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Sustainability effects of water reuse and infiltration and inflow on a wastewater treatment plant

- a Multi Criteria Decision Analysis

Master's thesis in Industrial Ecology

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Abstract

To lower the environmental impact of wastewater treatment in the Gothenburg area, Rya wastewater treatment plant (WWTP) is constantly working towards a more environmentally friendly and efficient wastewater treatment process. The function of the WWTP is dependent on the inflow of wastewater. In this study, the sustainability effects of increased and decreased infiltration and inflow (I/I), which is water that reaches the sewer system that is not sewage water, are analyzed. Since the WWTP is connected to the entire sewer system of the connected municipalities, the wastewater inflow can increase significantly because of the excess water from I/I in the system. The sustainability effects of two types of water reuse, upstream reuse and downstream reuse, were also analyzed. Upstream water reuse refers to water that is reused before it reaches the WWTP and downstream refers to treated wastewater that is used in some type of industry. To assess the sustainability effects, six scenarios that represented increased or decreased fast and slow runoff I/I, as well as upstream and downstream water reuse were constructed and compared to a base case scenario using Multi Criteria Decision Analysis (MCDA). The criteria analyzed in the MCDA were *Effluent quality*, *Heavy metal content in sludge*, *Climate impact*, *Water use*, *Energy use*, *Sphere of action/Political support*, *Local environment quality & amenity*, *Working environment*, *Safety/Risks*, *Operating costs*, *Vulnerability* and *Flexibility*. Data and information for each criterion were gathered from measurements done at Rya WWTP, literature study and interviews with Gryaab employees and analyzed for wastewater inflow series constructed for each of the scenarios. The data and information were then presented to an expert panel that graded and weighed each criterion. The results showed that an increase in I/I has a negative effect on overall sustainability at the WWTP, while decreased I/I has a positive effect. Fast runoff I/I was deemed to be the most preferred to lower since it had the largest effect on sustainability and was mostly due to increased combined sewer overflows caused by the selective increase of wastewater inflow. Upstream reuse is preferable to downstream since it lowers drinking water use and reduces wastewater inflow to the WWTP which has positive sustainability effects at the WWTP.

Keywords: Wastewater, Wastewater treatment, Wastewater treatment plant (WWTP), Sustainability, Infiltration and inflow (I/I), Greywater reuse, Water reuse, Multi Criteria Decision Analysis (MCDA).

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Introduction

With the environmental challenges that the world is facing today, industries are starting to adapt and change their activities to mitigate their contributions to environmental change. This study will focus on Rya wastewater treatment plant (WWTP) in Gothenburg that constantly work to reduce their environmental impact. The sustainability effects that were covered in this study include environmental, social, economic and technical impacts. The sustainability effects were evaluated for possible future scenarios for the WWTP.

1.1 Background

The urban water system transports drinking water to households and industries. Water that has been used is then transported to the WWTP where pollutants are removed. Rya WWTP in Gothenburg treats the wastewater from eight municipalities in the Gothenburg region. They handle the wastewater from about eight percent of Sweden´s population, which adds up to an average wastewater flow of 4 m^3/s [1]. Therefore, their potential to lower environmental impact related to water use is significant. One way of further reducing the environmental impacts from wastewater is by reducing the amount of water needing treatment at the WWTP to increase resource and energy efficiency as well as lower emissions.

A strategy that might offer more efficient utilization of water is water reuse, either upstream or downstream of the WWTP. Upstream water reuse refers to for example greywater reuse before the water goes to treatment at the WWTP while downstream reuse is when water is reused after treatment at the WWTP. Thereby, less wastewater treatment would be used for the same amount of water services considering that some water services do not require drinking water quality. An example of upstream water reuse is greywater reuse for hygiene purposes such as for shower water or flushing toilets. Downstream water reuse could be irrigation in agriculture with treated water from the WWTP or use of this water in other industries, as so-called technical water, where drinking water quality is not a necessity [2], [3].

Another strategy to reduce environmental impacts from the WWTP is reducing infiltration and inflow (I/I), which is excess water that mixes with wastewater and reaches the wastewater plant. There are two types of I/I, slow runoff and fast runoff. Slow runoff I/I is

water that gets into the sewer system through damaged pipes or gaps in pipe connections while fast runoff I/I is stormwater that is collected mainly in cesspits and ends up in the sewer system. The amount of water from fast and slow runoff I/I depends on weather, sewer system design and the aging status of the sewer pipes. Between the years 2011 and 2015, I/I was estimated to make up about 61 percent of the total incoming water to Rya WWTP [4]. I/I water does not need to be treated the same way as wastewater since it is practically rainwater. However, because it ends up in the sewer system and mixes with the wastewater it requires treatment. This causes unnecessary resource use and problems for the WWTP that could be avoided by reducing the amount of I/I that enters the system [5], [6].

In this study, the sustainability effects of future scenarios for water reuse and I/I will be evaluated by using a multi-criteria decision analysis (MCDA) assessment method. The MCDA method will build on the MCDA method previously used at Gryaab, with some developments and modifications of the criteria that are evaluated to fit the specific scenarios.

1.2   Goal & scope

The first aim of this study is to develop a list of criteria for MCDA that in the future can be used as a library of criteria to choose from when conducting a MCDA. This is done to ensure well described and thorough sustainability assessments in the future, as well as the one in this study. The purpose of the MCDA is to describe and evaluate the expected sustainability effects of different future scenarios regarding changes to the system, for Rya WWTP in Gothenburg. After the criteria are chosen, different future scenarios for up- and downstream water reuse, as well as increased or decreased rates of fast and slow runoff I/I will be evaluated for each criterion and then graded and weighted to give a final result.

1.3   Specification of issue under investigation

1. Are the most important sustainability judgment criteria for the WWTP included in the assessment method and what others are commonly included in sustainability assessments?

2. What are the sustainability effects for the WWTP of increased water reuse downstream or upstream the plant?

3. Based on the result for the WWTP, what is the preferred water reuse strategy in terms of sustainability?

4. What are the major sustainability effects for a WWTP if fast and slow runoff I/I is decreased or increased, respectively?

5. Based on the result for the WWTP, is it most preferred to reduce fast or slow runoff I/I in terms of sustainability?

6. Based on the result for the WWTP, is increased fast or slow runoff I/I least preferred in terms of sustainability?

1.4 Limitations

The system boundary of the study includes the WWTP and combined sewer overflows from the sewer system. Therefore, the WWTP recipient Göta river and all CSO recipients are included. It is assumed for the scenarios that all measures that must be done to achieve the change has already taken place, so construction and other aspects to achieve the change is not included in the study. The scenarios are in the operating phase and already fully implemented. The study is also limited to the criteria that are chosen for the MCDA, so no other aspects will be analyzed that are not stated in the MCDA method.

2

Theory

In this section, theoretical background about the Gothenburg wastewater system and treatment and some of the sustainability challenges associated with the wastewater treatment system will be presented. Two possible system improvements, water reuse and decreased fast and slow runoff I/I are also described. Lastly follows a brief description of drinking water use and of the multi criteria decision analysis method.

2.1 About the urban water system and wastewater treatment at Rya WWTP

This study focuses on the Rya WWTP and combined sewer overflows that are part of Gothenburg's water system. Gothenburg's water systems and Rya WWTP are part of the public sector. Gryaab oversees Rya WWTP that is owned by the municipalities Ale, Bollebygd, Göteborg, Härryda, Kungälv, Lerum, Mölndal and Partille [7]. The urban water system in Gothenburg and the neighboring municipalities is divided into one pipe system for drinking water and one for sewage water. The drinking water system is approximately 1,760 km long and it is monitored and maintained by Kretslopp och vatten. The sewage system is about 2,560 km long and is monitored and maintained by both Kretslopp och vatten and Gryaab. Gryaab is also responsible for treating the wastewater to reduce water pollution before the water is let out at the mouth of the Göta river [8]. In 2021, 800 435 people were connected to the sewer system, which means that Rya WWTP on its own treats wastewater from almost 10% of Sweden's population [9].

Combined sewer overflows (CSOs) occur when the capacity limit at the WWTP is reached because of high wastewater inflow. Untreated water that is a mix of wastewater and I/I is then discharged at CSO points in the municipalities connected to the WWTP. Since the untreated water contain pollutants that are harmful to human health and the environment, CSOs are not desired even though they are necessary when WWT capacity is not enough [10].

In Gothenburg, combined sewer systems, which are pipe systems where both sewer water and stormwater are collected all together, are more frequent in older parts of the system compared to newer parts. The difference between a combined and separate system is that in a combined system both the sewage water and the urban stormwater runoff are collected

in the sewer system and eventually treated in the WWTP, while in a separate system the stormwater runoff is handled as a separate flow and is usually redirected to ditches or other water bodies and infiltrated locally [11]. In a separate system, approximately 20 percent of precipitation reached the WWTP, and with a combined system the number is 75 percent [12]. Since fast runoff I/I is dependent on rainfall, and it makes up about 61% of the yearly volume of wastewater inflow to Rya WWTP it makes the inflow at times unpredictable. A combined system is therefore not considered to be favorable compared to a separate system for the Rya WWTP. However, one advantage of the combined design compared to a separate design is that stormwater can help flush out the pipes. Also, redirecting the water to other water bodies is not necessarily better than directing the stormwater to the WWTP since it can drag pollutants with it from the streets [12].

The part of Gothenburg that has most of the combined design is in the central parts of the city, which is more problematic to change compared to less central parts due to buildings and activities being more concentrated [12]. During the planning of Rya WWTP in the 1960s, the area assigned for the WWTP was chosen based on the assumption that the WWTP would manage the rising demand for treatment of water with population growth by separating the combined systems in Gothenburg over time. However, there are still large enough parts of the system that are of combined system design that it causes a problem for Rya WWTP, because of the difficulties to access and separate them [12].

The wastewater treatment process at Rya WWTP consists of the process steps that can be seen in Figure 2.1 below.
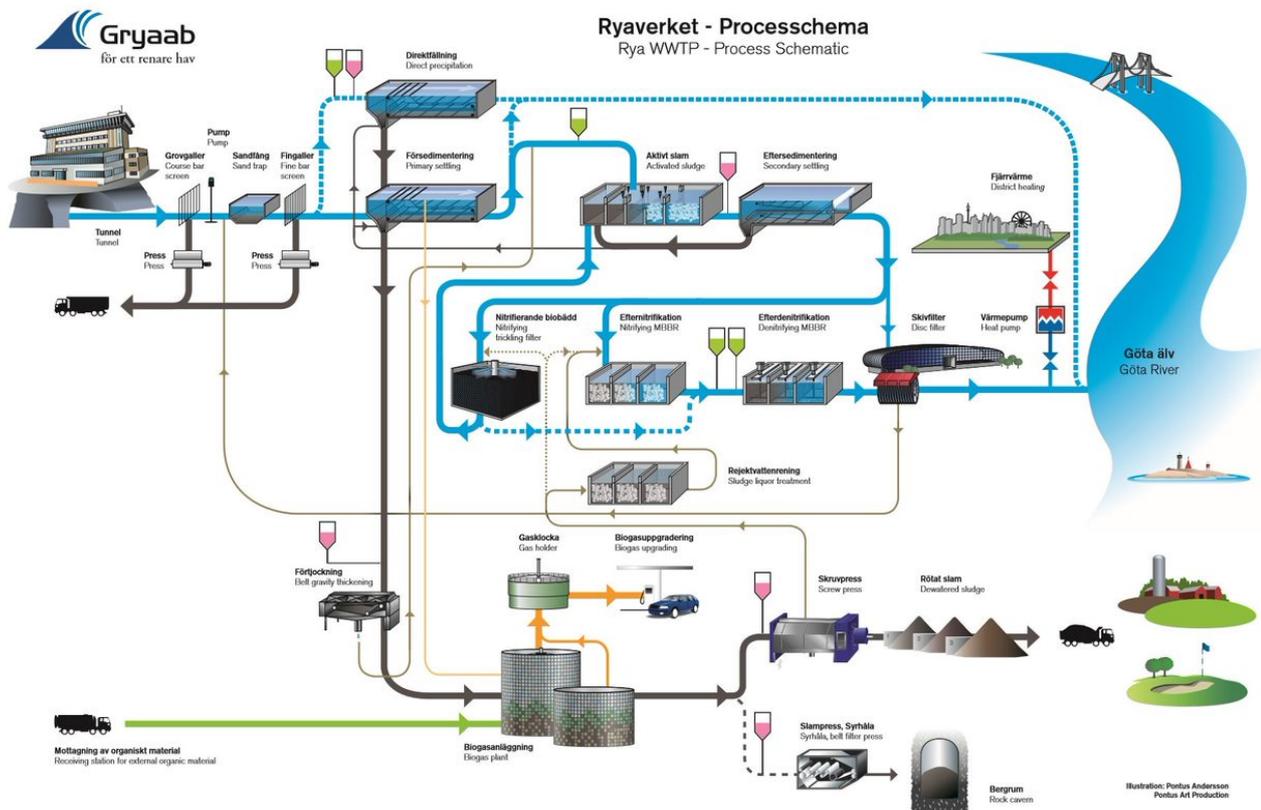
Figure 2.1: Process schematic of the wastewater treatment process at Rya WWTP.

The incoming wastewater is led to a coarse bar screen where larger items in the water, such as paper and plastics are separated. The reject is then moved by compressed air, pressed and transported to combustion to produce district heating. The wastewater is then pumped into the WWTP to a sand trap to remove sand particles, followed by a fine bar screen where additional, but finer items are removed. The fine reject is then pressed and transported to combustion [13].

After that, the wastewater goes to primary settling where it is mixed with excess sludge from the activated sludge before being distributed to twelve primary settling pools. There, the wastewater is separated from the primary sludge. Surface sludge is removed here, and the primary sludge is pumped to a gravity belt thickener. The primary settling step has a hydraulic capacity of 15 m^3/s, which includes direct precipitation which is a step that is used during flows over 8.5 m^3/s to remove phosphorous with precipitation chemicals before it is released to the recipient directly [13], [14]. However, the water treated with direct precipitation does not reach the same level of pollutant removal compared to the standard process since it bypasses the biological and chemical steps, which means that it is desirable to lower the amount of incoming water to the WWTP and avoid flows over 8.5 m^3/s.

The water is then pumped to the activated sludge step, where there are anoxic and aerobic zones. In the anoxic zones, nitrate is converted to nitrogen gas, and in the aerobic zones, organic material is degraded. Here, phosphate is precipitated by adding ferric sulphate. Then, the sludge water goes to secondary settling where polymers are added to act as a flocculant and make bigger flocs of the activated sludge. The sludge is then collected and pumped back to the activated sludge [13].

From there, some water is led to the nitrifying and denitrifying process steps and the rest goes to the disc filter. In the nitrifying trickling filter step, ammonia is converted to nitrate in a biofilm. In the nitrifying moving bed biofilm reactor (MBBR) step, ammonia is converted to hydrogen gas and nitrogen gas. The nitrified water from the nitrifying trickling beds and the nitrifying MBBR step is then mixed in the denitrifying MBBR, where bacteria convert nitrate to nitrogen gas which is released to the atmosphere. Then, this water is led to the disc filter step where flocs and particles are separated from the water, and the water is led to the outlet of the WWTP where it is released to Göta river [13].

The sludge from the primary settling and the direct precipitation is, after the gravity belt thickening, led to the biogas plant where the organic matter in the sludge is converted to biogas. The remaining, stabilized sludge is dewatered by screw pressing and then transported to storage where it lays until it is being used as, for example, fertilizer [13].

2.2 Sustainability challenges

The services provided by a WWTP are crucial to ensure reliable and clean water in society and to reduce stress on the environment caused by wastewater discharges. However, there are more sustainability challenges for water system because, according to [15], there are three main sustainability issues that need to be addressed by the urban water industry: resource depletion of both water and nutrients, increased amounts of harmful chemicals that are a risk for the environment or humans, and the effects that are expected from climate change such as change in water quantities and quality.

Gryaab has chosen a couple of sustainability challenges as well that they consider of significant importance. These challenges are avoiding eutrophication caused by a nutrient surplus, climate change due to use of fossil fuels and GHG emissions from the treatment processes and construction as well as reducing excess water inflow [16].

Two of the major water problems in developed countries are water resource depletion and water contamination. These problems could be mitigated by more efficient water use and treatment [17]. Two strategies for more efficient water use are water reuse and reduced fast and slow runoff I/I, which will be described in Sections 2.3 and 2.4.

Due to climate change, precipitation patterns are predicted to change in many parts of the world including the northern hemisphere [17]. The prediction is that rainfall will occur less frequently, but in greater amounts compared to the present situation. In turn, this will lead to more droughts and floods as the precipitation pattern gets more extreme, which will negatively affect the urban water system both by uneven inflows of water into the WWTP, but also by losses of nutrients such as nitrogen that is then transported with the water into the urban water systems. Nutrient losses are predicted to increase because it is accumulated in soil during dry periods and then lost in the wet seasons by leaching [18].

Eutrophication is an environmental impact that can cause excessive algal growth that creates an adverse living environment for other plants and water-living species. Eutrophication is caused by increased levels of nutrients, so controlling and reducing the nitrogen and phosphorus in the outflow is important in the WWTP to reduce the eutrophication intensity in nearby water bodies [19]. When the wastewater inflow to the WWTP is diluted with I/I, the phosphorus reduction at the WWTP becomes less effective [12].

Recycling of nutrients back to nature from wastewater is beneficial because it avoids depletion of nutrients in the soil but can also reduce impacts caused by mining of phosphorous. Mining of phosphorous is approximately 22 million tonnes yearly and 90 percent of phosphorus resources are used for fertilizers in agriculture. Since phosphorous is a non-renewable resource more mining leads to depletion of the reserves and could lead to the need for mining of lower concentrated areas which means that the environmental impact of mining will increase per unit of phosphorous extracted [20].

In the wastewater from households, part of the nutrients, mainly phosphorous is recovered in sludge since nitrogen and carbon are mainly released as gases. This prevents eutrophication and makes it possible to recycle the nutrients back into the soils. Every year about

55,000 tonnes of sludge is produced at Gryaab which can be used as fertilizers [21]. The sludge is tested to assure that it is below limits set by Revaq before Gryaab let the sludge be used as fertilize in agriculture. This is not necessary by law, but Gryaab believes that these extra steps ensures that the sludge is safe to use for agriculture [22].

Gryaab has done carbon footprint measurements that show the total amount of GHG that are released connected to the WWTP. It is found that the wastewater treatment process generated most emissions, second was the sludge treatment and third the production and usage of chemicals. Emissions from energy usage and transportation also contributed to the carbon footprint [9]. The release of GHG contributes to global warming which in turn can result in a variety of environmental changes. Therefore, it is of interest to develop the treatment process and the urban water system in a direction that lowers the GHG emissions from wastewater treatment.

There are also sustainability challenges in other sustainability dimensions than the ecological mentioned in this section. Examples of social sustainability challenges are for example the effects that the wastewater treatment has on people living in surrounding areas and public acceptance. It is also important to have economic sustainability in mind when assessing the holistic sustainability of the WWTP [23].

2.3 Water reuse

Water reuse is one way of mitigating water depletion and is crucial in countries that are combating water scarcity. Therefore, water reuse schemes have gotten attention as an alternative for supplying water for human activities. In Sweden, water scarcity is not considered a common problem as of now. However, water re-use can have other benefits besides saving water since it makes it possible to utilize the water more while lowering the intensity for WWTP processes as well as drinking water production. Water reuse that takes place before treatment at the WWTP is called upstream water reuse while downstream water reuse takes place after treatment at the WWTP.

Downstream reuse of wastewater can be done in industries and agriculture, for example as boiler water or for irrigation. Today, large quantities of drinking water are used for these types of purposes. However, it has been found that in many different industries, the same type of lower quality water could be utilized since drinking water quality is not a necessity. Therefore, there is an opportunity for WWTPs to provide a basic water quality from wastewater that is not of the same, high quality as drinking water but good enough for purposes such as industrial use and irrigation [2].

One example of downstream water reuse projects that is up and coming is using treated water from Rya WWTP in a planned Northvolt battery factory. This is seen as a smart use of the treated water that replaces drinking water and promotes circular and sustainable water use [24]. The treated water would in the battery factory be used as a cooling agent [25].

When downstream water reuse is done for irrigation in agriculture, there is an opportunity to cycle the nutrients that are following the wastewater into the WWTP back to soil and crops [2]. Reused wastewater can contribute to the fertilization of crops and trees, either on its own or in combination with a lower dose of the previously used fertilizer. Irrigation with wastewater has been found to elevate the salinity of the soil, however, this can be combated by sufficient precipitation to leach the salts out of the soil [26].

Greywater reuse for personal hygiene is a way to reuse water upstream from the WWTP and lower the amount of drinking water used for human activities. Greywater is wastewater from sinks, washing machines and showers for example, excluding water from toilets. It has been tried for various non-contact purposes such as irrigation, groundwater recharge, industrial use and non-potable urban use. The most common reuse practiced in buildings is greywater reuse for toilet flushing but can also be used for car washing and the first rinse in dishwashers or washing machines, for example [27]. The Orbital shower system, which is a shower installation that filters the used shower water and reuses it, is one example of upstream reuse that is commercially available [28].

Since shower and sink water together is a large percentage of the water used in a household, taking back the water and its heat content could give significant savings in drinking water and heating energy. This type of in-house recirculation is also beneficial because less water needs to be returned to the WWTP, which could result in lower drinking water use as well as fewer emissions of GHGs and energy use from the treatment process [3].

However, greywater needs to be treated before reuse to remove contaminants such as pathogens, organic matter, oils, surfactants, particulates and salts. The greywater also needs treatment for removing odor and color, and to make sure that there are no other health risks besides pathogens. Therefore, for this type of water reuse to be possible, there is also a need for quite advanced process equipment and a system for this to be financed and installed in buildings. There must also be social acceptance of this new concept for this type of water reuse to be feasible since it effects people's homes [3].

2.4 Infiltration and inflow (I/I)

As previously mentioned, infiltration and inflow (I/I) is water that enters the sewage system leading to the WWTP that is not considered wastewater. Slow runoff I/I is mainly groundwater or stormwater that enters the system because of defects or damages in the piping system. Stormwater that enters the system through various drains because of a combined sewer system design is defined as fast runoff I/I. Because more water enters the sewage system due to I/I, the WWTP receives an increased water flow. This creates a need for a higher plant capacity compared to if there was no excess water from I/I, if CSOs are to be avoided [6], [29].

In Gothenburg, parts of the sewer system are of combined design. This means that the sewer system additionally takes care of the stormwater that is collected in drains or spouts. Because of this, the water flow to the WWTP fluctuates depending on rainfall [5]. Fluctuating levels of incoming water makes a flexible wastewater treatment necessary

since the daily volume of incoming water will vary. Since climate change is predicted to cause heavier but less frequent rainfalls, fast runoff I/I can be expected to increase in the future, which would increase the variations in water flows to the WWTP [18]. Therefore, the WWTP needs to be flexible and have enough capacity to handle an increased inflow. The constant need to be able to regulate large variations in water flow is a burden, which is why it would be beneficial to lower the variations in wastewater inflow by redirecting stormwater away from the sewer system, lowering the fast runoff I/I.

One way to reduce the slow runoff I/I is by replacing and repairing pipes and pipe connections that would reduce the leakage into the wastewater pipes. Inflow can be reduced by replacing combined systems with separate ones so that less water collected in drains ends up in the sewer system [29].

2.5 Drinking water

The drinking water use per person and day in Sweden was on average 140 liters and in Gothenburg it was estimated around 200 liters [30], [31]. Drinking water is produced from treating a combination of surface water and groundwater and require significant amounts of resources and energy. The treatment consists of three main steps, which are chemical, mechanical and biological treatment [32]. These processes consume precipitation chemicals, bacteria, active carbon and limestone, among other resources [32], [33]. The electricity for production and distribution used per cubic meter of drinking water produced was 0.38 kWh/m^3 in Gothenburg 2011 [34].

