated:

Viscosity of water at 20 °C $\mu = 10.02 \cdot 10^{-4}\ [Pa\ s]$

Density of water at 20 °C $\rho = 998.3\ [kg/m^3]$

$$u = \frac{\mu}{\rho} = \frac{10.02 \cdot 10^{-4}\ [Pa\ s]}{998.3\ [kg/m^3]} = 1.00 \cdot 10^{-6}\ [m^2/s]$$

Then the Reynolds number was calculated:

$$Re_{pump} = \frac{v_{WWS} \cdot d_{pipe}}{u} = \frac{5.09\ [m/s] \cdot 0.2\ [m]}{1.00 \cdot 10^{-6}\ [m^2/s]} = 10.15 \cdot 10^2\ [-]$$

To calculate the friction loss, the friction factor must first be determined. To derive the friction factor, the pipe was assumed to be made of steel, which gives an absolute surface roughness of 0.00015 ft [47]. The relative surface roughness is then obtained by dividing the absolute surface roughness by the diameter of the pipe in unit feet:

Absolute surface roughness for steel $Ar_{steel} = 0.00015\ [ft]$

Assumed diameter of the pipe $d_{pipe} = 0.20\ [m] = 0.66\ [ft]$

$$Relative\ surface\ roughness = \frac{Ar_{steel}}{d_{pipe}} = \frac{0.00015\ [ft]}{0.66\ [ft]} = 2.27 \cdot 10^{-4}\ [-]$$

The friction factor can then be retrieved from a friction factor plot for circular pipes, using Reynolds number and the relative surface roughness. From the friction factor plot, a friction factor of $1.55 \cdot 10^{-2}$ was obtained [47].

The expansion coefficient ($K_e$) is 1 since $S_b$ are assumed to go against infinity in comparison to $S_a$ see equation 2. The contraction coefficient ($K_c$) will have a value of 0,4 since $S_b$ can be assumed to go to infinity in comparison to $S_a$, see equation 4.

The loss coefficient is the loss that occurs when the pipe bends, a bend of 90° gives a loss coefficient of 0.75 and a bend of 180° gives a loss coefficient of 1.5 [47]. To calculate the loss coefficient, the assumption has been made that the pipe will be bent four times at 90°. Calculation of the loss coefficient:

$$K_f = 4 \cdot 90\ °C = 4 \cdot 0.75 = 3.00\ [-]$$

The friction loss can then be calculated:

Length of pipe $L_{pipe} = 15\ [m]$

Contraction coefficient $K_C = 4.0\ [-]$

Expansion coefficient $K_e = 1\ [-]$

Friction factor $f = 1.55 \cdot 10^{-2}\ [-]$

Loss coefficient $K_f = 3.00\ [-]$

$$Friction\ loss = \left(4 \cdot f \cdot \frac{L_{pipe}}{d_{pipe}} + K_C + K_e + K_f\right) \cdot \frac{v_{WWS}^2}{2}$$

$$Friction\ loss = \left(4 \cdot 1.55 \cdot 10^{-2}\ [-] \cdot \frac{15\ [m]}{0.2\ [m]} + 4.0\ [-] + 1\ [-] + 3.00\ [-]\right) = 117.22\ [J/kg]$$

The theoretical effect was then calculated using the friction loss and mass flow. Calculation of the theoretical effect:

Mass flow for the WWS $\dot{m}_{WWS} = 82.21\ [kg/s]$

$$P_{teori} = \text{Friction loss} \cdot \dot{m}_{WWS} = 117.22\ [J/kg] \cdot 82.21\ [kg/s] = 9.64\ [kW]$$

The calculations to estimate the pump effect is simplified and in reality, the losses will be greater, which will result in the actual energy consumption being higher. In addition, a pump does not have an efficiency of 100 %, which will also lead to the real energy consumption being greater. Based on this, the assumption is made that the real energy consumption is 50 times greater than the calculated power:

Increase power by 50 % $\eta = 0.5$

$$P_{pump} = \frac{P_{teori}}{\eta} = \frac{9.64\ [kW]}{0.5} = 19.27\ [kW] = 19.27\ [J/s]$$

The pumps energy consumption for 1 m$^3$ WWS was then calculated:

$$E_{pump} = \frac{P_{pump}}{\dot{V}_{WWS}} = \frac{19.27\ [J/s] \cdot 86400\ [s/day]}{7115\ [m^3/day]} = 0.23\ [MJ]$$

$$= 6.59 \cdot 10^{-2}\ [kwh]$$

The consumption for 1 m$^3$ WWS is $6.59 \cdot 10^{-2}$ kWh.