2.6 Multi Criteria Decision Analysis (MCDA)

There are many approaches as to how to conduct a MCDA. However, MCDA is essentially a method used for analyzing different options, such as different problems, choices, scenarios or anything else that is comparable in a decision-making process. MCDA enables for the options to be evaluated and ranked based on multiple criteria covering all sustainability dimensions, at the same time, which can otherwise be challenging for decision-making [35]. The criteria that are considered important are sorted, then options are evaluated, graded and weighted for each criterion and is then added up in a combined result that makes it feasible to compare the options and rank them [36].

3

Literature study for criteria list development

To establish a general list of criteria, a literature study was conducted looking at criteria commonly used in other MCDAs. The criteria were sorted into the categories environmental, health and hygiene, social, economic and technical criteria. Then criteria that were named differently but referred to the same thing were combined into one criterion and criteria that were considered too broad was replaced by several more limited criteria. This was done in multiple steps to ensure that criteria list cover as many distinguishable sustainability aspects as possible.

Table 3.1 shows the 38 criteria that were gathered from the literature study divided into the sustainability categories, as well as indicators for some criteria.

Table 3.1: General MCDA criteria list for sustainability assessments.

Ecologic		Indicator	Ref
Emissions	Toxic compounds to soil	Heavy metals to agriculture or other soils	[37], [38]
	Eutrophication	Concentration/amount of P to water	[23], [37]
	Acidification	SO2-equivalents	[37]
	Global warming	CO2-equivalents	[37]
	Effluent quality	Nutrients, toxic compounds & other pollutants	[37], [39]
Resource use	Nutrient recycling	N, P, K, S to agriculture or other applications	[37]
	Energy use	Energy use or recovery (kWh/year)	[23], [37]
	Natural resource use	Amount of natural resources used	[37], [38]
	Material use	Amount of material used, including hidden flows	[23]
	Water use	Volume of used water	[3], [23], [37]
	Chemical use	Amount of chemicals used	
	Land use	Area of used land	
Health & hygiene			
	Risk of infection/pathogen exposure	Risk of exposure to ex. wastewater or greywater	[37]
	Chemical risk	Risk of exposure to harmful chemicals	[37]
Social			
	Collaboration between crucial actors		[37]
	Sphere of action		[37]
	Legislative/political support		[37]
	Confidence in the environmental benefits		[37]
	Ability & motivation		[37]
	Reliability		[23], [37]
	Knowledge gain		[23], [37]
	Communication with users		[37]
	Effects on user		[37]
	Local environment quality & amenity		[38]
	Equity		[38]
	Local participation		[38]
	Acceptance		[37], [38]
	Access to urban water services		[23]
	Working environment		[23]
	Safety		
Economic			
	Cost of emissions/environmental impact	Taxes, fees, mitigation costs now & in the future (kr)	[37]
	Annual cost	kr	[23], [37], [39]
	Annual transition costs	kr	[23], [37]
	Transportation costs	kr	[37]
	Financial risk	Uncertainty of profitability	[37]
	Social profitability	Indirect or direct effects (costs/benefits) on society	[38]
Technical			
	Technical function (Flexibility, reliability)	Difficulty/simplicity of operation and effectiveness	[23], [37], [39]
	Convenience	Compatibility with current system and action plan	[37]

This criteria list was considered too broad to use for the sustainability analyses at the WWTP even though most of them can be used as an indicator related to the urban water industry. However, to use the criteria, they must be defined and limited based on project since some of the criteria can be used for different purposes. The whole criteria list is likely not appropriate to use for most sustainability analyses and therefore, the list should be seen as an archive to pick out criteria from, that are relevant for the specific project.

4

Methodology

In this section, the methodology for the study will be presented.

4.1   Multi Criteria Decision Analysis

The effects of I/I and water reuse were estimated from comparing scenarios developed in the Future City Flow simulation tool that are presented in Section 4.2 and 4.4. The first step of the analysis was to develop a list of criteria for MCDA, and then choose the relevant sustainability criteria for this study that data and information was then gathered for to facilitate comparison of the effects between the scenarios through grading and weighting.

To go from the general list of criteria that was presented in Table 3.1 to the list of criteria for the MCDA conducted in this project, one criterion at a time was evaluated based on if I/I and water reuse would affect that criterion and if it would fit within the system boundary. After that consideration, the authors together with the supervisor removed criteria deemed irrelevant to this study and a proposal of a final criteria list was drafted. This proposal was evaluated by two people from Gryaab and Chalmers that could recommend removing or redefining criteria from the list. Reasons for removing a criterion were that it was predicted to be unaffected, outside the system boundary or not possible to gather data and information to base comparison for scenarios. This resulted in twelve criteria being selected and defined for the MCDA conducted in this project, which can be seen in Table 4.1.

Table 4.1: Chosen MCDA criteria and their definitions in this project.

Criteria	Definitions
Effluent quality	The amounts of phosphorus, nitrogen and BOD_7 that is released from the WWTP to the recipient yearly
Heavy metal content in sludge	How much of the sludge that can be used as fertilizer, based on the content of cadmium (Cd)
Climate impact	The amount of greenhouse gases emitted in carbon dioxide equivalents
Water use	How much drinking water that can be saved
Energy use	Energy used for wastewater treatment
Sphere of action/political support	Whether there are laws that can affect the scenarios or if a scenario can help work towards or against a goal
Local environment quality & amenity	Effects on local recipients from CSOs. For example effects on smell, aesthetics or bathing water quality
Working environment	The daily effects on the working environment, such as stress levels and number of on-call hours.
Safety/risks	Safety risks that may arise regarding personal injuries or property damages as well as overall security aspects
Operating costs	Yearly operating costs for wastewater treatment
Vulnerability	Vulnerability at the WWTP based on possible limited access to certain chemicals in the future
Flexibility	The ability for the WWTP to handle an increased wastewater inflow

Data and information were then gathered, analyzed and condensed for each criterion to be used as a basis during the subsequent grading. Grading and weighting were done to facilitate the comparison of the scenarios for all the sustainability effects covered by the list, based on a grade from 1 to 5.

4.2 Formulation of scenarios

To answer how I/I-water and water reuse could affect ecological, social, economic and technical sustainability at Rya WWTP, seven scenarios were created that can be seen in the list below.

1. Base case, wet year with present volumes of I/I.

2. +20% fast runoff I/I

3. -20% fast runoff I/I

4. +20% slow runoff I/I

5. -20% slow runoff I/I

6. Upstream reuse, -70 liters per person and day.

7. Downstream reuse, -70 liters per person and day.

The first scenario represents a base case, and this was decided to be a wet year, meaning a year with more than the average amount of rainfall. The reason for choosing to conduct the study based on a wet year is because it is more challenging in terms of the amount of wastewater inflow the WWTP. However, this is a scenario that the WWTP should be able to handle. Studying the sustainability effects of I/I and water reuse during a wet year determines how sustainable the different scenarios are when the base inflow is already high. Then to highlight the effects of I/I, the total amount of I/I was increased and decreased by 20% by modification of the base case. Here, amounts of fast and slow runoff I/I, respectively, were changed by different measures that were simulated in FCF, which will be described below, to correspond to a change of 20% of the total I/I. This resulted in four different scenarios for I/I. The reason for only increasing and decreasing either fast runoff I/I or slow runoff I/I water is to be able to distinguish between their individual impact on the sustainability effects on Rya WWTP. Lastly, to see the effects of water reuse, scenarios that reuse water equal to the volume of 20% of I/I water over a year, which resulted in 70 liters per person and day, were created. Since reuse could take place upstream or downstream with different effects on Rya WWTP two scenarios were created, one for upstream and one for downstream reuse. Note here that all scenarios result in the same yearly amount of water, since 20% of the total I/I is equal to 70 liters per person and day over a year.

4.3 Flow series

Two types of flow series were made, one containing data on wastewater inflow to Rya WWTP in m^3/s, and one containing combined sewer overflows (CSOs) in m^3/s. Flow series were made for each scenario except for upstream water reuse. The flow series

contain flow data for each quarter-hour over a year that is obtained by simulation using Future City Flow (FCF). FCF is an urban water simulation tool created and developed by DHI [40]. FCF can be used to modify historic flow series based on changes in the urban water system as well as amount of rainfall and gives data on the wastewater inflow to Rya WWTP and CSOs. This allows for simulation of the effects of slow runoff I/I and fast runoff I/I on the wastewater inflow to Rya WWTP and out of CSO points.

The base case scenario was created using the standard wet year flow series in FCF which is based on the measures from the year 2007. All the non-base case scenarios are modified versions of the 2007 wet year in FCF and were created so that the total I/I volume increased or decreased by 20 percent.

Scenario 2 with 20% increase in fast runoff I/I was created in FCF by changing the "climate factor" for stormwater runoff to 2. This simulates a doubling of stormwater runoff to the system and creates in total a 20% increase of I/I. In Figure 4.1 the wastewater inflow to Rya WWTP for the +20% fast runoff I/I scenario, scenario number 2, compared to the base case can be seen, and in Figure 4.2 the total volume of combined sewer overflow on the system is shown.
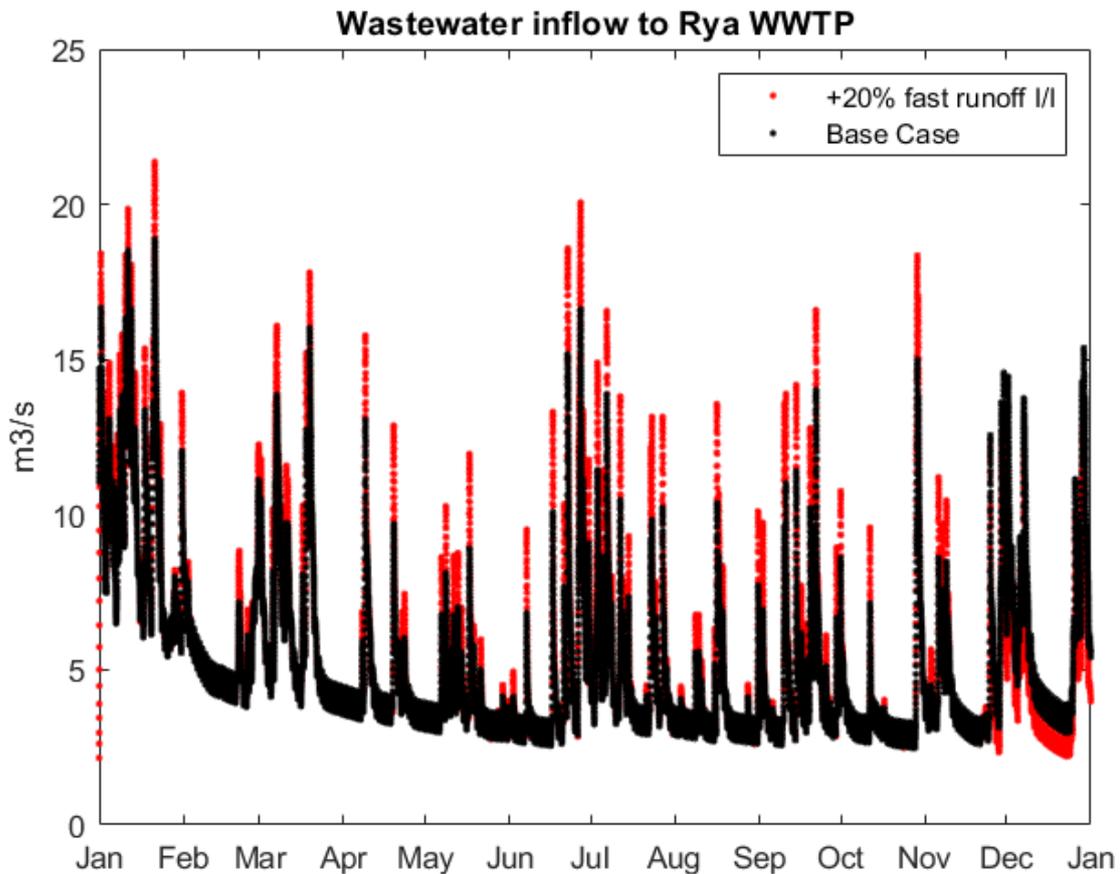
Figure 4.1: Wastewater inflow to Rya WWTP in m^3/s over a year for the base case and +20% fast runoff I/I.

In Figure 4.1 it is possible to sees that the +20% fast runoff I/I scenario has increased the flow at the flow peaks compared to base case meaning at flows that are high relative to what the flow is for most of the year.
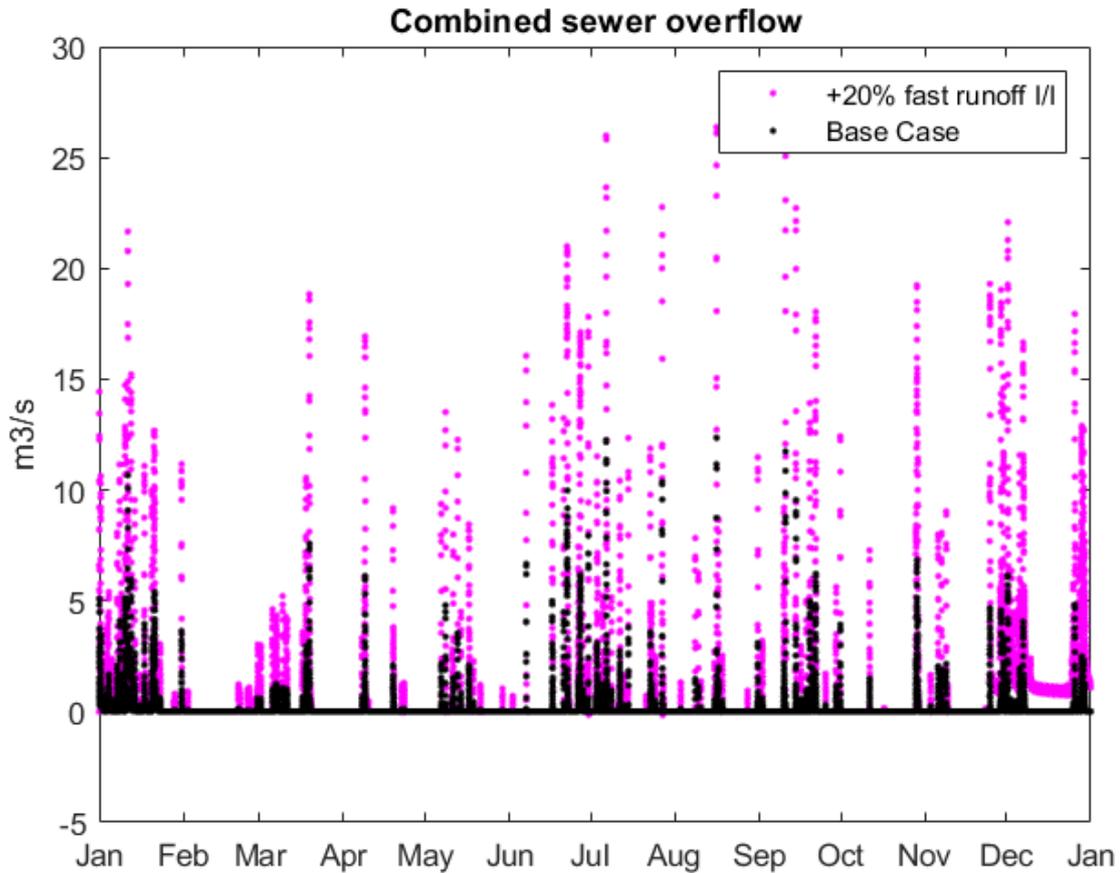
Figure 4.2: Combined sewer overflows for the base case and the +20% fast runoff I/I scenario.

By comparing the CSOs for +20 fast runoff I/I and the base case it is possible to see that the overflow is constantly higher for increased fast runoff I/I compared to the base case except for when there is no overflow.

Scenario number 3 with 20% decrease in fast runoff I/I water was created in FCF by simulating a separation of 60% of the combined systems in the Gothenburg area into separate systems. This resulted in a total decrease of 20% of the I/I volume. The wastewater inflow to Rya WWTP for this scenario is presented in Figure 4.3 and in Figure 4.4 the total volume of combined sewer overflow from the system for this scenario is shown.
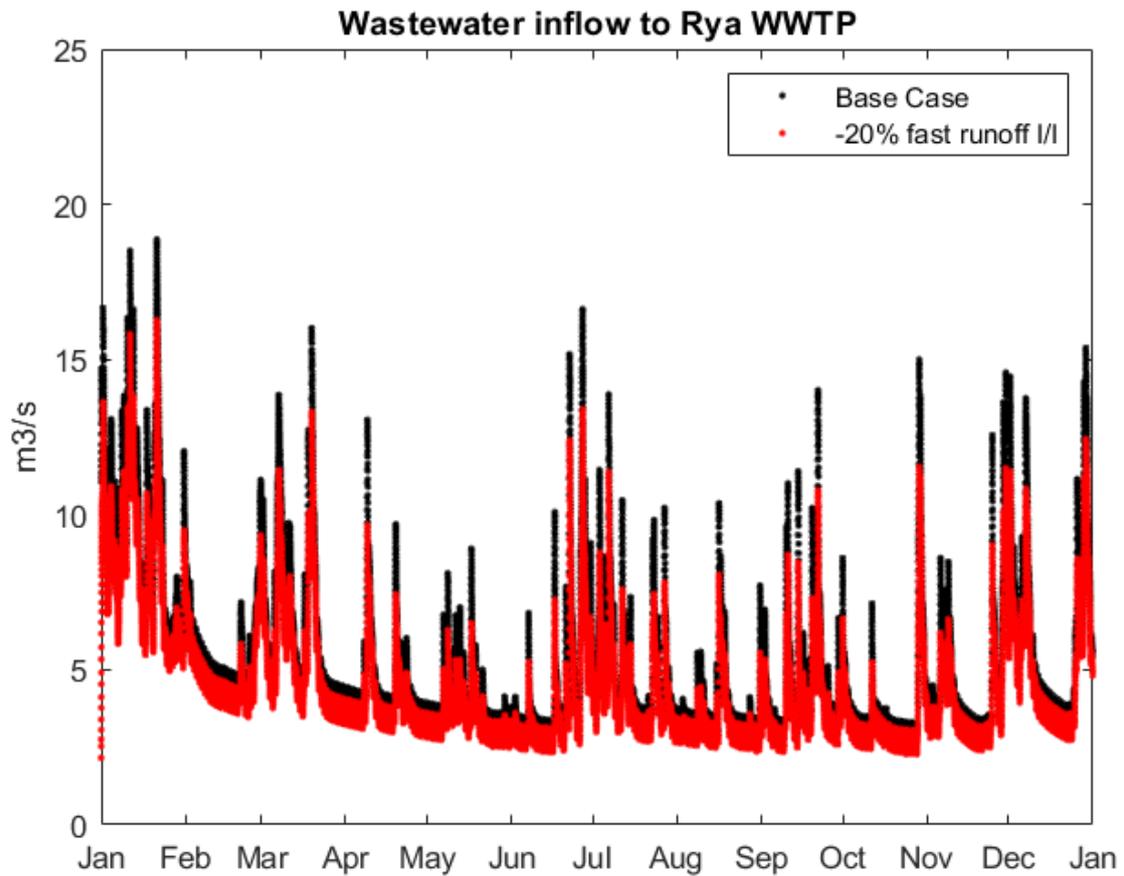
Figure 4.3: Wastewater inflow to Rya WWTP for the base case and -20% fast runoff I/I scenario.

By comparing the wastewater inflow series, it is possible to see that the wastewater flow is constantly lower for -20% fast runoff I/I compared to the base case and the difference is greater at flow peaks.
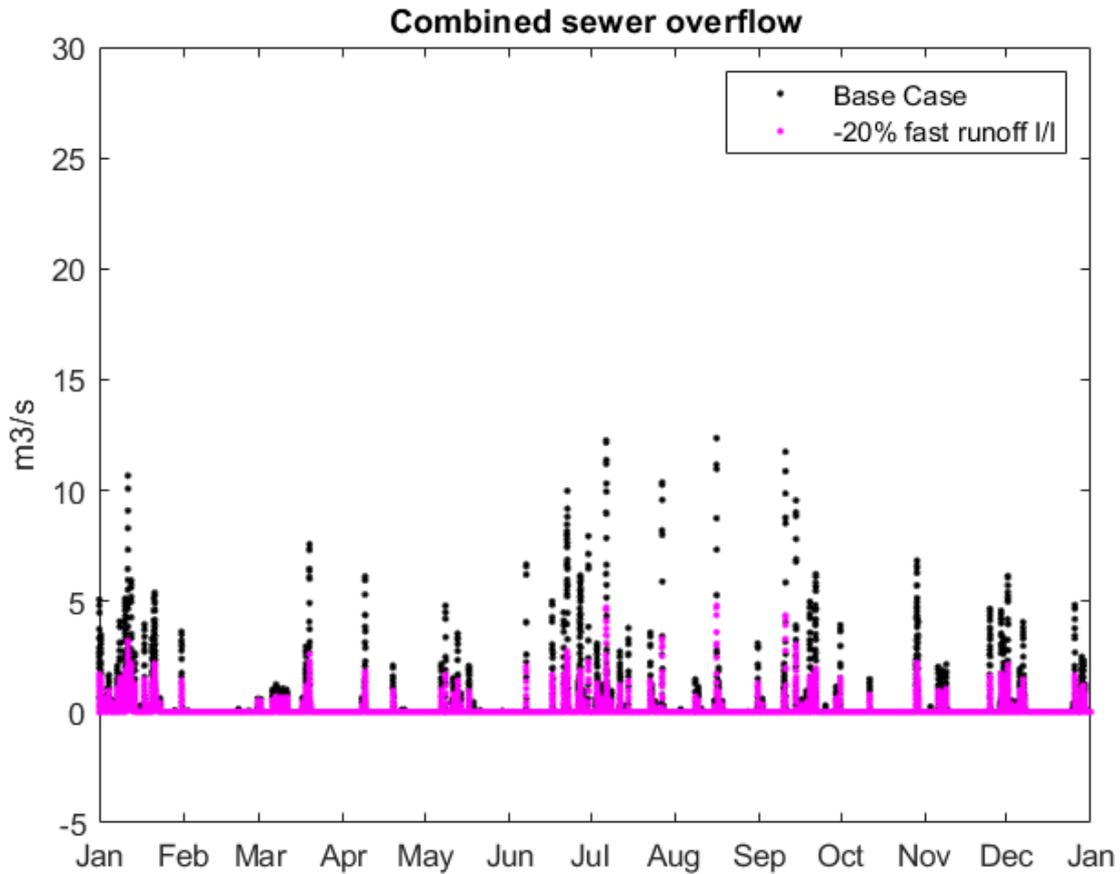
Figure 4.4: Combined sewer overflows for the base case and -20% fast runoff I/I scenario.

By comparing the flow series in Figure 4.4 it is possible to see that -20% fast runoff I/I has constantly lower combined sewer overflow compared to the base case except for when there is no overflow.

Scenario number 4 with 20% increased slow runoff I/I was created in FCF by changing the "climate factor" for leaks and drains to 1.25. This simulates an increase by 25% in water leaking and draining into the system going to the WWTP, which gives a total increase in I/I-water of 20% since slow runoff I/I is only a part of the total I/I. In Figure 4.5 the wastewater inflow to Rya WWTP for the +20% slow runoff I/I scenario can be seen, and in Figure 4.6 the total volume of combined sewer overflow on the system is shown.
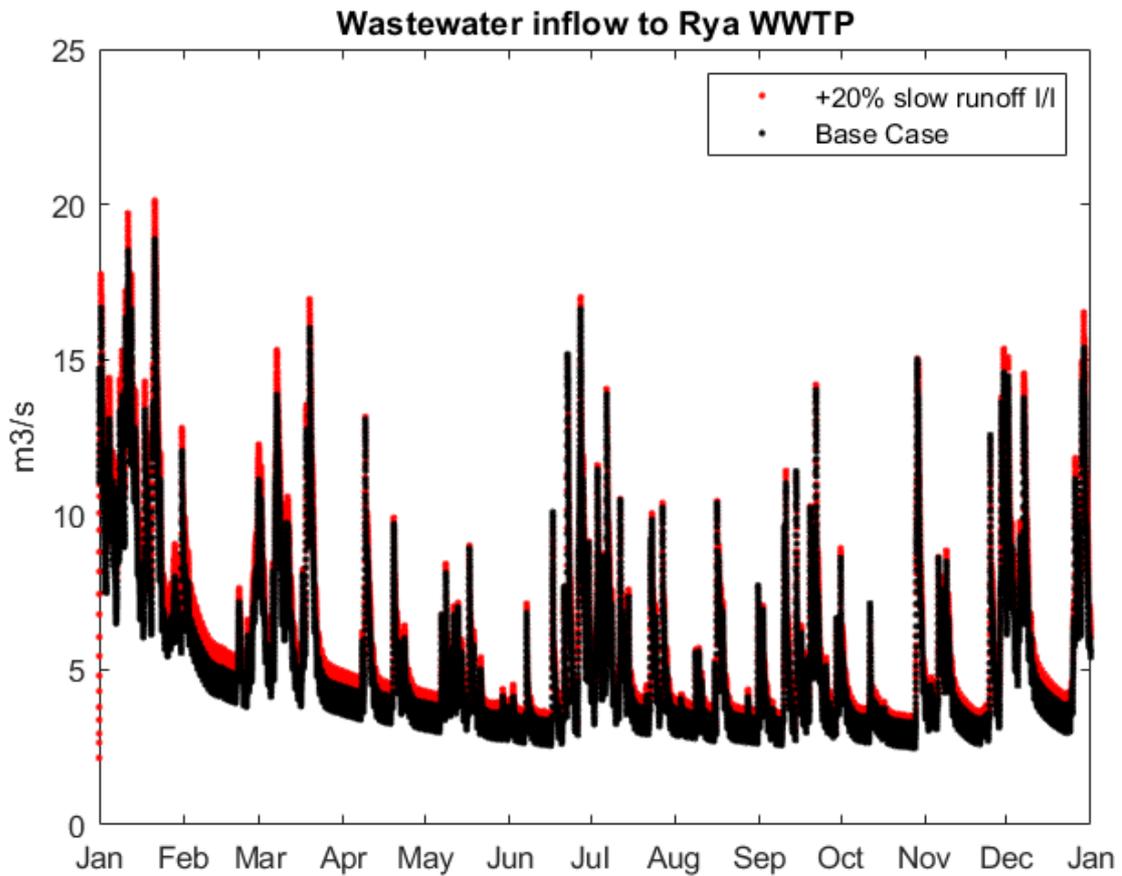
Figure 4.5: Wastewater inflow to Rya WWTP for the base case and +20% slow runoff I/I scenario.

By comparing the flow series in Figure 4.5 it is possible to see that the wastewater inflow is constantly higher for +20% slow runoff I/I compared to the base case.
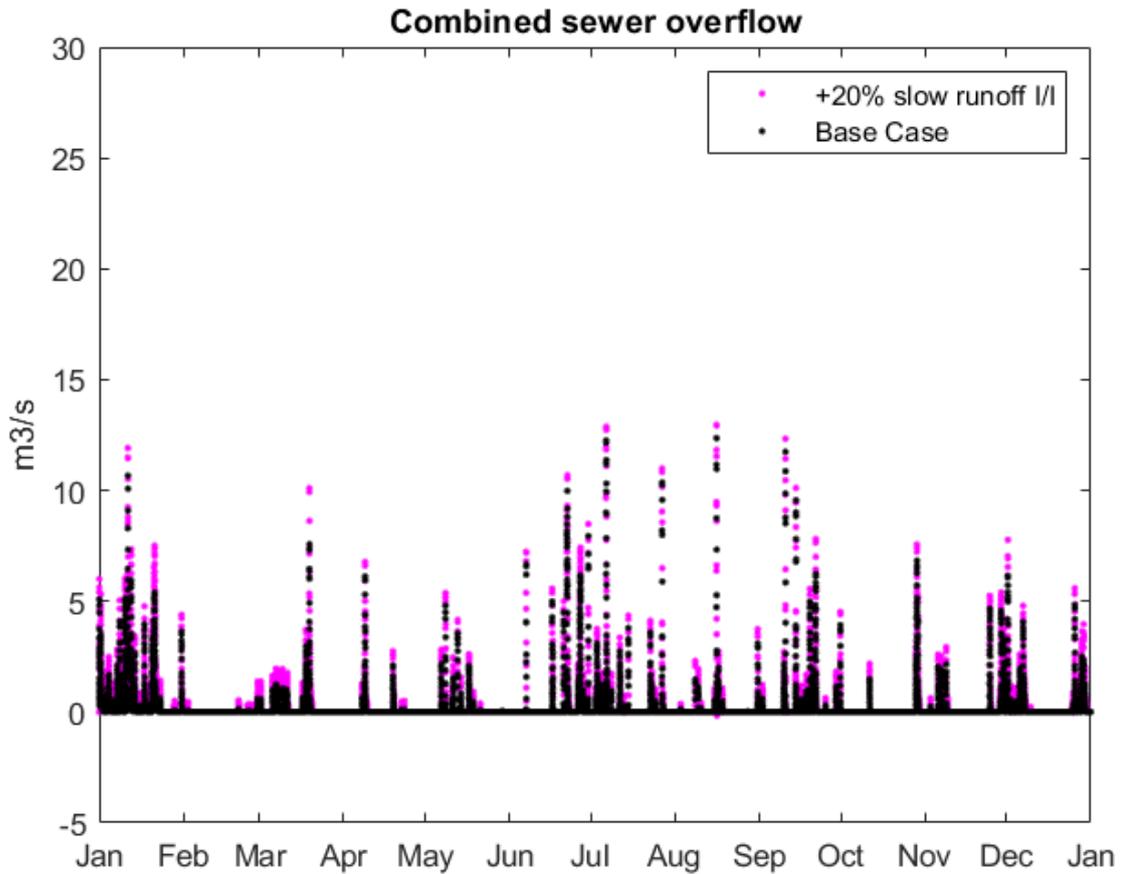
Figure 4.6: Combined sewer overflows for the base case and +20% slow runoff I/I scenario.

By comparing the flow series in Figure 4.6 it is possible to see that +20% slow runoff I/I has constantly higher CBO compared to the base case except for when there is no overflow.

The scenario with 20% decrease in slow runoff I/I was also created in FCF by simulating sealing of 40% of the pipes in the Gothenburg area. This gives a decrease of 20% in the total I/I water. In Figure 4.7 the wastewater inflow to Rya WWTP for the -20% slow runoff I/I scenario can be seen, and in Figure 4.8 the total volume of combined sewer overflow on the system is shown.
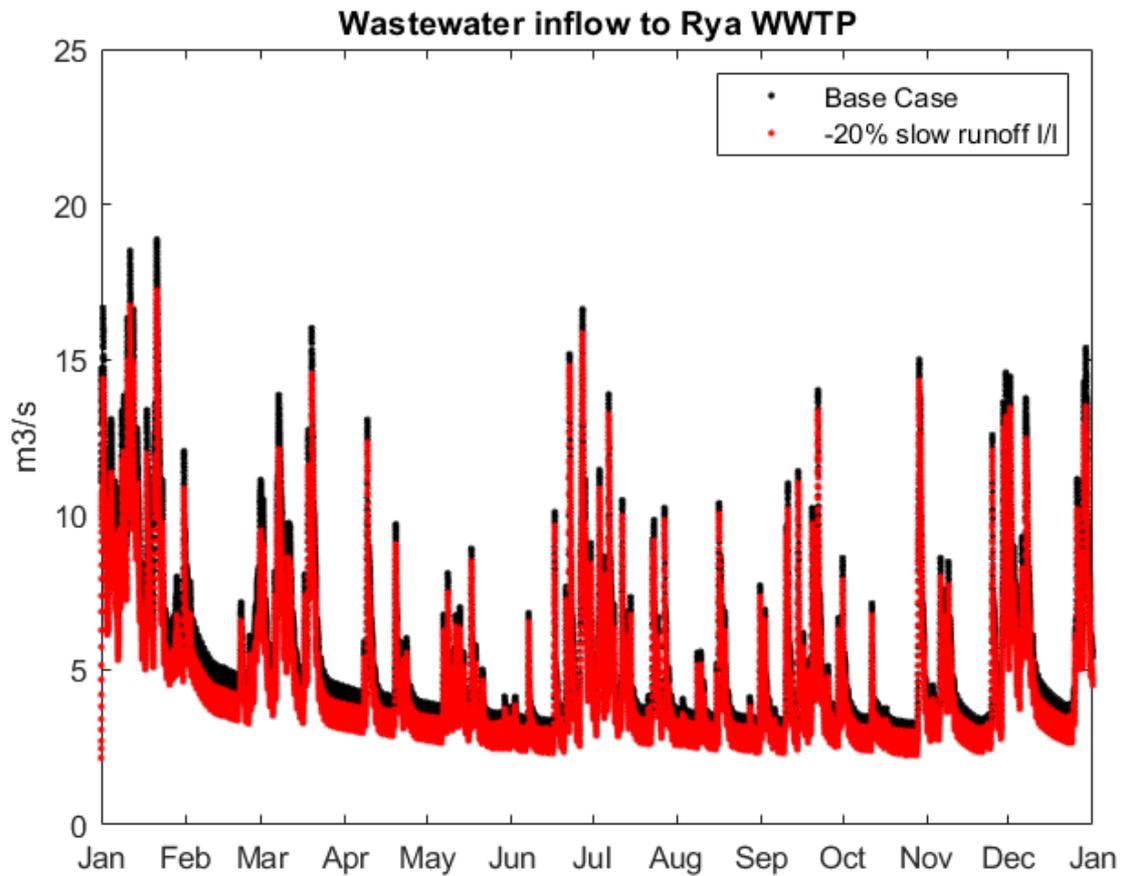
Figure 4.7: Wastewater inflow to Rya WWTP for the base case and -20% slow runoff I/I scenario.

By comparing the flow series in Figure 4.7 it is possible to see that the wastewater inflow is constantly lower for -20% slow runoff I/I compared to base case.
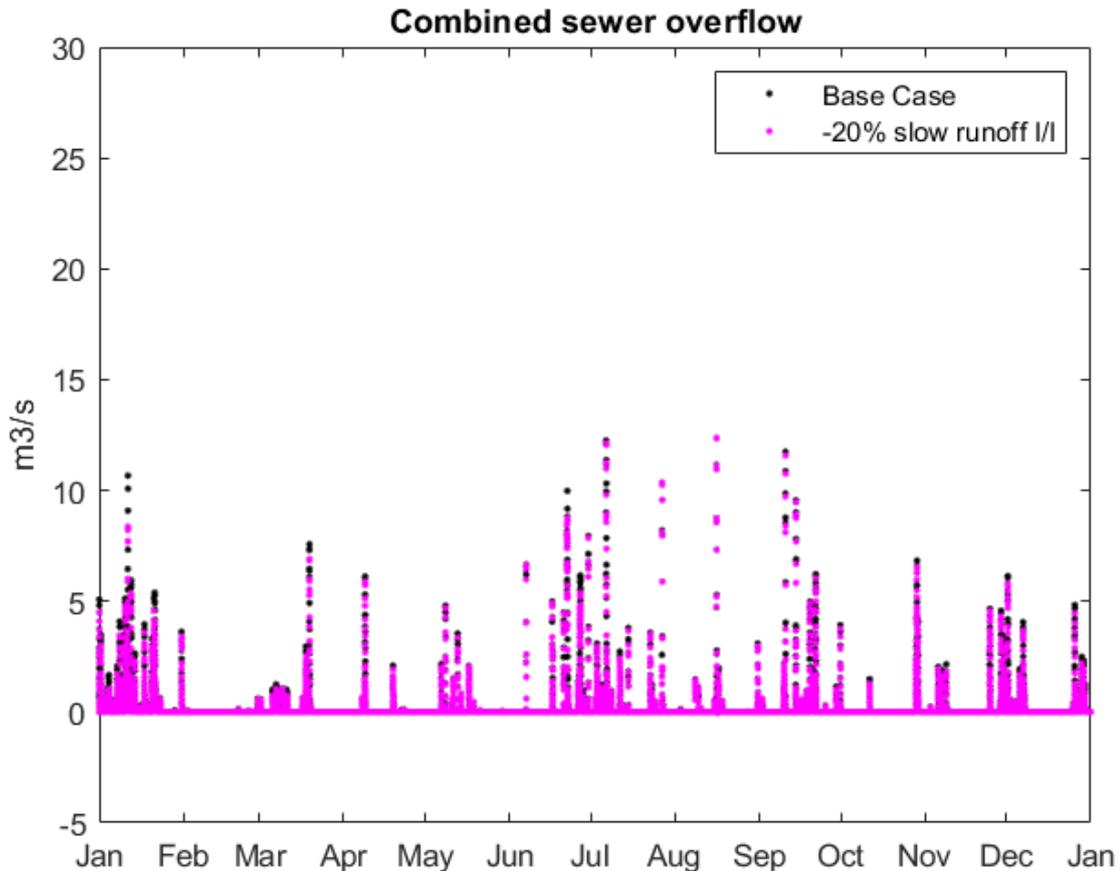
Figure 4.8: Combined sewer overflows for the base case and -20% slow runoff I/I scenario.

By comparing the flow series in Figure 4.8 it is possible to see that -20% slow runoff I/I has lower CBO compared to base case, but they are for most time the same.

The scenario for downstream water reuse will theoretically be the same as the base case in terms of wastewater inflow to the WWTP, since there is no change in the amount of water consuming services meaning that the same amount of water will end up going to the WWTP. The difference is that instead of releasing all the effluent from the WWTP to Göta river, some of it would be pumped to industries that could use it as so-called technical water. Depending on the routines at the industry, the water would then be released to the recipient from their own treatment facility or recirculated back to the WWTP. Either way, since the water most likely would end up the same way as the drinking water previously used by the industry, the wastewater inflow to Rya WWTP or the amount of combined sewer overflow would not change hence downstream reuse utilizes the same flow series as base case.

The scenario for upstream water reuse was created differently compared to the other scenarios since simulating a reduction in drinking water use was not possible in FCF. So instead, the volume of water equal to 20% of I/I-water was calculated from data given on I/I water in FCF. The number of people connected to the WWTP were 800,435 in 2021. The volume of water was divided by the amount of people connected to the WWTP and the number of days in a year (365 days per year) and resulted in approximately 70 liters

per person and day. This, in turn resulted in a reduction of 0.6547 m^3/s per continuously over a year. Therefore, 0.6547 m^3/s was subtracted from each data entry in the flow data file for the base case scenario to obtain a wastewater inflow data series per quarter hour for the upstream water reuse case.

However, this means that the wastewater inflow to Rya WWTP in this scenario is lower than what it should be since none of the reduction is removed from combined sewer overflow, only from the wastewater inflow to the WWTP. The reason that no combined sewer overflow was regulated in this project for upstream water reuse is because of the complexity of the CSOs but it can be expected to be in between the base case and reduced slow runoff. In Figure 4.9 the wastewater inflow to Rya WWTP for this scenario can be seen.
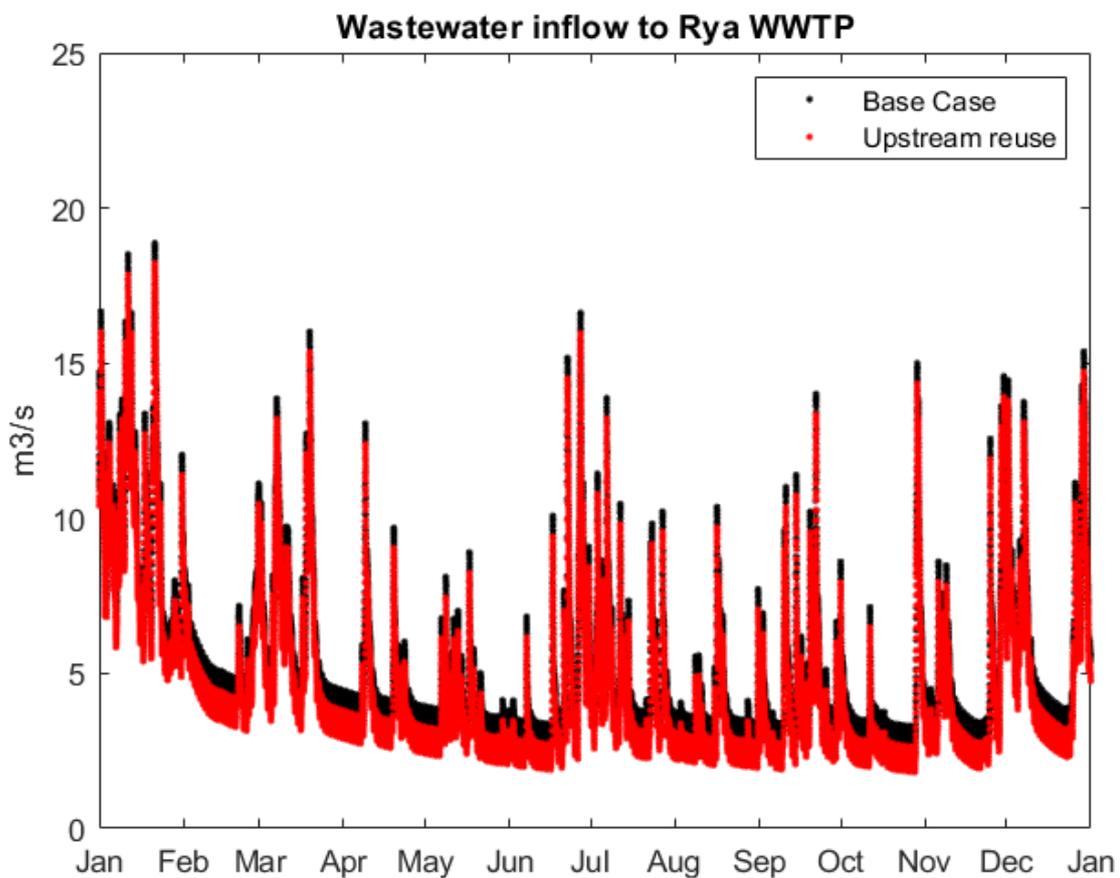
Figure 4.9: Wastewater inflow to Rya WWTP for the base case and upstream reuse scenario.

In Figure 4.9, upstream reuse scenario had a continuously lower wastewater inflow of 0.6547 m^3/s compared to the base case.

By comparing the flow series with the base case, it is possible to see the amount of wastewater that is increased or decreased throughout the year in each scenario's inflow and CSO. The scenarios had distinct patterns for increased fast runoff I/I wastewater inflow was increased at high flows (peaks) compared to the base case, increased slow runoff I/I had a more spread-out increase of wastewater compared to fast runoff I/I. The increase fast runoff I/I lead to more CSO compared to slow runoff I/I. The reduced fast

runoff I/I scenario had lower flow at higher flows (peaks) that resulted in more reduced CSOs compared to reduced slow runoff I/I that had a more spread out lowering of the flow that was less effective for reducing CSOs.

4.4 Preparation of data

In this section, the method for how data and information was gathered for the criteria *Effluent quality, Heavy metal content in sludge, Climate impact, Water use, Energy use, Sphere of action/Political support, Local environment quality & amenity, Working environment, Safety/Risks, Operating costs, Vulnerability* and *Flexibility* is presented.

4.4.1 Effluent quality

Data from 2019 to 2021 measured at the WWTP was obtained for weekly outflow concentration of biological oxygen demand (BOD_7) and daily outflow concentrations of total phosphorus and total nitrogen. Each effluent concentration was converted to mass flow (mg/s) data series, denoted f_m by multiplication of each data entry in the concentration series, denoted C_{out}, with the corresponding wastewater inflow, denoted f, and multiplied by a thousand, as shown in Equation (4.1) below.

$$f_m = (C_{out}(\frac{mg}{l}) \times f(\frac{m^3}{s}) \times 1000) \tag{4.1}$$

Mass flow data series for phosphorus, nitrogen and BOD_7 in the effluent water were plotted against wastewater inflow data for each scenario and outliers were removed to obtain a more precise polynomial relationship, see Figure 4.10, 4.11 and 4.12 below.
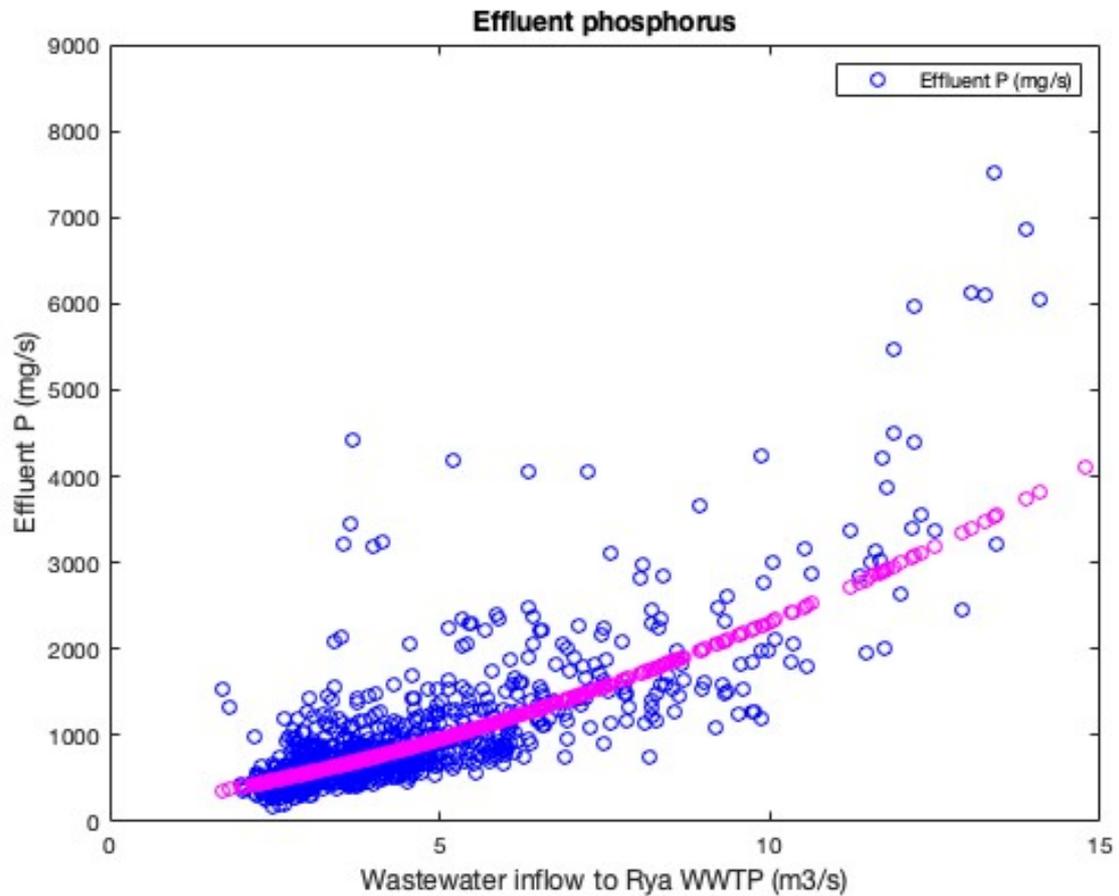
Figure 4.10: Effluent phosphorus in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink).