The total energy consumption for the future sludge management can then be calculated:

| | |
|---|---|
| Energy consumption current sludge management | $E_{current} = 0.3\ [kWh]$ |
| Energy consumption for the | $E_{ozonation} = 0.03\ [kwh]$ |
| Energy consumption for the biofiltration | $E_{biofilter} = 5.4 \cdot 10^{-5}\ [kWh]$ |
| Energy consumption for the pump | $E_{pump} = 6.59 \cdot 10^{\ -2}\ [kwh]$ |

$$E_{total} = E_{current} + E_{ozonation} + E_{biofilter} = E_{pump}$$

$$E_{total} = 0.3 + 0.03 + 5.4 \cdot 10^{-5} + 6.59 \cdot 10^{\ -2} = 0.39\ [kWh]$$

The total energy consumption for the future sludge management alternative is 0.39 kWh per 1 m3 produced WWS.

## Appendix 5: Chemicals and Transportations

In table 17 the chemical usage is presented for leading the WWS over to Käppalaverket, the future sludge management at Görvälnverket and the current sludge management at Görvälnverket.

*Table 17. The chemical usage for the alternatives.*

| **Alternative** | **Chemicals** |
|---|---|
| Leading the WWS Käppalaverket | In Käppalaverket the main chemicals added in 2040 would be ferrous sulphate and polymer, [36] |
| The future sludge management at Görvälnverket | In the future sludge management, polymer and polyaluminum chloride will mainly be added |
| The current sludge management at Görvälnverket | In the current sludge management polymer is added. |

The supplier for the chemical as well as the location of the supplier and the transportation distance are presented in table 18. In addition, the chemical usage is also presented in figure 18. The polymers used at Käppalaverket is assumed to come from the same supplier, SNF Nordic.

*Table 18. The chemical usage for the alternatives, as well as supplier, location of supplier and transportation distance.*

| **Leading the WWS Käppalaverket** | **Supplier** | **Location of supplier** | **Transportation distance [km]** | **Reference** |
|---|---|---|---|---|
| Polymer | Kemira | Netherlands | 1250 | [49] |
| Ferrous sulphate | SNF Nordic | Svaneholm, Sweden | 480 | [49] |
| **The future sludge management at Görvälnverket** | **Supplier** | **Location of supplier** | **Transportation distance [km]** | **Reference** |
| Polymer | Kemira | Netherlands | 1250 | [31], [35] |
| Polyaluminum chloride | Kemira | Helsingborg, Sweden | 580 | [31], [35] |
| **The current sludge management at Görvälnverket** | **Supplier** | **Location of supplier** | **Transportation distance [km]** | **Reference** |
| Polymer | Kemira | Netherlands | 1250 | [35] |

In figure 19 the external actor responsible for the removal of the dewatered sludge, the location of the external actor and the transport distance are presented.

*Table 19. The external actor responsible for the removal of dewatered sludge, the location of the external actor and the transport distance.*

| Alternative | External actor responsible for the removal of dewater sludge | Location of external actor | Transportation distance [km] | Reference |
|---|---|---|---|---|
| Leading the WWS Käppalaverket | Rang Sells | Högbytorp, Stockholm | 102 | [14] |
| The future sludge management at Görvälnverket | Rang Sells | Högbytorp, Stockholm | 56 | [31] |
| The current sludge management at Görvälnverket | Rang Sells | Högbytorp, Stockholm | 56 | [31] |

# Appendix 6: Assessment for Scoring

A description of the scores for each criterion used in WISER are presented in table 20.

*Table 20. Description of the scoring for each criterion.*

| Criterion | Score | Description of score |
|---|---|---|
| **Adaptability** | 6 to 10 | The alternative entails a significantly improved ability to handle changes in the external environment |
| | 1 to 5 | The alternative entails a moderate improved ability to handle changes in the external environment |
| | 0 | The alternative entails no changes in ability to handle changes in the external environment |
| | -1 to -5 | The alternative entails a moderate deteriorated ability to handle changes in the external environment |
| | -6 to -10 | The alternative entails a significantly deteriorated ability to handle changes in the external environment |
| **Permissions** | 6 to 10 | Obtaining the necessary permits for the alternative will be obtained with certainty |
| | 1 to 5 | Obtaining the necessary permits for the alternative should be obtained with certainty |
| | 0 | Obtaining the necessary permits for the alternative is assessed as equally probable as improbable |
| | -1 to -5 | Obtaining the necessary permits for the alternative is considered uncertain |
| | -6 to -10 | Obtaining the necessary permits for the alternative is considered very uncertain |
| **Availability** | 6 to 10 | The alternative entails a significantly improved change with regard to the possibility of influence |
| | 1 to 5 | The alternative entails a moderate improved change with regard to the possibility of influence |
| | 0 | The alternative entails no change with regard to the possibility of influence |
| | -1 to -5 | The alternative entails a moderate deteriorated change with regard to the possibility of influence |
| | -6 to -10 | The alternative entails a significantly deteriorated change with regard to the possibility of influence |