For the effluent nitrogen (mg N/s), a quadratic relationship to the wastewater inflow below 8 m^3/s and a linear relationship for wastewater inflow above 8 m^3/s was constructed, see Figure 4.11.
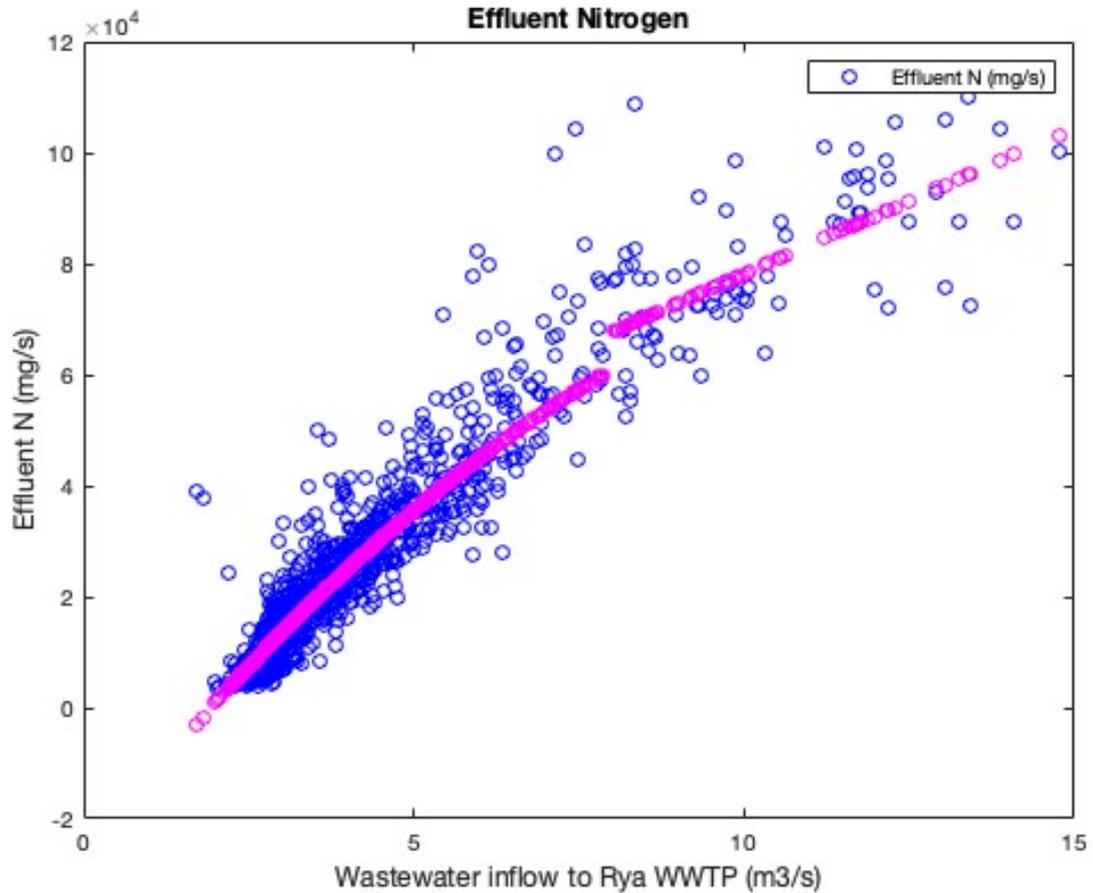
Figure 4.11: Effluent nitrogen in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink).

For effluent BOD_7 (mg O_2/s), a linear relationship to the wastewater inflow was constructed based on the data, which can be seen in Figure 4.12.
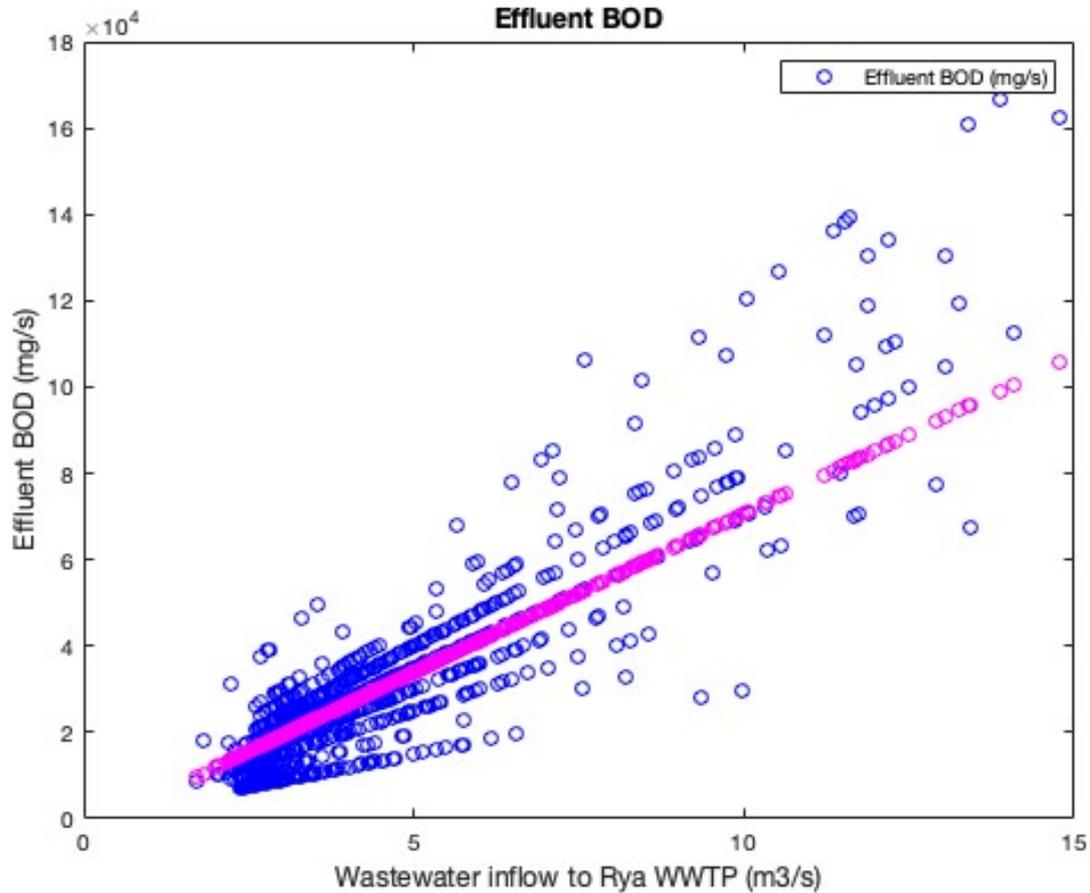
Figure 4.12: Effluent BOD in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink).

All the equations for the relationships of phosphorus, nitrogen and BOD created based on the data can be found in Table 4.2.

Table 4.2: Polynomial relationships for nutrients in relation to the wastewater inflow to the WWTP and deviation limits for outliers.

Outflow (mg/s)		Relationship mass outflow vs inflow to WWTP	Outliers removed with deviation >
Phosphorous		$10.6751x^2 + 110.6213x + 137.7057$	0.2
Nitrogen	Flows < 8	$-509.2114x^2 + 15101.8363x - 27232.3999$	4
	Flows > 8	$5254.2166x + 25625.5899$	4
BOD		$7343.1092x - 2764.2129$	2

The polynomial relationships were then used with the wastewater inflow of the scenarios to calculate mass flow data series for each scenario. Yearly total mass for all nutrients were calculated for the scenarios as shown in Equation (4.2) below.

$$\sum f_m(\frac{mg}{s}) \tag{4.2}$$

Yearly concentration averages were calculated as shown in Equation (4.3) below.

$$\frac{\sum f_m(\frac{mg}{s})}{\sum f(\frac{m^3}{s}) \times 1000} \tag{4.3}$$

The emissions from combined sewer overflow contained on average 7% sewage water during the year 2020 this is equivalent to dilution of 14.3 times [41]. The wastewater inflow to Rya WWTP had previously been estimated to be 13 times diluted [42]. These levels of dilution were used to estimate a relationship between the concentration in the wastewater inflow to Rya WWTP denoted C_{Rya}, and the concentration of water in CSOs denoted C_{CSO}, see Equation (4.4).

$$C_{CSO} = C_{Rya} \times (\frac{13}{14.3}) \tag{4.4}$$

All the historic data for concentrations of phosphorus, nitrogen and BOD_7 to Rya WWTP was on weekly basis. The weekly basis proved to be insufficient to make realistic relationships between concentration and wastewater inflow. So instead, the mean value concentration, denoted C_{Mean}, was calculated and the standard deviation for each nutrient, denoted S. Then a high and low estimate of the concentration in wastewater inflow to Rya WWTP was calculated and denoted as C_{RyaH} and C_{RyaL} respectively in Equation (4.5) and (4.6).

$$C_{RyaH} = C_{Mean} + S \tag{4.5}$$

$$C_{RyaL} = C_{Mean} - S \tag{4.6}$$

Using the low and high estimates for Rya WWTP concentration high and low estimates for combined sewer overflow was calculated and denoted as C_{CSOH} and C_{CSOL} respectively in Equation (4.7) and (4.8).

$$C_{CSOH} = C_{RyaH} \times (\frac{13}{14.3}) \tag{4.7}$$

$$C_{CSOL} = C_{RyaL} \times (\frac{13}{14.3}) \tag{4.8}$$

To calculate the emissions (E_{CSO}) of P, N and BOD from combined sewer overflow, Equation (4.9) was used for both high and low CSO concentration estimates. V_{CSO} is the volume of CSOs.

$$E_{CSO} = C_{CSO} \times V_{CSO} \tag{4.9}$$

4.4.2 Heavy metal content in sludge

Historical data from 2014/12/29 to 2022/03/21 of the Cd/P ratio was divided based on daily measured wastewater inflow to Rya WWTP and sorted into approved and not approved batches of sludge based on the Revaq certification limit at the time, which had been adjusted for analytical uncertainties of the laboratory measurements. The time of the measurement is important since the limit quota set by Revaq has become stricter over the years from 2014 to 2022. If the Cd/P ratio was above the Revaq limit, then the sludge was considered failed and if below the limit ratio it was considered approved. The time lag between when the wastewater enters the WWTP to when the Cd/P ratio is measured in the sludge is accounted for in the data used. The distribution of the approved and failed sludge batches can be seen in Figure 4.13.
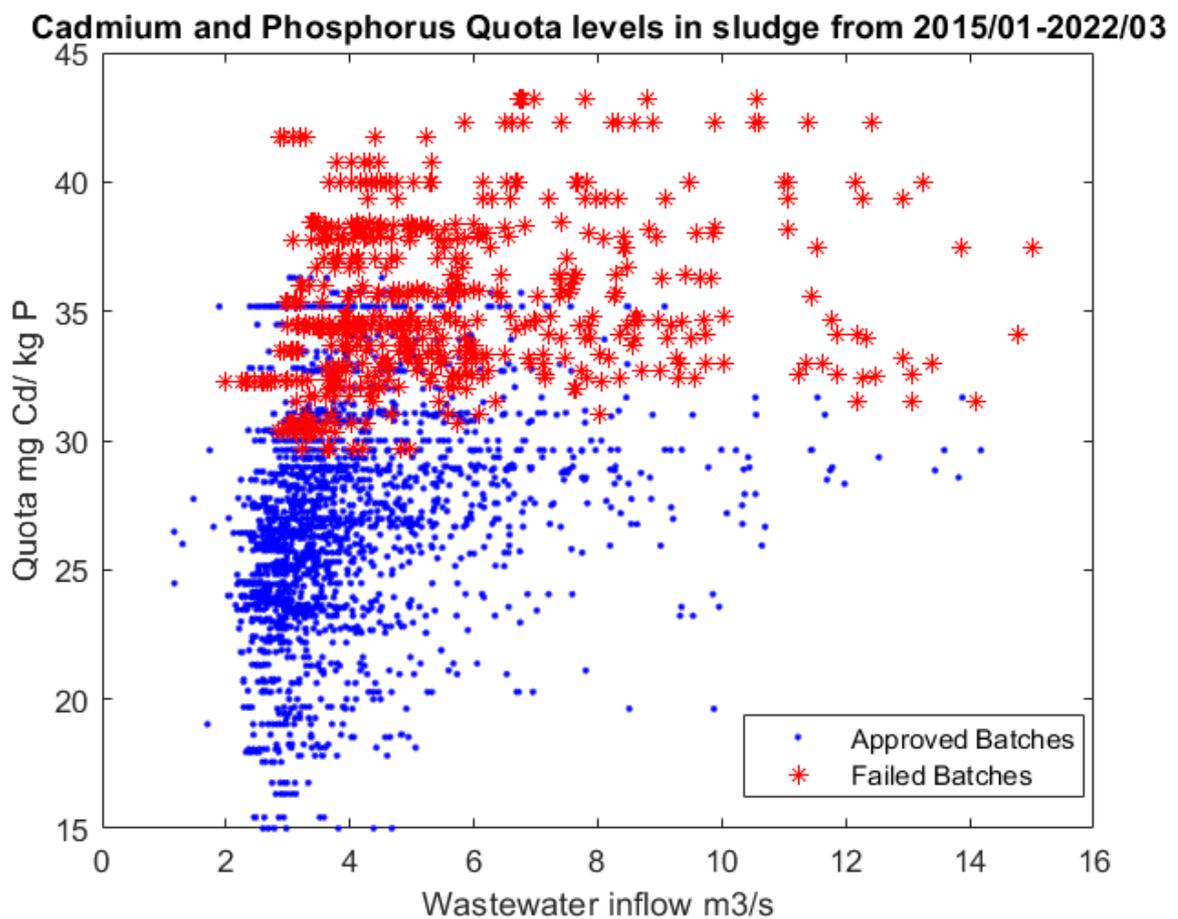
Figure 4.13: The approved and failed batches of sludge based on the Revaq limit for the Cadmium and phosphorus quota and wastewater inflow.

In the sorted data the share of failed versus approved sludge batches were calculated for flow intervals of 0.5 m^3/s from no flow to the maximum measured flow. A filtered plot of the data was made were intervals of 2 m^3/s was used with 0.5 m^3/s as step length to reduce the fluctuations at higher flow that could be because of less data points. The relationship created from the data points in the flow intervals can be seen in Figure 4.14 and the flow distribution can be seen in Figure 4.15.
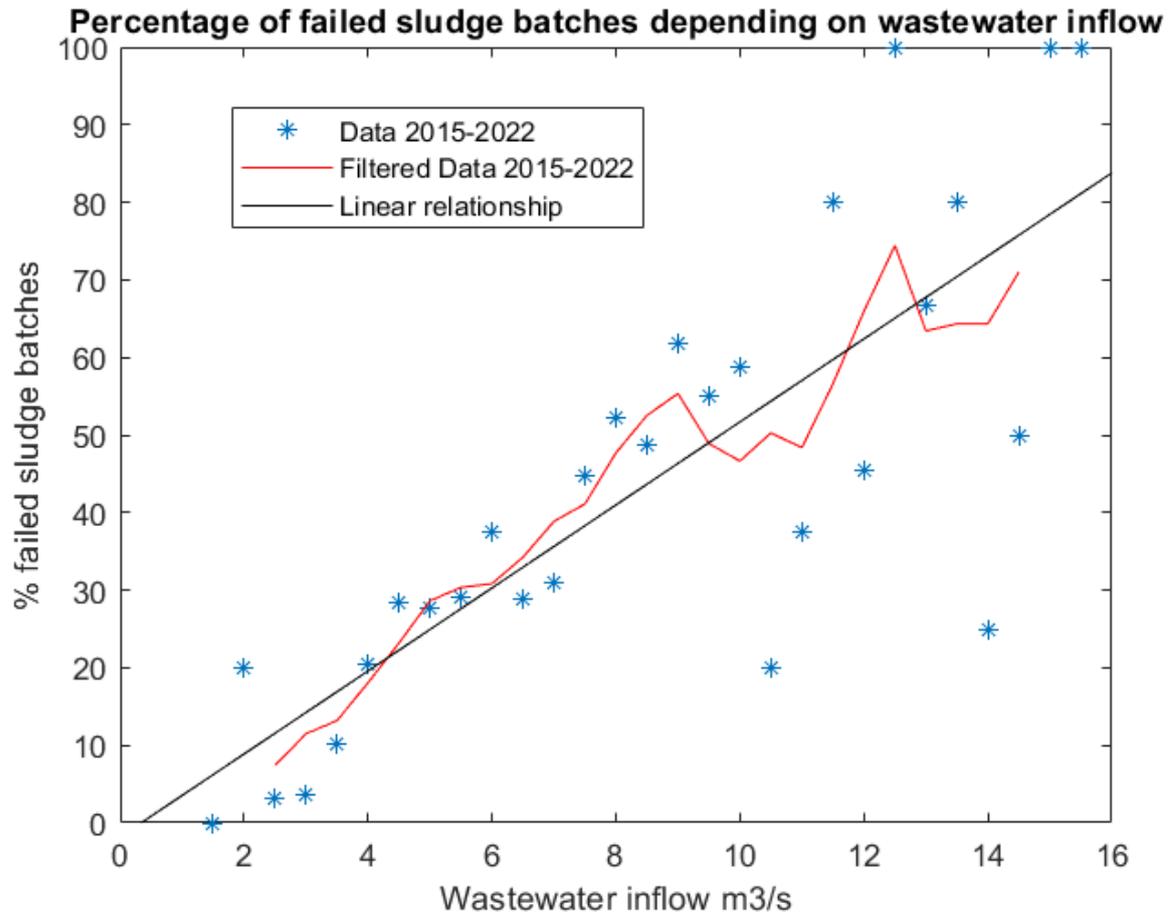
Figure 4.14: The percentage of failed sludge batches at different wastewater inflows. The filtered data uses bigger flow intervals compared to the data plot and the linear relationship constructed from the data can be seen with the slope $y = 100(0.053508x + (-0.018219))$, y is the percentage of failed batches and x is the wastewater inflow in m^3/s.

It can be seen in Figure 4.14 that the percentage of failed sludge batches increases to accordance to increased wastewater inflow.
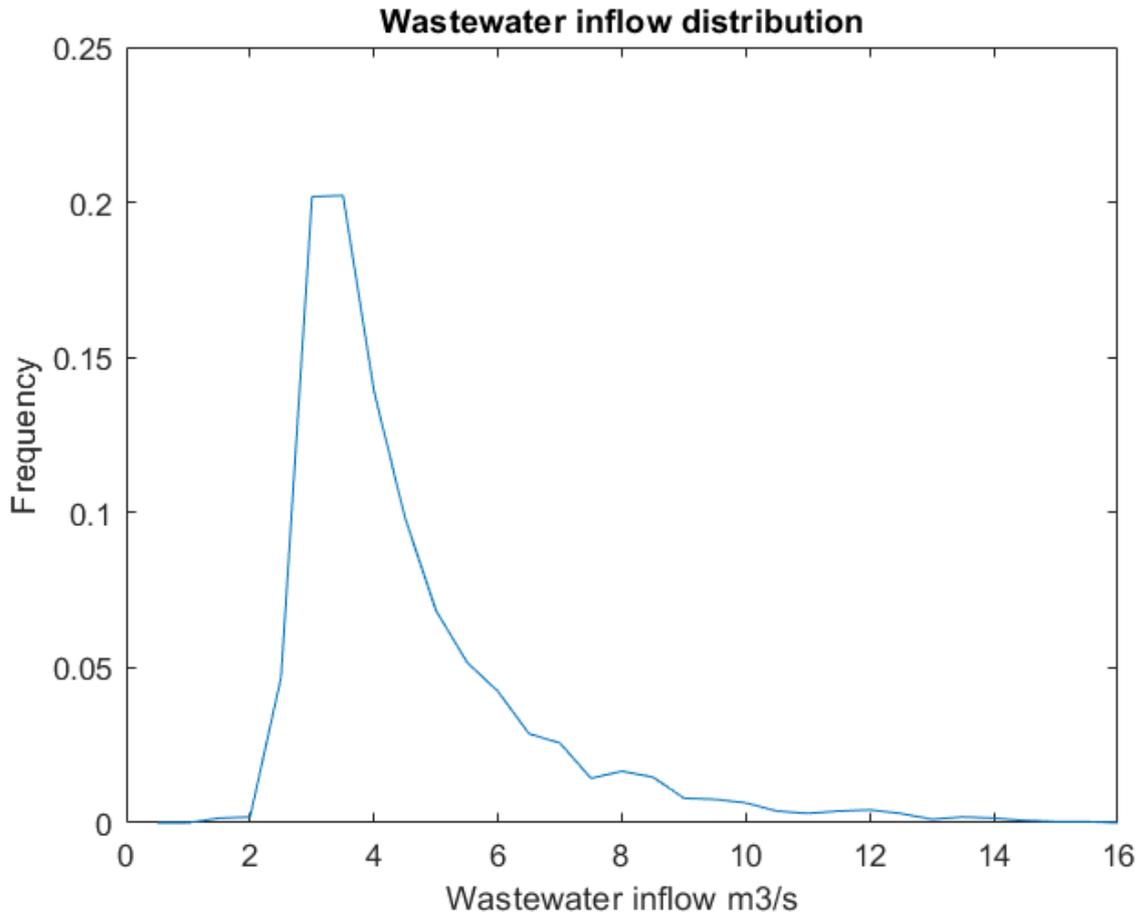
Figure 4.15: The distribution of wastewater inflow for the sludge data 2015/01-2022/03 with the frequency on the y axis describing how frequently a certain level of wastewater inflow occurs.

From Figure 4.15 it is possible to see that most of the flows are between 2 and 6 m^3/s and measured flows above 9 m^3/s are relatively scarce in comparison.

4.4.3 Climate impact

To calculate the climate impact as carbon dioxide equivalents (CO$_2$eq.) for each scenario, a tool that had been used previously to calculate the carbon footprint of Rya WWTP was used. The data input that was changed from the data input of the year 2021 based on the produced data for the scenarios was the following: Yearly phosphorus, nitrogen, BOD$_7$ and COD in effluent and inflow, yearly wastewater inflow to the WWTP, electricity and chemicals used for direct precipitation.

Other parameters in the tool were not expected to change depending on wastewater inflow and therefore they were assumed to remain the same as for the previous carbon footprint calculation on Rya WWTP.

Yearly mass of phosphorus, nitrogen and BOD_7 effluent for each scenario were calculated as stated for the *Effluent quality* criterion. Yearly amounts of COD effluent as well as yearly inflow of P, N, BOD_7 and COD were also calculated as shown in Appendix A. Energy use and amounts of direct precipitation chemicals were calculated as stated in the method sections for the *Energy use* and *Vulnerability* criteria.

4.4.4   Water use

For the upstream and downstream water reuse scenarios 70 liters of drinking water per person and day was calculated based on the amount of I/I water stated in Section 4.3. In the other scenarios there were no measures or changes that indicated that drinking water use would change and it was therefore assumed that there would be no increase or decrease in drinking water used.

4.4.5   Energy use

In the *Energy use* criterion only electricity consumption was considered. The parts of the wastewater plant that were included were all part of the wastewater treatment process, so the electricity used in the building for lighting, kitchen appliances, computers and so on was not considered. Data from the following equipment was analyzed and plotted against the wastewater inflow to the WWTP: inlet pumps, in and outlet pumps for nitrifying trickling filter, pumps used for activated sludge, pumps used for secondary settling, pumps used for nitrifying MBBR, compressors for air to activated sludge and compressor for nitrifying MBBR. The data had been gathered from 2019 to 2022 and the combined data for all the equipment can be seen as black dots in Figure 4.16.
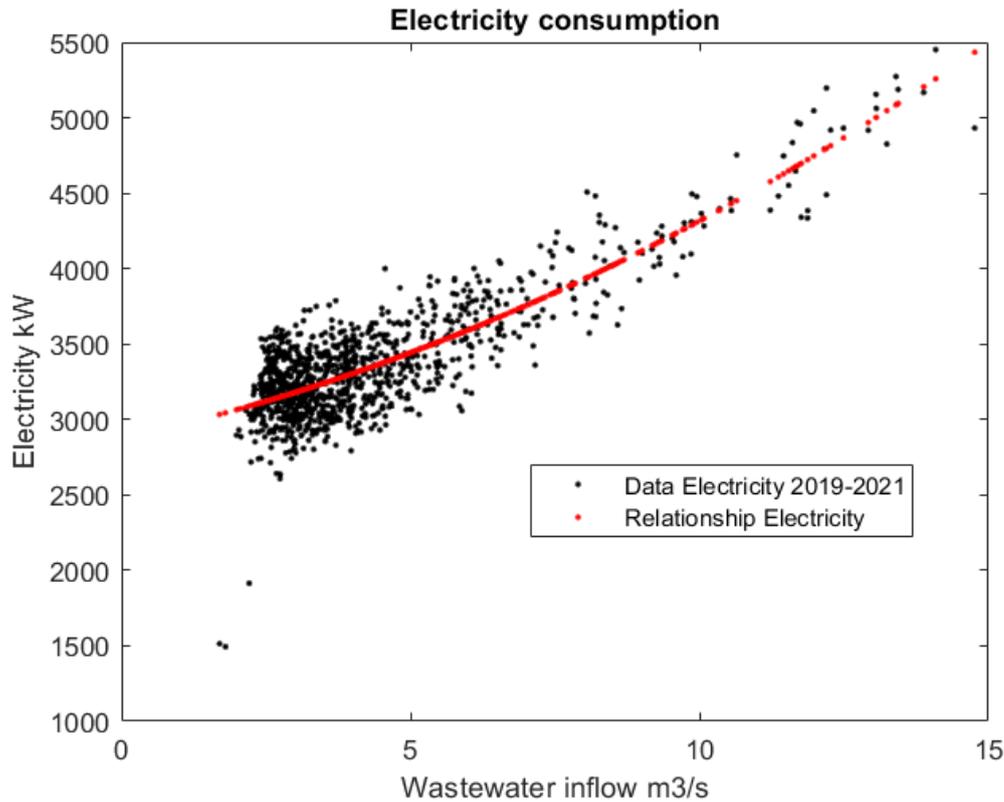
Figure 4.16: Total electricity used at the WWTP for inlet pumps, in and outlet pumps for nitrifying trickling filter, pumps used for activated sludge, pumps used for secondary settling, pumps used for Nitrifying MBBR, compressors for air to activated sludge and compressor for Nitrifying MBBR, in relation to the wastewater inflow to the WWTP. The red dots follow the polynomial relationship $y = 6.1284x^2 + 82.847x + 2875.1$ where y = electricity consumption in kW and x =wastewater inflow in m^3/s.

4.4.6 Sphere of action/political support

Political support was assessed by a literature study of the sustainability goals of the United Nations, Sweden and Gothenburg, and the goals relevant to water use were picked out. To assess the sphere of action, laws for water reuse were studied as well as reported experiences from water reuse projects in Sweden.

4.4.7 Local environment quality & amenity

A literature study was conducted to determine what effects on the quality and amenity of the local environment combined sewer overflow water could have. The local environment being the area surrounding the recipient receiving the combined sewer overflow water. The total amount of combined sewer overflow water for each scenario was calculated by summing up all flows to each of the combined sewer overflow recipients. The combined sewer overflow data, which includes how much combined sewer overflow water goes to each combined sewer overflow recipient per quarter-hour, was given from FCF.

4.4.8   Working conditions

Interviews were conducted with four experienced people working at Rya WWTP, where questions about working conditions in relation to increased or decreased wastewater inflow to the WWTP were asked. These questions covered topics such as workload, tasks and stress related to the volume of inflowing wastewater. The questions asked during interviews can be seen in Appendix B.

Data on weekly on-call hours for the personnel was collected and plotted against the weekly wastewater inflow and a linear relationship was constructed based on the data, see Figure 4.17.
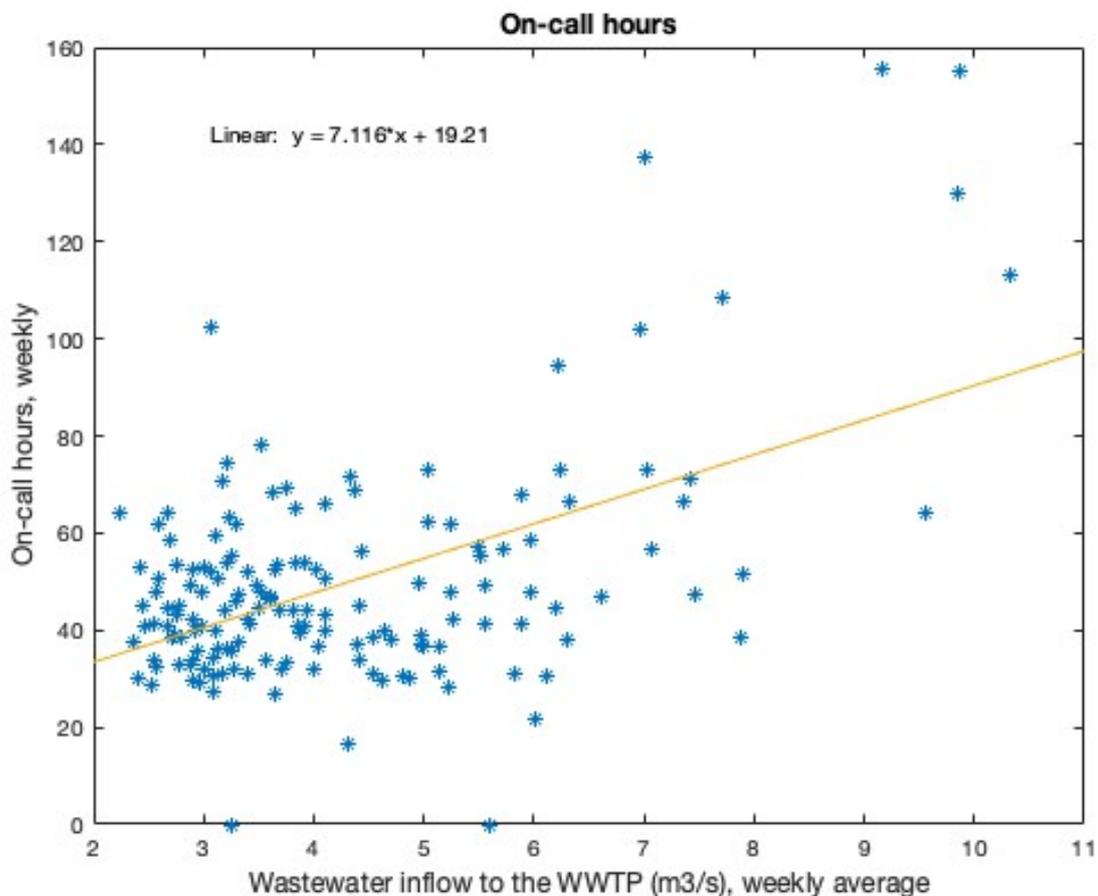
Figure 4.17: Linear relationship for weekly on-call hours in relation to weekly average wastewater inflow to the WWTP.

The linear relationship was then used to calculate yearly on-call hours for each of the scenarios based on wastewater inflow data, which was then used as a basis in the grading procedure.

4.4.9 Safety/risks

Interviews were conducted with four experienced people working at Rya WWTP, where questions about risks and safety (see Appendix B) at the WWTP in relation to increased or decreased wastewater inflow were asked. A literature study was also done where documents regarding routines for high flows were studied to get a better understanding of which routines there are to ensure safety during high flows.

A cumulative flow diagram was made to show the distribution of flows over the year, to give an understanding of how much time would be spent over and under certain flows for the different scenarios. The cumulative sum was calculated based on each scenario's flow distribution curve that can be seen in Figure 4.18.
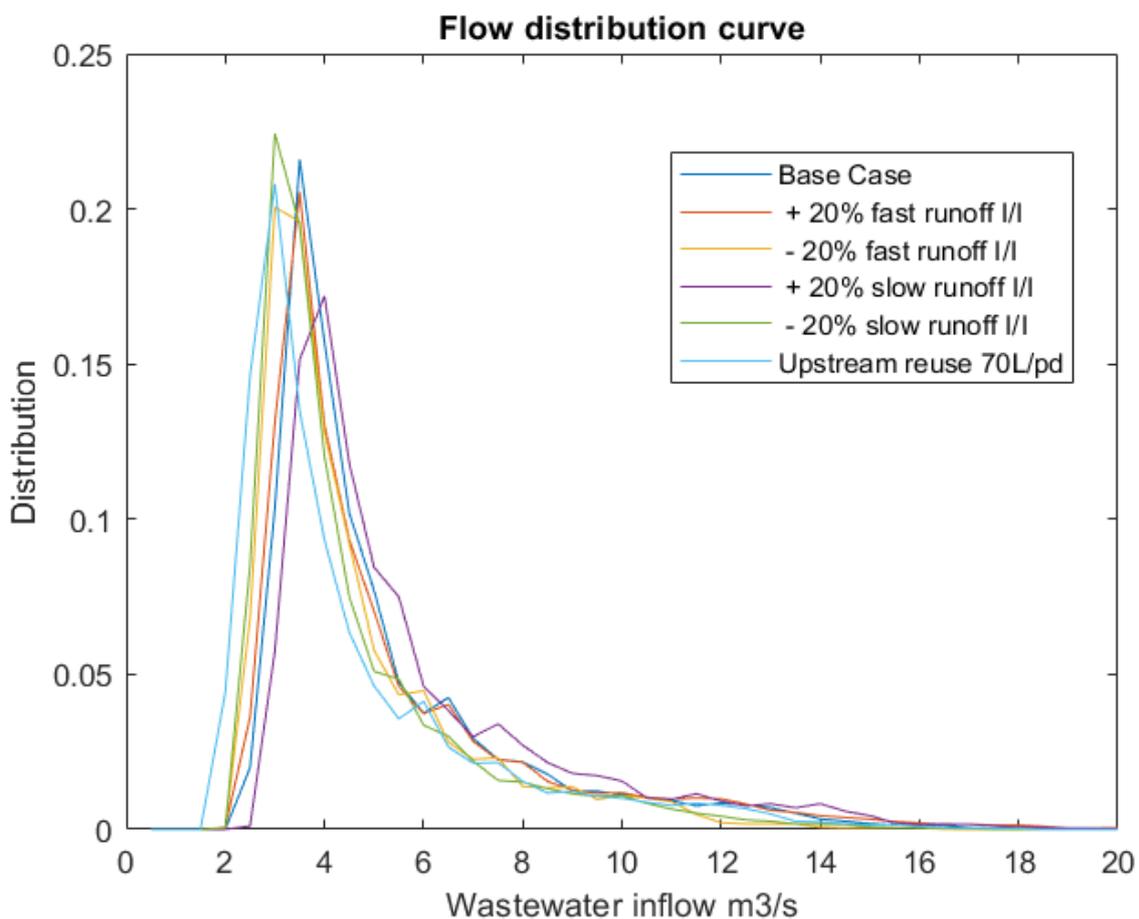
Figure 4.18: Shows the distribution of different levels of wastewater inflow to Rya WWTP that indicates how frequently flows in certain levels occur.

4.4.10 Operating costs

The operating costs were calculated for the resources consumed that were affected by the wastewater inflow to Rya WWTP. The resources were the direct precipitation chemical Polyaluminum Chloride (PAC), direct precipitation polymer and electricity for inlet

pumps, in and outlet pumps for nitrifying trickling filter, pumps used for activated sludge, pumps used for secondary settling, pumps used for nitrifying MBBR, compressors for air to activated sludge and compressor for nitrifying MBBR. The costs of PAC, polymer and electricity used for calculating operating costs can be seen in Table 4.3.

Table 4.3: Costs for direct precipitation chemicals and electricity [43], [44].

Resource	Price	Unit
Polyaluminium Chloride (PAC)	2.36	kr/kg
Polymer	23.73	kr/kg
Electricity	0.81	kr/kWh

All other costs besides the items in Table 4.3 were assumed to be constant. The costs of a scenario were calculated as the total mass of PAC, polymer and electricity used in a scenario that is calculated in Section 4.4.5 and 4.4.11 multiplied with the respective price in Table 4.3. Then sum of the cost for PAC, polymer and electricity was deducted by the sum of the cost for PAC, polymer and electricity for the base case resulting in the difference in cost between a scenario and the base case. The difference was used as the results for each scenario.

4.4.11 Vulnerability

A literature study was conducted to determine the likelihood of a shortage of direct precipitation chemicals and the effects on the WWTP if a shortage would occur.

To measure the vulnerability connected to use of chemicals the amount of chemicals used per year were calculated for each scenario from a polynomial relationship created based on data for PAC and polymer used for the years 2019-2021 and the wastewater inflow to the WWTP, the relationship and data can be seen in Figure 4.19 and 4.20. To get amount of PAC consumed the relationship from the had to be divided by 0.09 because the measures at Rya WWTP only tracks the aluminum since it is what causes the precipitation. The reason that it's divided by 0.09 is because the aluminum constitutes 9% of the total mass when PAC is deployed in the direct precipitation treatment.
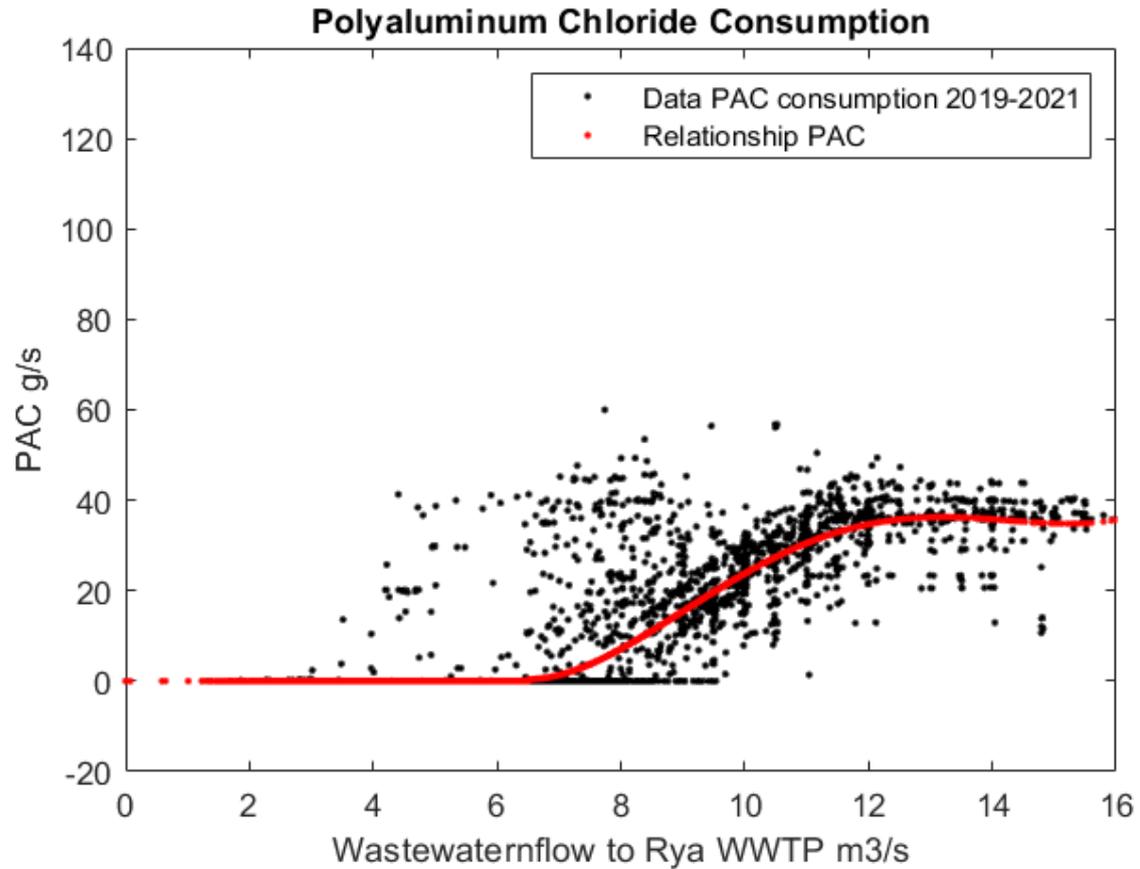
Figure 4.19: The polynomial relationship for PAC used in relation to the wastewater inflow to the WWTP. The polynomial relationship is shown as a red dotted line and the data for used PAC in relation to wastewater inflow is shown as black dots. If the wastewater inflow is between 6.5 and 16 m^3/s the consumption follows the equation $y = 0.032902x^4 - 1.5319x^3 + 25.365x^2 - 171.58x + 405.94$ where y is PAC consumption in g/s and x is wastewater inflow in m^3/s. If x is below 6.5 then the y is equal to 0 and if x is above 16 then y is equal to 36.
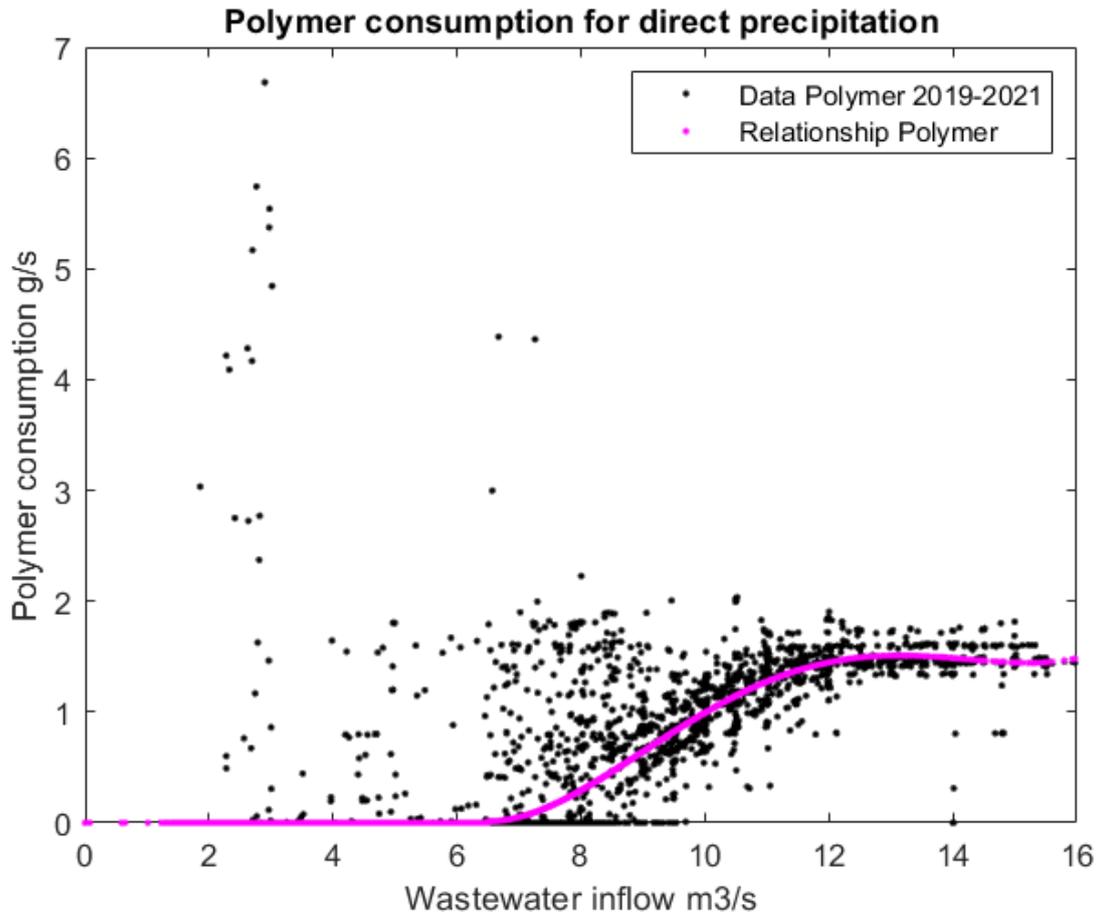
Figure 4.20: The polynomial relationship for direct precipitation polymer used in relation to the wastewater inflow to the WWTP. The polynomial relationship is shown as a magenta dotted line and the data for used polymer in relation to wastewater inflow is shown as black dots. If the wastewater inflow is between 6.5 and 16 m^3/s the consumption follows the equation $y = 0.0014147x^4 - 0.065766x^3 + 1.0877x^2 - 7.3575x + 17.417$ where y is polymer consumption in g/s and x is wastewater inflow in m^3/s. If x is below 6.5 then the y is equal to 0 and if x is above 16 then y is equal to 1.5.

4.4.12 Flexibility

The capability of the wastewater plant to increase capacity by opening additional treatment steps or re-directing water was considered by calculating the amount of time the extra treatment steps would be active at the wastewater plant. In order to calculate the amount of time the extra steps were active the following capacities were used for biological and chemical treatment: 8.5 m^3/s, direct precipitation: 12.0 m^3/s and only mechanical treatment: 16 m^3/s. Water that goes through the biological and chemical treatment is considered to get a full treatment compared to direct precipitation which mainly removes phosphorus and mechanical treatment that mainly removes bigger particles and waste. If the flow was above 16 m^3/s, the water was assumed to be released without treatment. The capacities were used to sort the flow series for the scenarios and calculate the amount of time in a year that the different partial treatment steps would be active. This was done by first summarizing the amount of data entries for the wastewater inflow for 8.5-12 m^3/s, 12-16 m^3/s and >16 m^3/s then dividing the amount of data entries for each flow

interval by the total amount of data entries for a scenario. This gives the amount of time that direct precipitation, only mechanical treatment and no treatment because each data entry amounts to the same amount of time.

4.5 Grading

The reason for grading the scenarios in each criterion is to compress the data and information gathered to facilitate the overall comparison between the scenarios. Context of what a grade indicates is given from the grading scale that describes how the data and information correlate to what is predicted as acceptable in the year 2030. This was done by sorting the scenarios for each criterion according to the grading scale that in Table 4.4 based on the data and information given for each criterion. The comparison is facilitated by the conversion of data and information for different criteria into grades that are reflected on the same scale and therefore comparable.

Table 4.4: The grading scale with corresponding grade descriptions.

Grade	Grade description
1	Significantly worse than future acceptable level
2	Worse than future acceptable level
3	Future acceptable level
4	Better than future acceptable level
5	Close to optimal level

The grading was carried out by a panel consisting of seven people. All the people in the panel work in the industry of urban water and have experience and knowledge of wastewater treatment. Two are employed at Chalmers and the other five are employed by Gryaab. The panel was given guidance that they should agree on what is considered an acceptable future level for each criterion and then sort the scenarios using the grading scale. To facilitate for the panel, goals and limits set for the future by Gryaab, Gothenburg, Sweden and United Nations were used to help the panel agree on what a future acceptable level could be for each criterion. However, goals and limits were not found for all criteria, which meant that the panel had less information to base their decision on what a future acceptable level is for some criteria.

To make sure that the grades were set proportionally to the data provided, a linearity plot between the grade and indicator for the criterion was provided. The linear pattern helped by indicating when a grading point deviated from the data and information provided for the criteria. If a grading point deviated from the linearity plot the group was advised to reconsider their grading based on the data and information presented in the criteria. However, there was exceptions for when a grade was set to 1 or 5 meaning, it could not go higher or lower.

All twelve scenarios were graded by the panel during a session with the authors as moderators together with the supervisor. When the scenarios had been graded for all criteria the grades for each criterion were summarized to an average grade for each of the scenarios, as shown in Equation (4.10).

$$\text{Average grade} = \frac{\sum \text{Grades}}{\text{Number of Criteria}} \tag{4.10}$$

4.6 Weighting

The weighting of the criteria was done by the same panel as for the grading except for one person that could not be present. The reason for weighting the criteria was to allow the panel to influence how each criterion should affect the results. If no there was no weighting, then the influence of a grade for a criterion would be lower the bigger the critera list but with weighting it is possible to bring forward certain criteria that were considered more influential, impactful or impacted than other. The weighting was divided up into three steps: Initial weighting, weighting in smaller groups and weighting with the whole panel.