| | | |
|---|---|---|
| **Feasibility** | 6 to 10 | The alternative is deemed to be completed in a significant shorter than the set target year |
| | 1 to 5 | The alternative is deemed to be completed in a moderate shorter than the set target year |
| | 0 | The alternative is deemed to be completed by the set target year |
| | -1 to -5 | The alternative is deemed to be completed in a moderate longer than the set target year |
| | -6 to -10 | The alternative is deemed to be completed in a significant longer than the set target year |
| **Quality of water resources** | 6 to 10 | The alternative will significantly improve the raw water quality |
| | 1 to 5 | The alternative will moderately improve the raw water quality |
| | 0 | The alternative has no impact on the raw water quality |
| | -1 to -5 | The alternative will moderately deteriorate the raw water quality |
| | -6 to -10 | The alternative will significantly deteriorate the raw water quality |
| **Energy use and greenhouse gas emissions** | 6 to 10 | The alternative will significantly reduce the energy use and greenhouse gas emissions |
| | 1 to 5 | The alternative will moderately reduce the energy use and greenhouse gas emissions |
| | 0 | The alternative has no impact on energy use and greenhouse gas emissions |
| | -1 to -5 | The alternative will moderately increase the energy use and greenhouse gas emissions |
| | -6 to -10 | The alternative will significantly increase the energy use and greenhouse gas emissions |
| **Land use** | 6 to 10 | The alternative will significantly reduce the land requirement |
| | 1 to 5 | The alternative will moderately reduce the land requirement |
| | 0 | The alternative has no impact on the land use |
| | -1 to -5 | The alternative will moderately increase the land requirement |
| | -6 to -10 | The alternative will significantly increase the land requirement |

| | | |
|---|---|---|
| **Chemical use** | 6 to 10 | The alternative will significantly reduce the chemical use |
| | 1 to 5 | The alternative will moderately reduce the chemical use |
| | 0 | The alternative has no impact on chemical use |
| | -1 to -5 | The alternative will moderately increase the chemical use |
| | -6 to -10 | The alternative will significantly increase the chemical use |
| **Local emissions** | 6 to 10 | The alternative will significantly reduce local emissions |
| | 1 to 5 | The alternative will moderately reduce local emissions |
| | 0 | The alternative has no impact in local emissions |
| | -1 to -5 | The alternative will moderately increase local emissions |
| | -6 to -10 | The alternative will significantly increase local emissions |
| **Investment costs** | 6 to 10 | The alternative entails a significant expense |
| | 1 to 5 | The alternative entails a moderate expense |
| | 0 | The alternative entails no investment cost |
| | -1 to -5 | The alternative entails a moderate revenue |
| | -6 to -10 | The alternative entails a significant revenue |
| **Operation costs** | 6 to 10 | The alternative will significantly increase the operation cost |
| | 1 to 5 | The alternative will moderately increase the operation cost |
| | 0 | The has no impact on operation cost |
| | -1 to -5 | The alternative will moderately reduce the operation cost |
| | -6 to -10 | The alternative will significantly reduce the operation cost |

# Appendix 7: Scoring of Criteria

The scoring for each criterion used in WISER is presented in table 21. Each criterion has been assigned three scores, the most likely score, the minimum score, and the maximum score. Description of the scores for each criterion are presented in Appendix 6.

*Table 21. The minimum, maximum and most likely score assigned for each criterion.*

| | **Alt 1** | **Alt 2** | | **Alt 1** | **Alt 2** |
|---|---|---|---|---|---|
| **Adaptability** | | | **Land use** | | |
| Min | -2 | -1 | Min | -2 | -5 |
| Most likely | 2 | 2 | Most likely | 0 | -3 |
| Max | 3 | 3 | Max | -1 | -1 |
| **Permissions** | | | **Chemical use** | | |
| Min | 3 | 2 | Min | -6 | -3 |
| Most likely | 5 | 4 | Most likely | -2 | -2 |
| Max | 6 | 6 | Max | -1 | -1 |
| **Availability** | | | **Local emissions** | | |
| Min | -5 | -1 | Min | 4 | 2 |
| Most likely | 0 | 0 | Most likely | 5 | 3 |
| Max | 5 | 1 | Max | 6 | 4 |
| **Feasibility** | | | **Investment costs** | | |
| Min | -4 | -3 | Min | 2 | 2 |
| Most likely | -3 | -1 | Most likely | 2 | 2 |
| Max | 0 | 0 | Max | 6 | 6 |
| **Quality of water resources** | | | **Operation cost** | | |
| Min | 7 | 3 | Min | 1 | 1 |
| Most likely | 9 | 5 | Most likely | 2 | 1 |
| Max | 10 | 6 | Max | 4 | 3 |
| **Energy use and greenhouse gas emissions** | | | | | |

| | | |
|---|---|---|
| Min | -8 | -4 |
| Most likely | -4 | -2 |
| Max | -3 | -1 |