During the initial weighting, the panel had access to the data and information from the grading session. After initial weights had been set, the automatically calculated percentage contribution based on the weight they assigned could be seen in a pie chart, which can be seen in Figure 4.21. The panel had to discuss and agree on the distribution of weight so that the percentage of contribution for the different criteria towards the overall result was satisfactory.
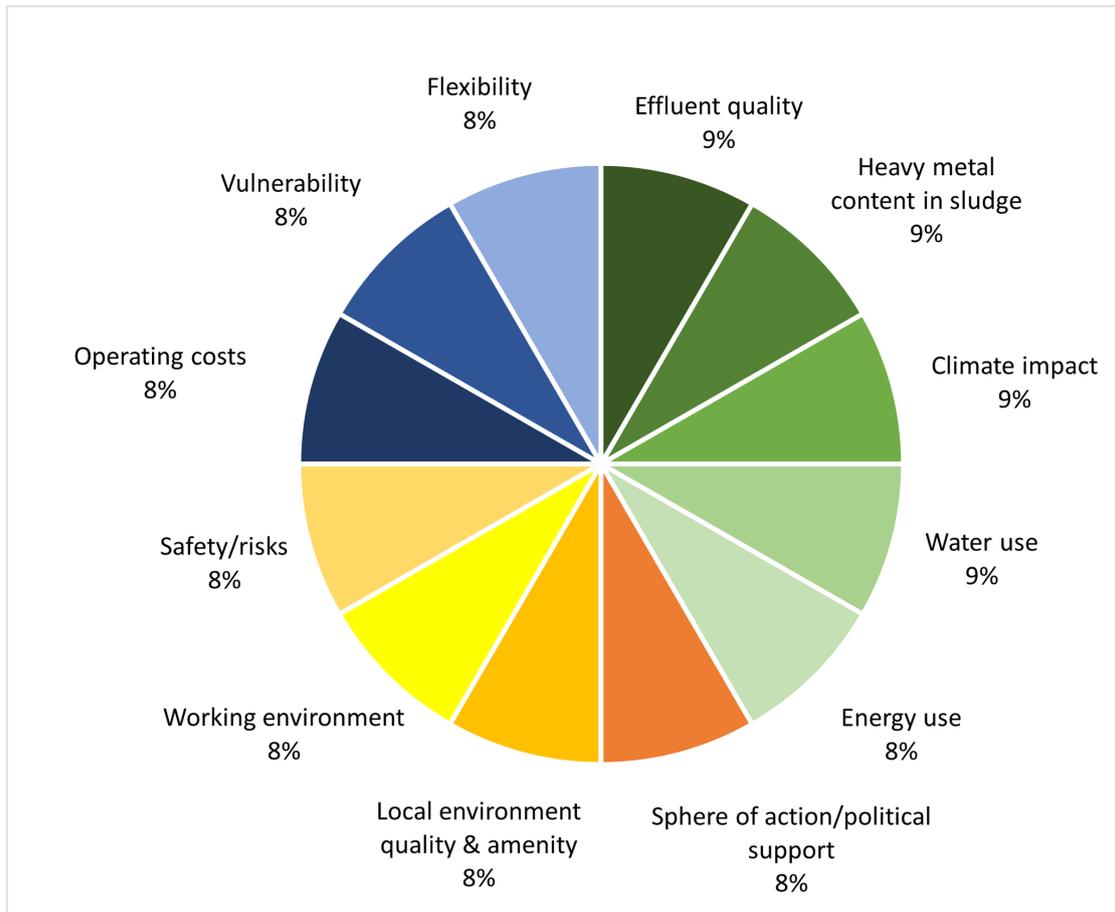
Figure 4.21: Pie chart showing the percentage of weight assigned to each criterion which was automatically updated during the initial weighting.

The group weighting was done in two steps. First, the panel was divided into two groups that encouraged each individual member to be more active compared to when the whole panel is gathered. Then, the groups were distributing their weights on each criterion with the help of the relative monetary value of one numeric grade step for the criterion. This gave the relative value of one grade unit of the criteria in Swedish kronor and was used as a guide for the weighting since it could be compared to monetary reference values for the criteria. The reason for using operational cost to calculate relative values for each criterion was because it had the indicator of Swedish kronor that was predicted to be the most familiar to the panel members. Because it was possible to find connections between the relative value of Swedish kronor and indicators of other criteria it seemed like the appropriate option. To calculate the relative value between the operational cost and the other criteria Equation (4.11) was used, where K is the quota, V_A is the value of a grade step for criterion A, V_B is the value of a grade step for criterion B, W_A is the weight of criterion A and W_B is the weight of criterion B. *Operational cost* is always criterion B in the equation.

$$K = \frac{V_A}{V_B} \cdot \frac{W_B}{W_A} \tag{4.11}$$

After the group weighting, the panel was gathered and the results of the two groups were presented. The panel then had to agree on a final weight distribution using both the arguments presented by groups one and two.

When the all the weight distributions were done, the percentage of contribution was applied to the grades according to Equation (4.12), where W_r is the weighted result and W is the weight T_W is the total weight for all criteria and G_C is the grade set in a criterion.

$$W_r = \frac{W}{T_W} \cdot G_C \qquad (4.12)$$

5

Results

In this chapter, the results from data preparation for each criterion, the results from grading, weighting of each criterion and the weighted results are presented.

5.1 Results from data preparation

In this section, the resulting data and information gathered will be presented for each criterion. This was the material used for grading.

5.1.1 Effluent quality

Yearly amounts of total phosphorus, total nitrogen and BOD_7 emissions from Rya WWTP as well as both low and high estimates of the emissions from combined sewer overflow can be seen in Table 5.1, 5.2 and 5.3.

Table 5.1: Phosphorus emissions (tonnes per year) from the WWTP and both high and low estimates of the phosphorus emissions from CSOs. Since the upstream reuse scenario lack CSO data, it is estimated that the emissions from CSOs are somewhere between the base case and –20% slow runoff I/I. Therefore, the low estimate is in the range of 7-8 and the high estimate is between 13-15. The mean values of the ranges are therefore used for the upstream reuse scenario. For the total phosphorus, the low estimate is used.

Phosphorus		CSOs low	CSOs high	Effluent P	Tot P (low)
Base case		8	15	34	42
+ 20% fast runoff I/I		44	80	36	80
- 20% fast runoff I/I		4	7	29	33
+ 20% slow runoff I/I		15	27	39	54
- 20% slow runoff I/I		7	13	29	36
Upstream reuse 70 l/p.d	Estimated to:	7.5	14	30	37.5
Downstream reuse 70 l/p.d		8	15	34	42

Table 5.2: Nitrogen emissions (tonnes per year) from the WWTP and both high and low estimates of the nitrogen emissions from CSOs. Since the upstream reuse scenario lack CSO data, it is estimated that the emissions from CSOs are somewhere between the base case and –20% slow runoff I/I. Therefore, the low estimate is in the range of 58-71 and the high estimate is between 103-125. The mean values of the ranges are therefore used for the upstream reuse scenario. For the total nitrogen, the low estimate is used.

Nitrogen		CSOs low	CSOs high	Effluent N	Tot N (low)
Base case		71	125	1 129	1 200
+ 20% fast runoff I/I		369	653	1 139	1 508
- 20% fast runoff I/I		31	56	950	981
+ 20% slow runoff I/I		126	223	1 292	1 418
- 20% slow runoff I/I		58	103	927	985
Upstream reuse 70 l/p.d	Estimated to:	64	114	912	976
Downstream reuse 70 l/p.d		71	125	1 129	1 200

Table 5.3: BOD_7 emissions (tonnes per year) from the WWTP and both high and low estimates of the BOD_7 emissions from CSOs. Since the upstream reuse scenario lack CSO data, it is estimated that the emissions from CSOs are somewhere between the base case and –20% slow runoff I/I. Therefore, the low estimate is in the range of 303-367 and the high estimate is between 600-727. The mean values of the ranges are therefore used for the upstream reuse scenario. For the total BOD_7, the low estimate is used.

BOD_7		CSOs low	CSOs high	Effluent BOD_7	Tot BOD_7 (low)
Base case		367	727	1 132	1 499
+ 20% fast runoff I/I		1 917	3 797	1 152	3 069
- 20% fast runoff I/I		164	324	987	1 151
+ 20% slow runoff I/I		655	1 297	1 264	1 919
- 20% slow runoff I/I		303	600	975	1 278
Upstream reuse 70 l/p.d	Estimated to:	335	664	980	1 315
Downstream reuse 70 l/p.d		367	727	1 132	1 499

It can be seen in Table 5.1, 5.2 and 5.3 that the increased slow runoff I/I case has the highest phosphorus, nitrogen and BOD_7 emissions from the WWTP, however the total (from WWTP and CSOs) phosphorus, nitrogen and BOD_7 emissions are higher in the increased fast runoff I/I scenario. In the decrease scenarios, the emissions from the WWTP are lower than the base case, however the decrease (compared to base case) is slightly larger in the decreased fast runoff I/I scenario than for a decrease in slow runoff I/I. When 70 liters of water per person and day is reused upstream, there is a reduction in both emissions from the WWTP and emissions from combined sewer overflow compared to the base case. However, the reduction is smaller than for reduced I/I-water for phosphorus and BOD_7 and larger than reduced I/I-water for nitrogen emissions. Downstream reuse of 70 liters per person and day is got the emissions as the base case since it has the same flow series.
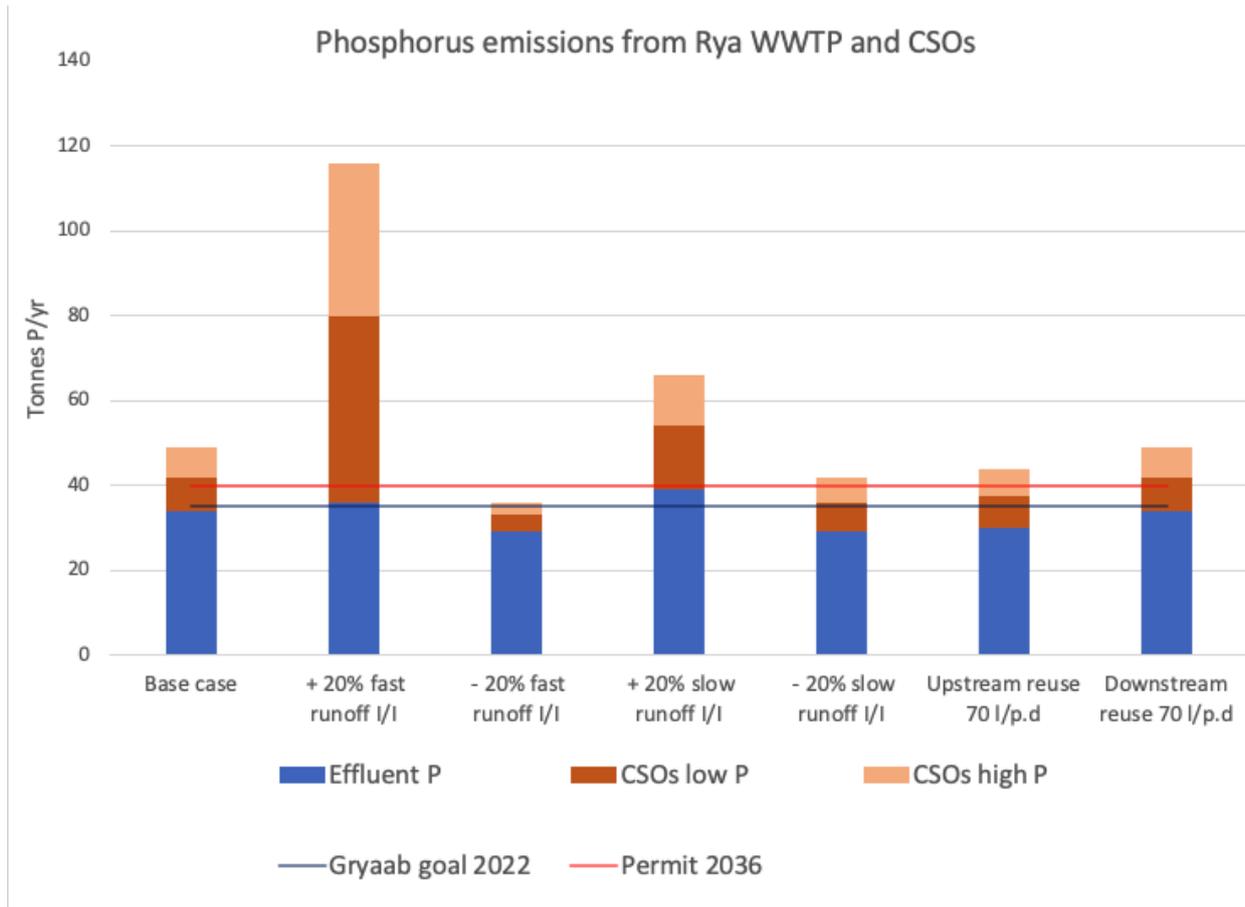
Figure 5.1: Effluent phosphorus from the WWTP as well as high and low estimates of phosphorus emissions from CSOs, as well as lines showing the limit for the environmental permit and the goal set by Gryaab for 2022.

Figure 5.1 shows the goal that Gryaab set for phosphorus emissions in 2022 which is 35 tonnes per year and the limit for the environmental permit which is a three-year average of 40 tonnes per year. These limits are for the emissions from the WWTP, and it can be seen on the blue staples that the scenarios with increased I/I-water result in emissions, from the WWTP that exceeds Gryaab's goal for 2022. All scenarios have emissions from the WWTP below the environmental permit limit. However, if total emissions are accounted for, only the decreased I/I-water scenarios and the upstream reuse scenario are making it below the environmental permit limit when the low estimate for combined sewer overflow emissions is used. If the high estimate were to be correct, only a decrease of 20% fast runoff I/I would help the WWTP reach the environmental permit in the case of a wet year.
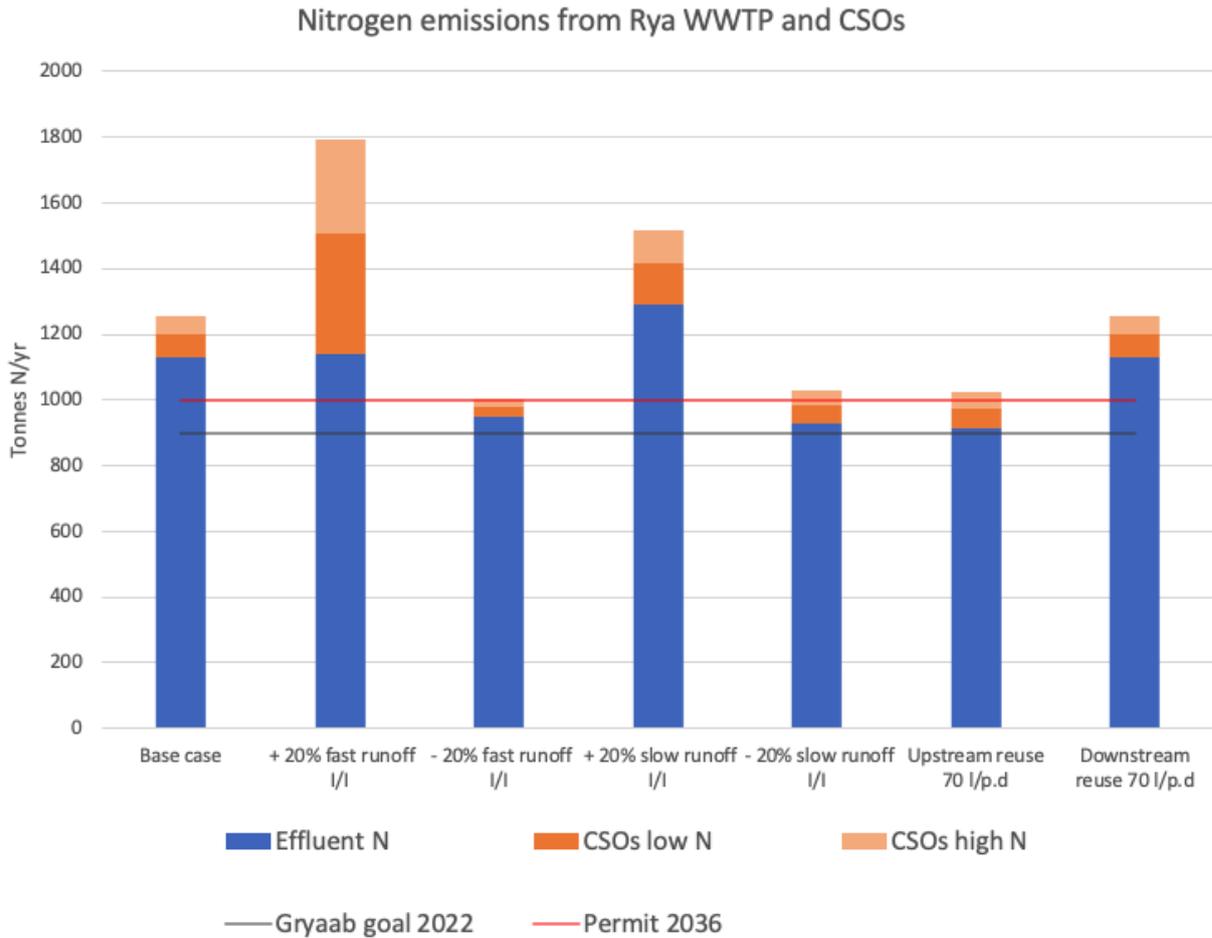
Figure 5.2: Effluent nitrogen from the WWTP as well as high and low estimates of nitrogen emissions from CSOs, as well as lines showing the limit for the environmental permit and the goal set by Gryaab for 2022.

Figure 5.2 shows the goal that Gryaab set for nitrogen emissions in 2022 which is 900 tonnes per year and the limit for the environmental permit which is a three-year average of 1000 tonnes per year. These limits are for the emissions from the WWTP, and it can be seen on the blue staples that all scenarios result in emissions, from the WWTP, that exceed Gryaab's goal for 2022. Only the scenarios resulting in a decreased wastewater inflow to the WWTP have emissions below the environmental permit limit when the low estimate for CSO emissions is used. If the high estimate were to be used, then all scenarios would exceed the limit of the environmental permit.
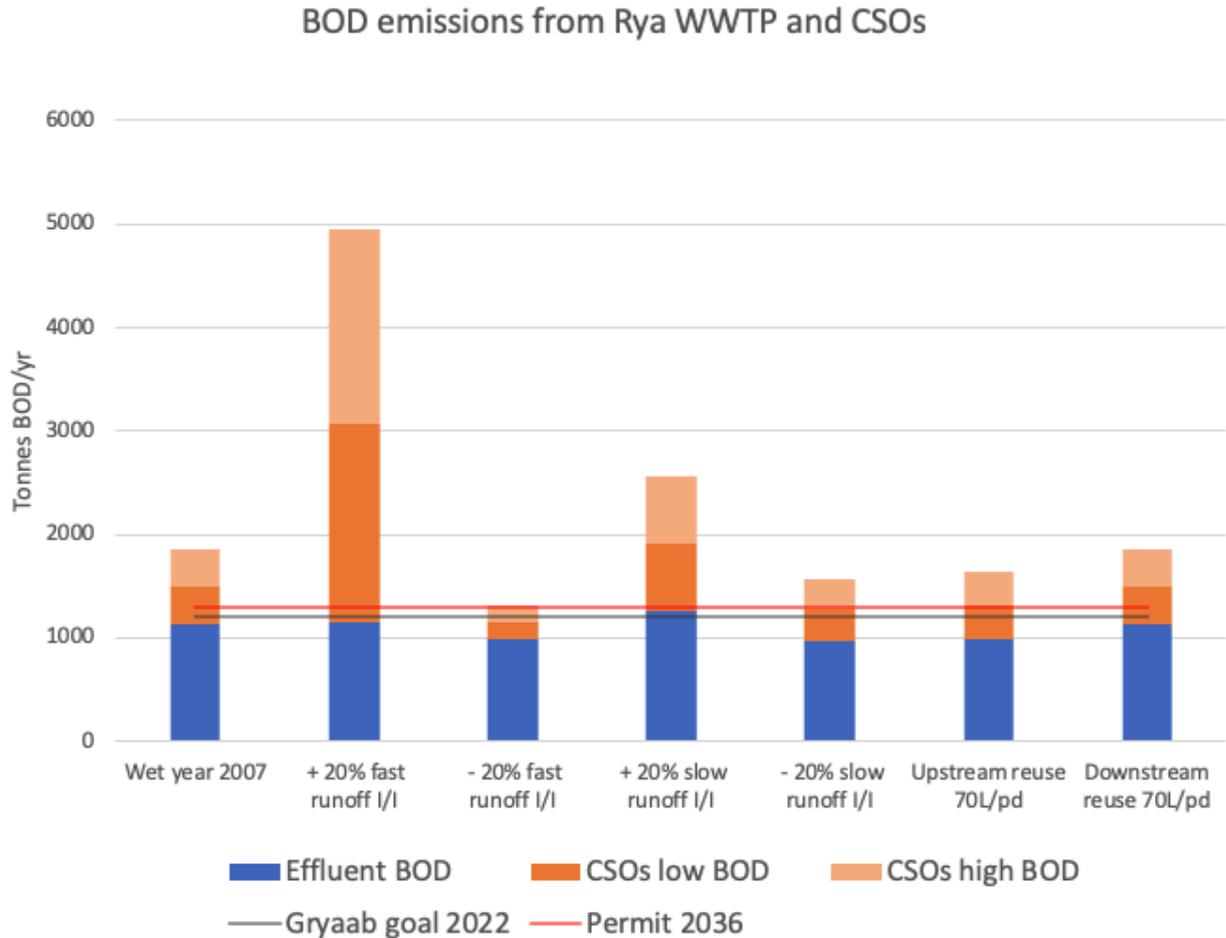
Figure 5.3: Effluent BOD_7 from the WWTP as well as high and low estimates of BOD_7 emissions from CSOs, as well as lines showing the limit for the environmental permit and the goal set by Gryaab for 2022.

Figure 5.3 shows the goal that Gryaab set for BOD emissions in 2022 that is 1200 tonnes per year and the limit for the environmental permit which is a three-year average of 1300 tonnes per year. These limits are for the emissions from the WWTP, and it can be seen on the blue staples that all scenarios result in emissions, from the WWTP only, that are below both Gryaab's goal for 2022 and the environmental permit limit. When the low estimate for CSO emissions is used, only the scenario with a decrease in fast runoff I/I has BOD emissions lower than both Gryaab's goal and the environmental permit limit. If the high estimate were to be used, then all scenarios would exceed the environmental permit limit. The +20% fast runoff I/I scenario stands out as the emissions from CSO is more than double that of +20 slow runoff I/I which has the second highest emissions of BOD.

5.1.2   Heavy metal content in sludge

In Table 5.4 the percent of sludge batches that have a Cd/P ratio higher than the limit for what is allowed in order to be Revaq certified is shown.

Table 5.4: Percent failed batches based on the Cd/P ratio for Revaq certification of sludge.

	% Failed batches
Base case	26.6
+ 20% fast runoff I/I	27.1
- 20% fast runoff I/I	23.2
+ 20% slow runoff I/I	29.7
- 20% slow runoff I/I	22.9
Upstream reuse 70 l/p.d	26.6
Downstream reuse 70 l/p.d	26.6

The reuse cases have the same result as the base case since the type of water that is reused not typically contains heavy metals. Therefore, a decrease in drinking water used does not affect these results. The results show that an increase in I/I-water results in less approved sludge batches, where an increase in slow runoff I/I seems to give the highest percentage of failed batches. Likewise, decreased I/I-water results in fewer failed batches of sludge.

In Figure 5.4 the percentages of failed sludge batches are shown as staples and the average percentage of failed sludge batches between December 2014 and March 2022 is shown as an orange line. The goal set by Gryaab for 2022 is that a maximum of 30% of the batches should fail the requirements for Revaq certification. However, this 30% also include other requirements and the Cd/P ratio is only one of them.
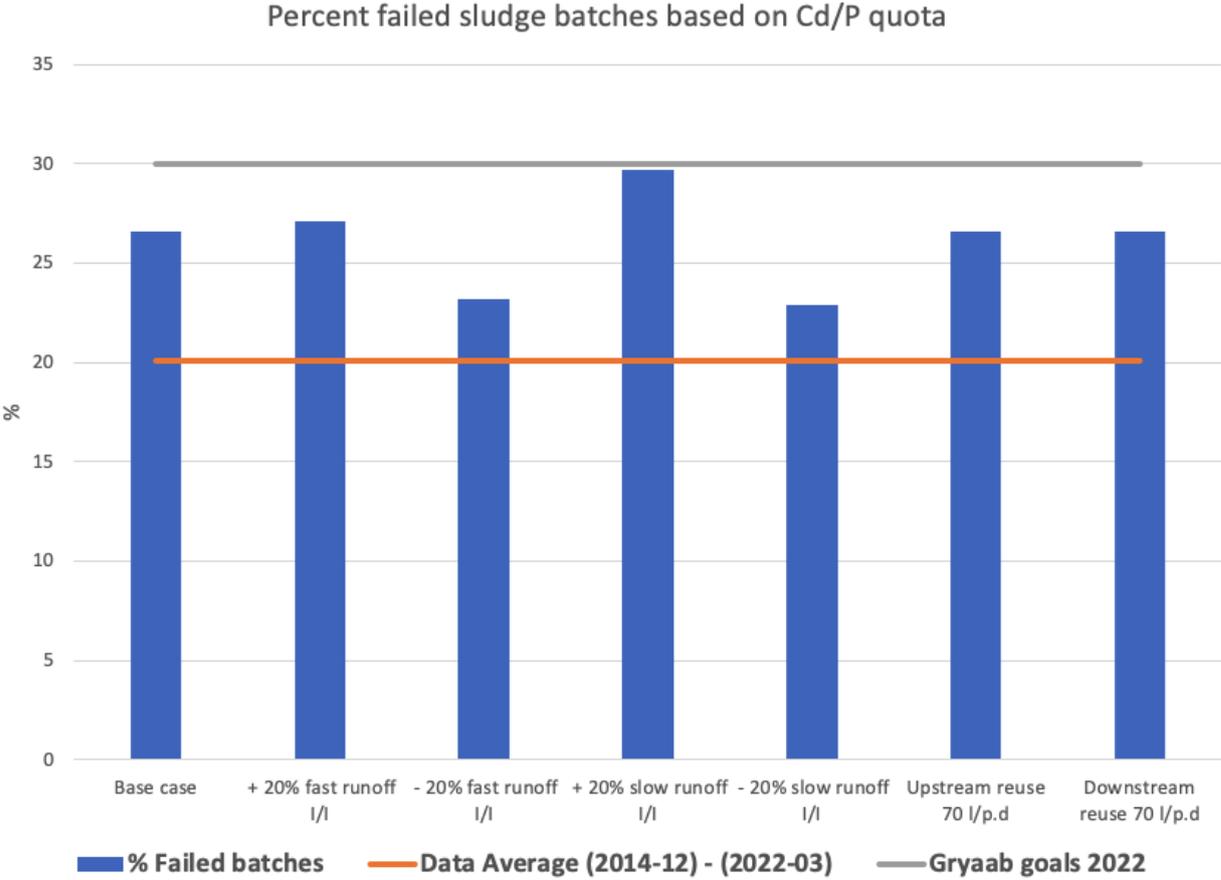
Figure 5.4: Percent failed batches based on the Cd/P ratio for Revaq certification of sludge.

In Figure 5.4 it can be seen that all scenarios would live up to Gryaab's goal if only the Cd/P ratio was accounted for. It can also be seen that the percentage of failed batches is higher for all wet year scenarios than for the average of recent years.

5.1.3   Climate impact

In Table 5.5 the climate impact for each scenario is shown, as well as the contributions from chemicals, energy use and from N and BOD_7 emissions.

Table 5.5: Total carbon dioxide equivalents for each scenario as well as partial contributions from chemicals, energy use and nitrogen and BOD_7 emissions.

	CO_2eq	CO_2eq Other	CO_2eq Chemicals	CO_2eq Energy use	CO_2eq N, BOD_7
Base case	14 375	5 657	6 314	540	1 864
+ 20% fast runoff I/I	14 499	5 657	6 411	542	1 888
- 20% fast runoff I/I	13 823	5 657	6 044	528	1 594
+ 20% slow runoff I/I	14 867	5 657	6 548	550	2 112
- 20% slow runoff I/I	13 810	5 657	6 062	527	1 563
Upstream reuse 70 l/p.d	13 929	5 657	6 314	529	1 553
Downstream reuse 70 l/p.d	14 375	5 657	6 190	540	1 864

As seen in Table 5.5 chemical use has a relatively large contribution to the total CO_2-equivalents compared to the other contributing categories. The difference in CO_2-equivalents from chemicals is relatively small between scenarios compared to the total carbon footprint. Overall, increases in I/I-water are shown to increase the carbon footprint for Rya WWTP. While decreases in I/I-water and upstream water reuse (70 liters per person and day) are shown to decrease the carbon footprint compared to the base case. This can also be seen in Figure 5.5 below.
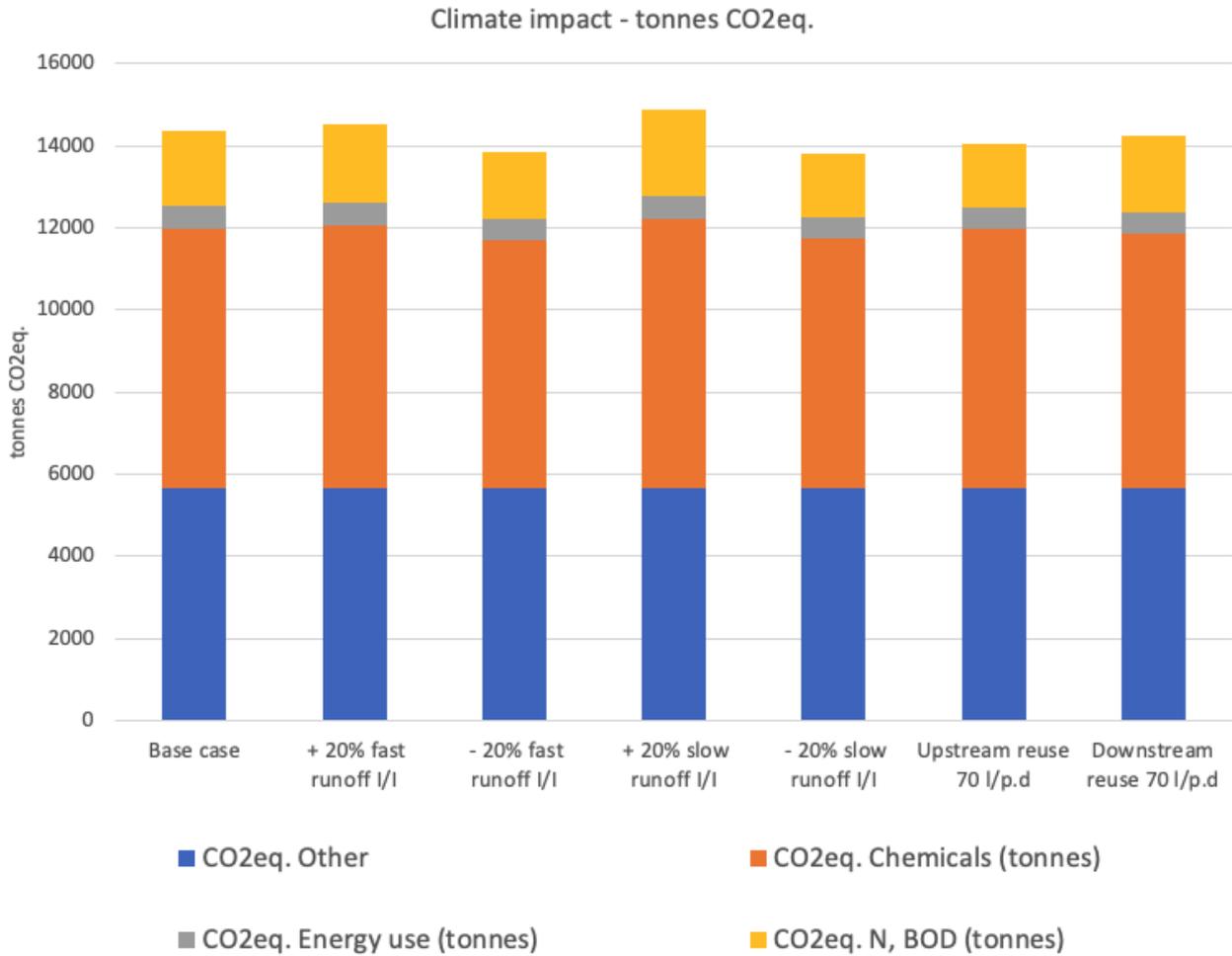
Figure 5.5: Total carbon dioxide equivalents for each scenario shown as the contributions from chemicals, energy use, nitrogen and BOD_7 emissions and other, presented as a bar diagram.

5.1.4 Water use

Conservation of drinking water is only found in the scenarios where water is reused. Since the amount of reused water was predetermined when the scenarios were formulated, they both generate water savings of 70 liters per person and day. In Table 5.6 the amount of saved drinking water for each scenario can be seen.

Table 5.6: Saved drinking water in liters per person and day for each scenario.

	Saved drinking water (l/pd)
Base case	0
+ 20% fast runoff I/I	0
- 20% fast runoff I/I	0
+ 20% slow runoff I/I	0
- 20% slow runoff I/I	0
Upstream reuse 70 l/p.d	70
Downstream reuse 70 l/p.d	70

5.1.5   Energy use

The difference in electricity consumption at the WWTP for the equipment stated in section (Metod energy use) can be seen in Figure 5.6 as the difference in GWh consumed compared to the base case.
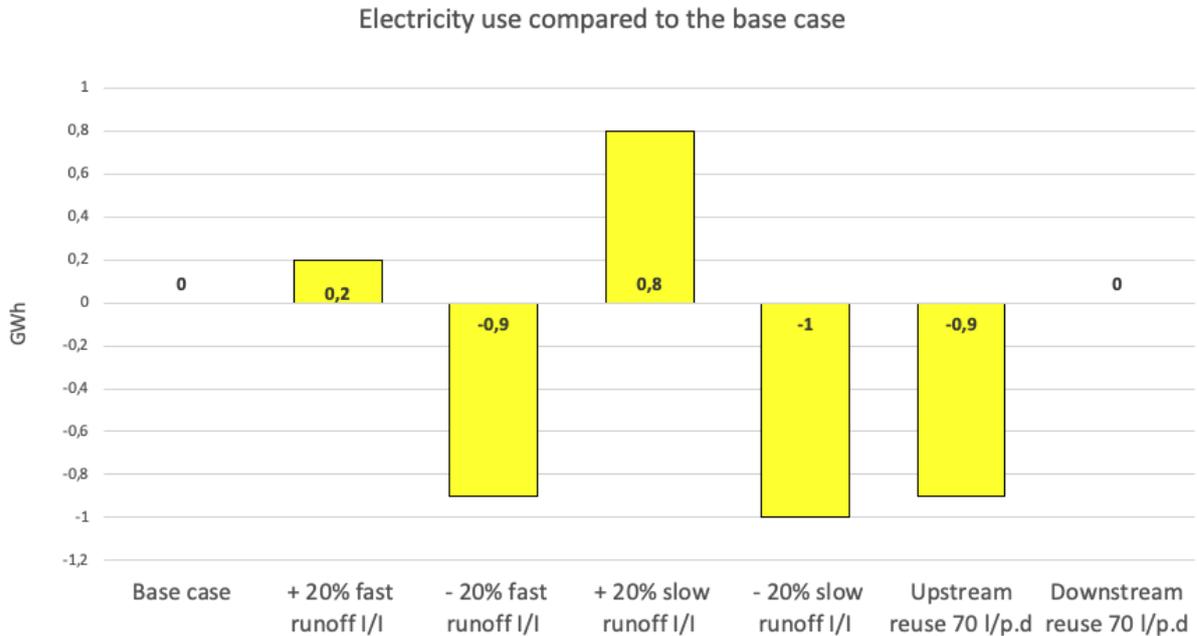
Figure 5.6: Electricity used by pumps and compressors in the wastewater treatment process compared to the base case.

An increase in I/I-water gives increased the electricity consumption while a decrease in I/I-water, as well as upstream reuse, leads to a lower energy consumption. The +20% fast runoff I/I scenario had less of an increase compared to +20% slow runoff I/I.

5.1.6   Sphere of action/political support

The material intended to be used as a basis for deciding the grades for each scenario for the criterion *Sphere of action/political support* resulted in a qualitative basis of information regarding goals and legal aspects for each scenario, which can be seen in Table 5.7.

Table 5.7: Political and legal aspects to consider for each scenario.

	Affected goals or legal aspects	References
Base case	No changes that contribute to any of the goals are made.	[45]
+ 20% fast runoff I/I	More water to treat can be seen as negative for goal 6.4 in agenda 2030, increased water-use efficiency. Additional water also increases combined sewer overflows, which makes it hard to reach Gothenburg's 2030 goal of reducing combined sewer overflows by at least 25 percent.	[45], [46]
- 20% fast runoff I/I	Can contribute to goal 6.4 in agenda 2030, increased water-use efficiency.	[45]
+ 20% slow runoff I/I	More water to treat can be seen as negative for goal 6.4 in agenda 2030, increased water-use efficiency. Additional water also increases combined sewer overflows, which makes it hard to reach Gothenburg's 2030 goal of reducing combined sewer overflows by at least 25 percent.	[45], [46]
- 20% slow runoff I/I	Can contribute to goal 6.4 in agenda 2030, increased water-use efficiency.	[45]
Upstream reuse 70 l/p.d	There is ambiguity in the requirements for greywater reuse, which is believed to be due to a lack of knowledge about how laws and governance should be used for greywater reuse. This has been observed when comparing individual cases where different permits were required for similar installations. Contributes to agenda 2030 goal 6.3 and 6A.	[3], [45], [47],
Downstream reuse 70 l/p.d	There is a possible problem in that there is no legal definition for technical water, which the water for downstream reuse is classified as. Contributes to agenda 2030 goal 6.3 and possibly 6A, as well as Gothenburg's circular economy strategy.	[45], [46], [48]

As stated in Table 5.7 above, the I/I-water scenarios are more straightforward since there are no legal obstacles for running a WWTP with a higher/lower amount of I/I-water. However, there are goals that can be worked towards by executing measures to reduce the different types of I/I-water, which is positive, and vice versa for increased I/I-water. The reuse scenarios can contribute towards reaching different goals but have potential requirements and law obstacles.

5.1.7   Local environment quality & amenity

The literature study led to finding of the following information regarding the effects of combined sewer overflow on the local environment:

Combined sewer overflow water goes to ditches, lakes and other watercourses [49]. Over-flowed water can affect the smell, appearance and bathing water quality of the local environment around the combined sewer overflow points due to its content. A large part of the combined sewer overflow water is rainwater, but with wastewater and stormwater viruses and bacteria (microorganisms) are carried out to the local environment [50].

Pathogenic microorganisms and litter from runoff water degrade bathing water quality and pose health risks at bathing sites. Eutrophication due to high levels of nutrients is also a risk in water that is close to combined sewer overflow points. Untreated combined sewer overflow water can also cause bad odors and aesthetically degrade the local area [51].

These different consequences of combined sewer overflow have the worst impact when it occurs near bathing sites, beaches, fish reproduction areas or in central areas such as parks and canals [49].

The yearly amount of combined sewer overflow water for each scenario can be seen in Table 5.8 below. This together with the information from the literature study was used as the grading material.

Table 5.8: CSO water volumes for each scenario. Since the upstream reuse scenario lack CSO data, it is estimated that the emissions from CSOs are somewhere between the base case and –20% slow runoff I/I, in the interval between 2.9 and 3.5.

		CSO water (Mm^3)
Base case		3.5
+ 20% fast runoff I/I		18.4
- 20% fast runoff I/I		1.6
+ 20% slow runoff I/I		6.3
- 20% slow runoff I/I		2.9
Upstream reuse 70 l/p.d	Estimated to:	3.2
Downstream reuse 70 l/p.d		3.5

As seen in Table 5.8, the +20% fast runoff I/I scenario by far has a greater volume of water going to combined sewer overflow compared to all other scenarios. Increased slow runoff I/I also leads to an increase in combined sewer overflow but not to the same degree. Lower I/I-water and upstream reuse results in a lower amount of water going to combined sewer overflow, as can be seen in Figure 5.7.
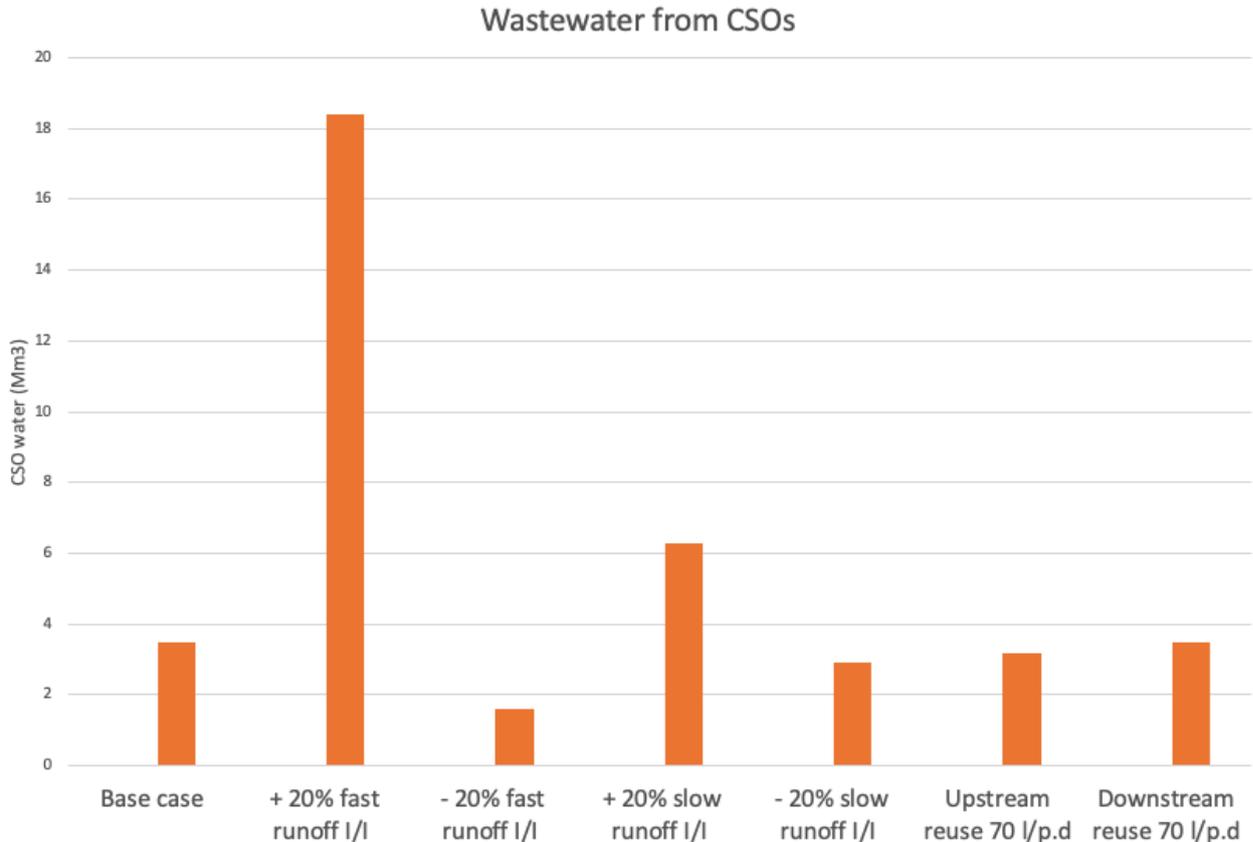
Figure 5.7: Total CSO water volumes for each scenario.

5.1.8   Working environment

The interviews with people working at Gryaab and Rya WWTP resulted in the following list of information:

At high flows:

- *Measures need to be taken more often to prevent breakdowns or other consequential errors in the process, workload increases.*

- *Additional tasks are added such as communication with other actors as well as start-up and operation of direct precipitation*

- *The on-call hours are increasing*

- *More time is spent at work, which can lead to lack of sleep/fatigue*

- *The stress level increases*

In Table 5.9 below, on-call hours for each scenario are presented.

Table 5.9: Yearly on-call hours for the personnel at Rya WWTP for each scenario.

	On-call hours/year
Base case	2 955
+ 20% fast runoff I/I	2 987
- 20% fast runoff I/I	2 723
+ 20% slow runoff I/I	3 167
- 20% slow runoff I/I	2 703
Upstream reuse 70 l/p.d	2 712
Downstream reuse 70 l/p.d	2 955

The on-call hours are increasing with more I/I-water coming to the system and decreases with less I/I-water, which can be seen in Figure 5.8. Upstream water reuse also lowers the wastewater inflow to Rya WWTP and therefore also results in less on-call hours.
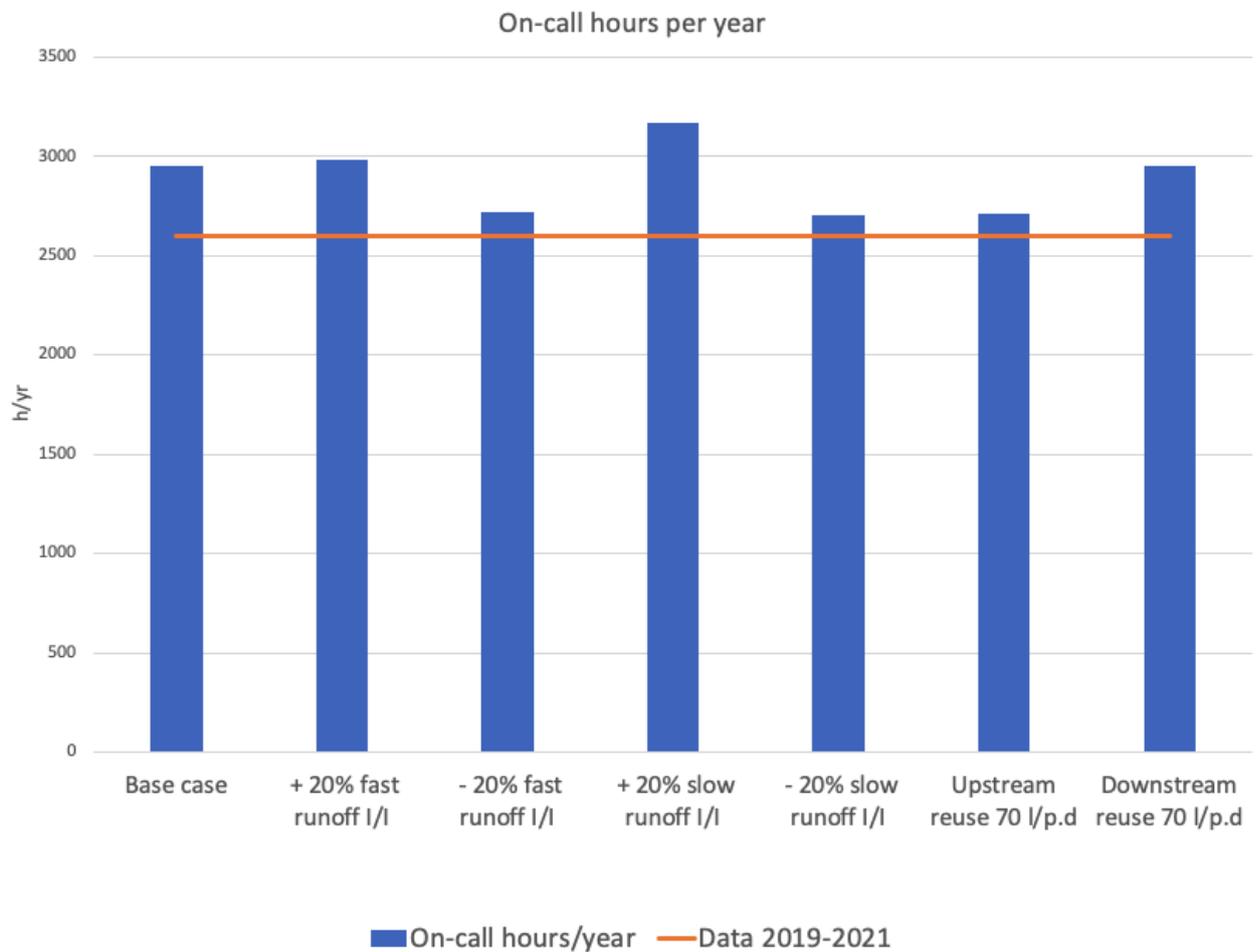
Figure 5.8: The on-call hours for each scenario and the average on-call hours for the years 2019-2021.

In Figure 5.8 it can be seen from the orange line that the on-call hours are higher during a wet year even if the I/I is reduced compared to data from 2019 to 2021.

5.1.9 Safety/risks

From the interviews conducted the following information was gathered regarding the difference in safety/risks when wastewater inflow is increased or decreased to the WWTP:

- *In case of high flows, equipment goes closer to its maximum capacity or reaches maximum capacity, which increases the wear on the equipment and increases the risk of breakdown.*

- *There is a greater risk for breakdown if the wastewater inflow is very high and, for example, flows over hatches. At ex. pump failure or if waste gets stuck in a screw press, the emergency services need to pull in and repair. There are always risks when working with machines under stress, e.g. for crush injuries.*

- *Being on-call due to high flows can lead to fatigue and stress that can affect focus negatively, which can potentially affect safety when performing tasks.*

In Figure 5.9 and 5.10 cumulative flow diagrams show the flow distribution over a year for the scenarios.
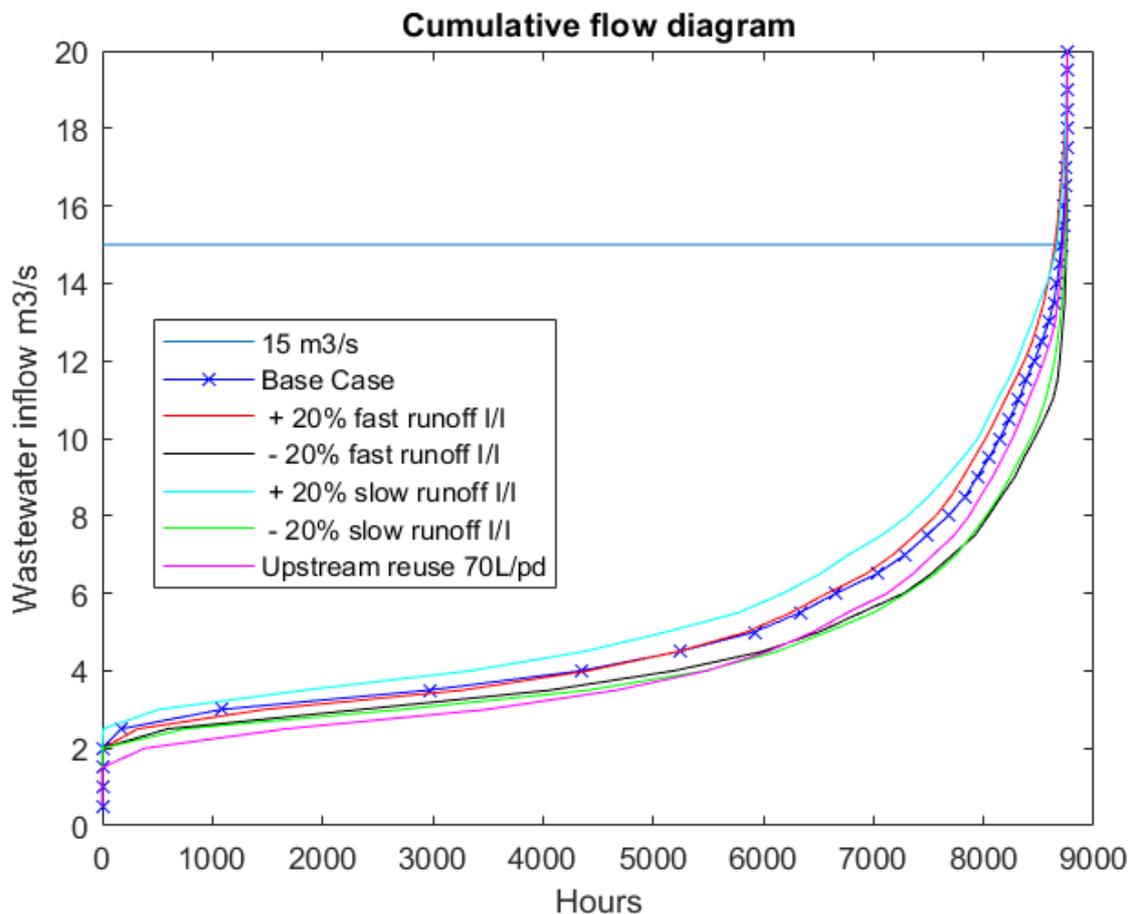
Figure 5.9: The distribution of wastewater inflow as a cumulative curve that makes it possible to see how many hours are spent above or under certain flows.
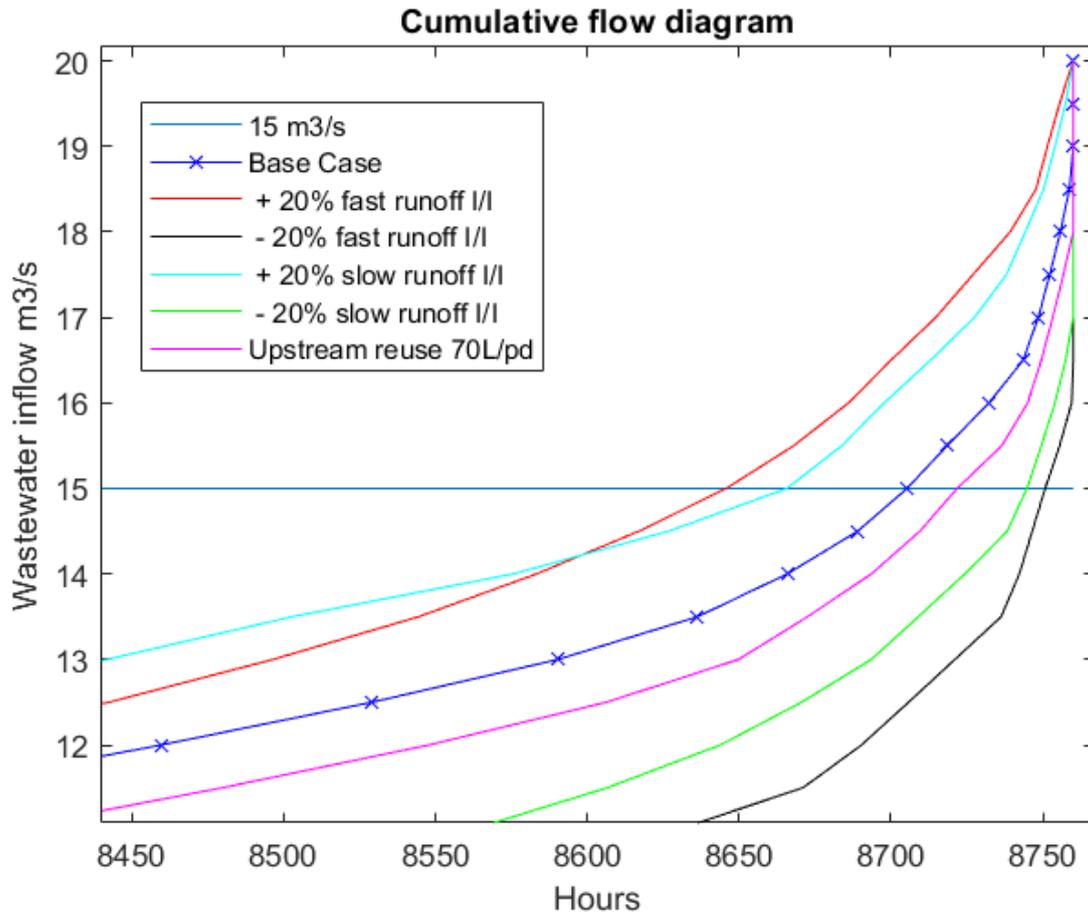
Figure 5.10: The distribution of wastewater inflow as a cumulative curve for the flows in the higher end of the scenarios that were in the interval of 11 to 20 m^3/s. This makes it possible to see how many hours are spent above or under flows within this interval.

From the cumulative flow diagram it is possible to analyze the amount of time at different flow intervals. For example, above 15 m^3/s the scenario $+20\%$ fast runoff I/I is for longer time compared to all the other scenarios. What can also be seen is that $+20\%$ slow runoff I/I has a higher flow over the year for flows up to around 14.5 m^3/s. It is also possible to see that the scenarios with reduced I/I and the upstream water the flow is over the year lower because they have more hours of the year for lower flows compared to the base case and increased I/I water. Downstream reuse has the same cumulative flow as the base case.

5.1.10   Operating costs

Calculated differences in operating costs (in millions of kr), which includes the used electricity and direct precipitation chemicals at the WWTP are shown in Table 5.10 below. These are in comparison to the base case.

Table 5.10: Differences in operating costs for electricity and precipitation chemicals for each scenario compared to the base case.

	Electricity (Mkr)	DF Polymer (Mkr)	DF PAC (Mkr)	Total (Mkr)
Base case	0.00	0.00	0.00	0.00
+ 20% fast runoff I/I	0.17	0.02	0.41	0.60
- 20% fast runoff I/I	-0.74	-0.05	-1.18	-1.96
+ 20% slow runoff I/I	0.68	0.04	1.00	1.71
- 20% slow runoff I/I	-0.77	-0.04	-1.07	-1.89
Upstream reuse 70 l/p.d	-0.67	-0.02	-0.53	-1.22
Downstream reuse 70 l/p.d	0.00	0.00	0.00	0.00

Since the calculation of operating costs only included the costs that were predicted to change noticeably with increased/decreased wastewater inflow, the results shown in Table 5.10 are changes relative to the base case. It was found that the increased wastewater inflow from I/I caused a rise in operating costs, where decreased I/I-water resulted in lower operating costs. Upstream reuse also lowered operating costs but not as much as a reduction in I/I-water. This can be seen in Figure 5.11 as well as the fact that increased fast runoff I/I did not result in as high of a rise in costs as increased slow runoff I/I.
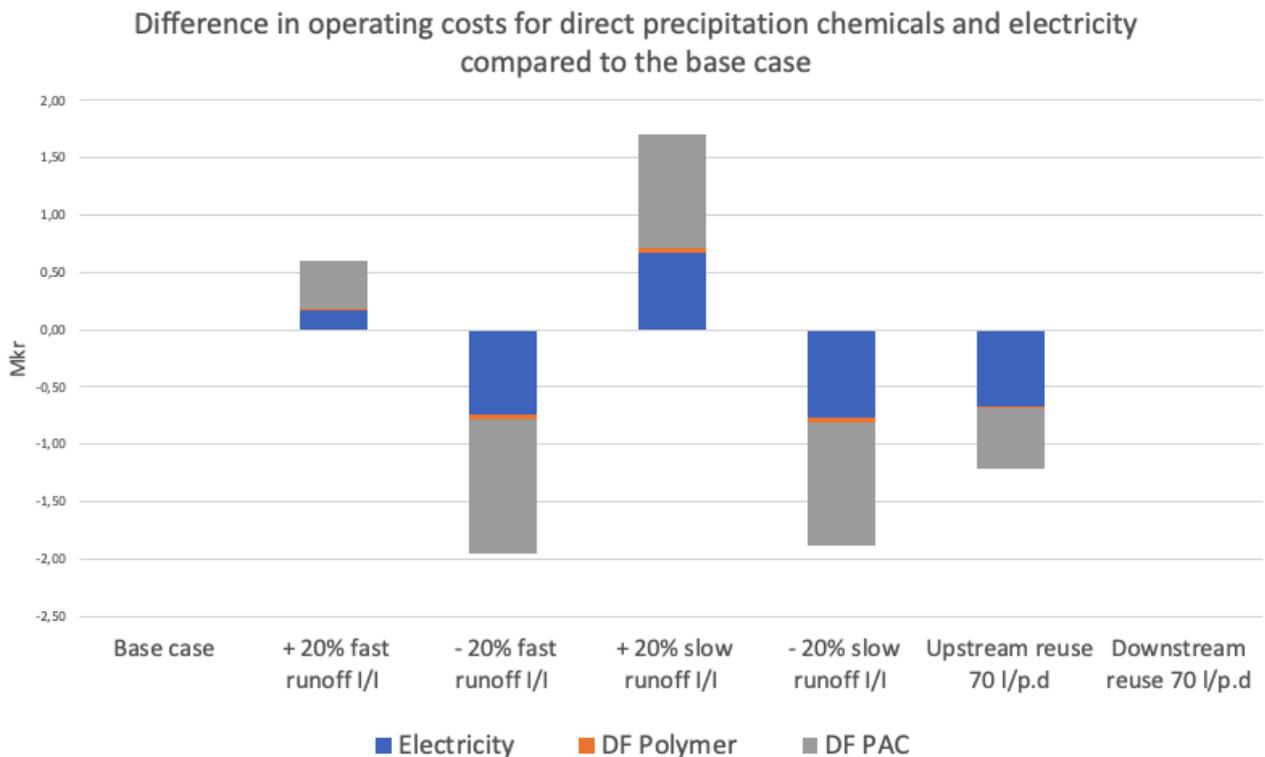
Figure 5.11: The difference between the operating costs for the base case and the other scenarios and cost contributions from electricity, polymer and PAC.

5.1.11 Vulnerability

The literature study resulted in the following information regarding chemical vulnerability in Sweden:

Right now, there is no shortage of chemicals in Sweden, but because we have an import dependence to supply ourselves with water treatment chemicals, for example a pandemic, war, the economic situation, trade and changes in production can cause changes in the supply of chemicals to Sweden. As there is no stock of water treatment chemicals within the country, it creates a vulnerability [52], [53].

In the event of a shortage of chemicals, precipitation chemicals in particular, drinking water production is the first priority, which means that treatment plants would have to discharge untreated or partially treated water, which in the event of a long-term shortage can have a major negative environmental impact on the recipient. Therefore, we need to be prepared for a possible shortage situation and take measures to reduce the effects of a shortage of chemicals [54].

Switching from using chloride-based precipitating chemicals is one way to reduce vulnerability [52], [54]. Another way to reduce the effects of a deficiency is to take measures to reduce the use of chemicals in the treatment process.

The resulting yearly use of direct precipitation chemicals for each scenario can be seen in Table 5.11 below.

Table 5.11: Yearly amounts of Polyaluminum Chloride (PAC) and polymer for direct precipitation.

	PAC (tonnes)	Polymer (tonnes)
Base case	1 232	4.6
+ 20% fast runoff I/I	1 408	5.3
- 20% fast runoff I/I	734	2.7
+ 20% slow runoff I/I	1 654	6.2
- 20% slow runoff I/I	777	2.9
Upstream reuse 70 l/p.d	1 008	3.8
Downstream reuse 70 l/p.d	1 232	4.6

As shown in Table 5.11, the mass consumption of PAC is larger than the use of polymer in the direct precipitation. In the Table 5.11 and in Figure 5.12 more PAC is consumed for increased I/I compared to the base case and the opposite effect if I/I was decreased.

The consumption of polymer for direct precipitation followed the same pattern for the scenarios as the PAC consumption that can be seen comparing Figure 5.12 and Figure 5.13.
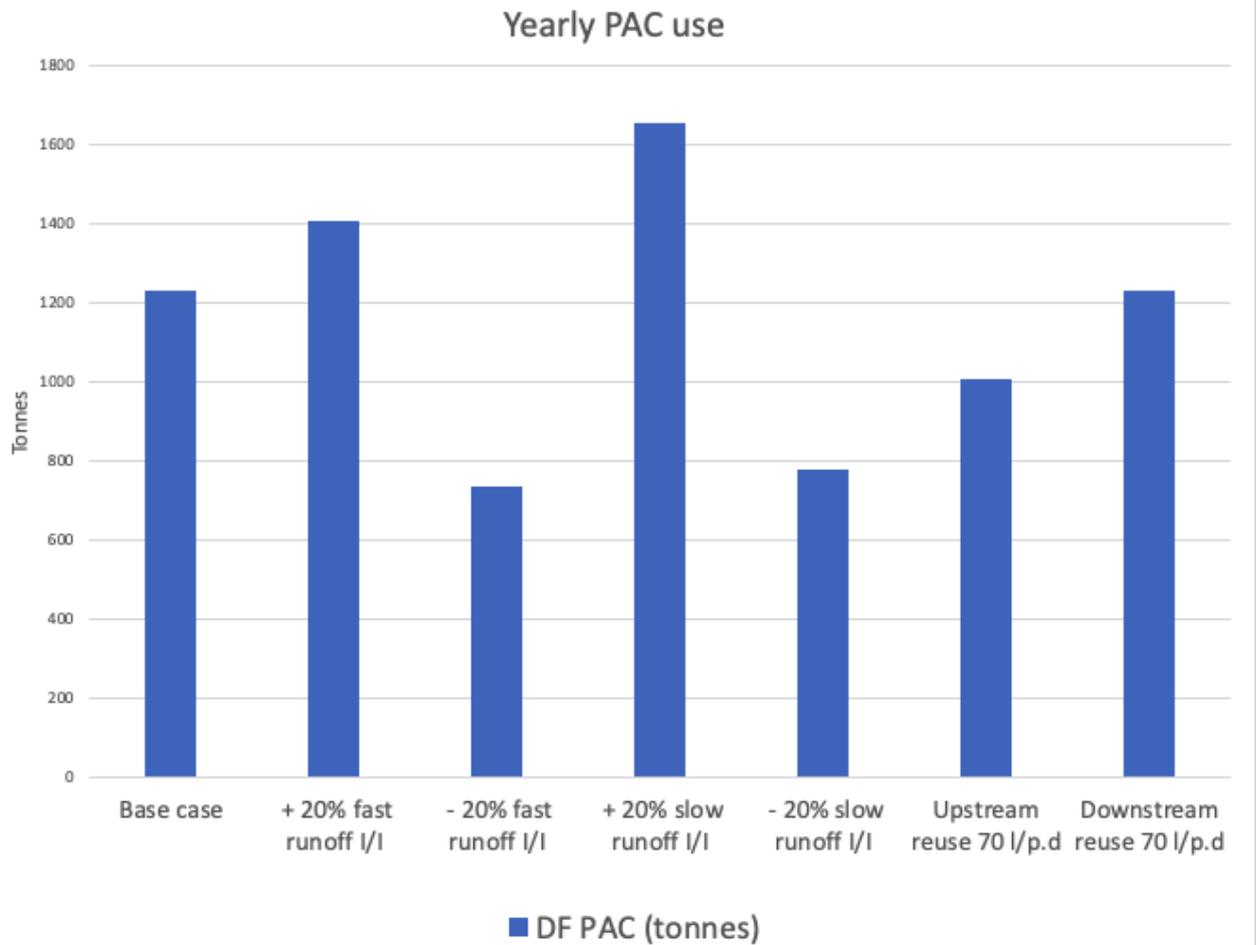
Figure 5.12: Yearly amounts of PAC used for direct precipitation.
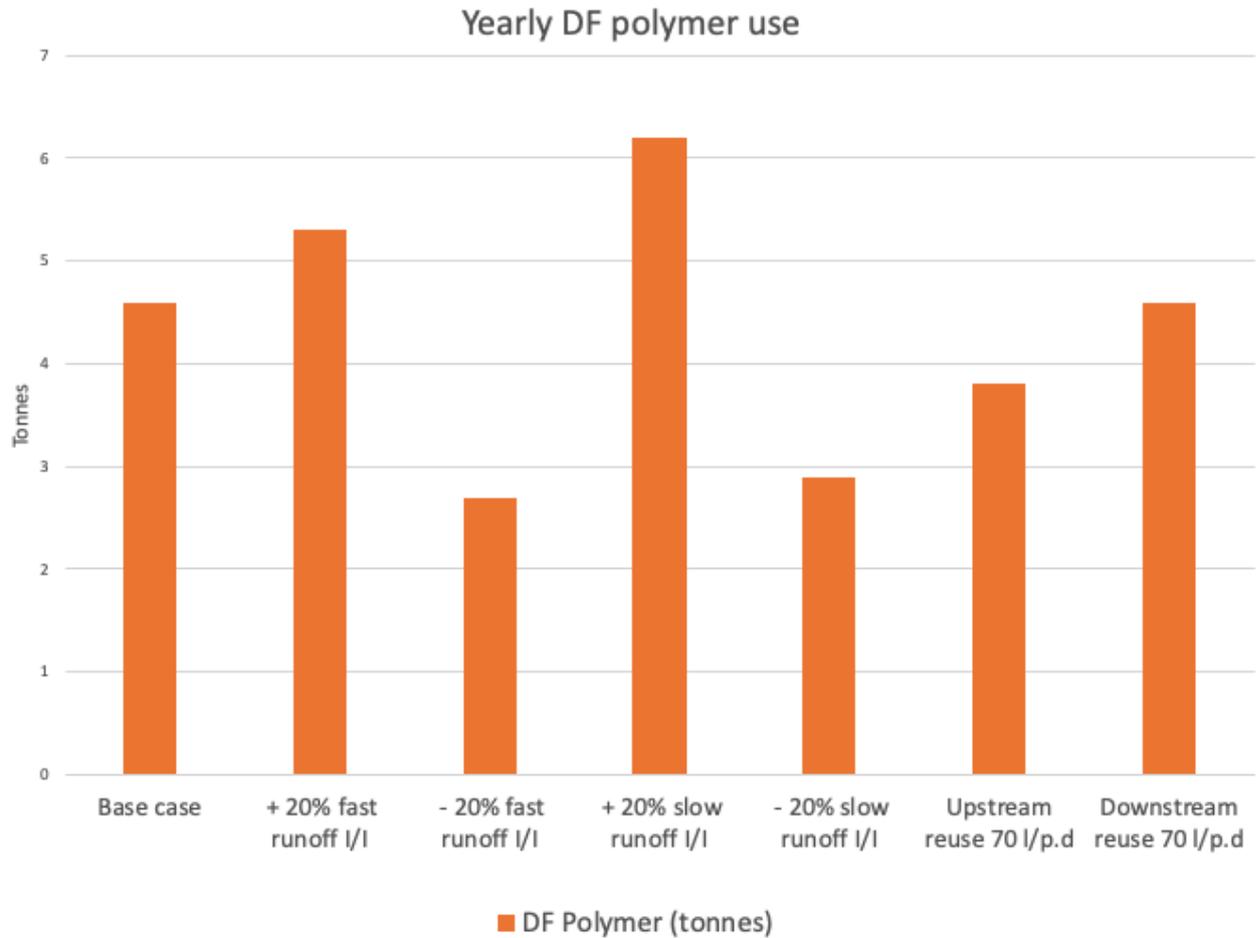
Figure 5.13: Yearly amounts of polymer used for direct precipitation.

5.1.12   Flexibility

Based on the capacities of different treatment steps at Rya WWTP the WWTP have limited capacity to handle more incoming water if the flow is already at maximum capacity for some of the treatment steps. Direct precipitation and only using mechanical treatment are used when the capacity of the usually used full treatment that includes both chemical and biological treatment is at maximum capacity. So, if these two steps are already used it indicates that the WWTP has no capacity left to use if the flow was to increase further. From Table 5.12 it is possible to see that +20% slow runoff I/I would utilize or partly utilize these steps the most out of all scenarios at 15.3% of the year. It can be seen in both Table 5.12 and Figure 5.14 that decreased wastewater inflow to Rya WWTP for scenarios that decreased I/I and upstream water reuse lowers the use of direct precipitation and only mechanical treatment compared to the base case.

Table 5.12: Percentage of the year where direct precipitation, mechanical treatment and overflow occur.

	Direct precipitation	Mechanical treatment	Overflow	Total %
Base case	7.5	3.5	0.4	11.4
+ 20% fast runoff I/I	7.8	4.0	1.0	12.8
- 20% fast runoff I/I	6.6	0.9	0.0	7.6
+ 20% slow runoff I/I	9.7	4.8	0.8	15.3
- 20% slow runoff I/I	6.3	1.4	0.1	7.8
Upstream reuse 70 l/p.d	6.8	2.6	0.2	9.6
Downstream reuse 70 l/p.d	7.5	3.5	0.4	11.4
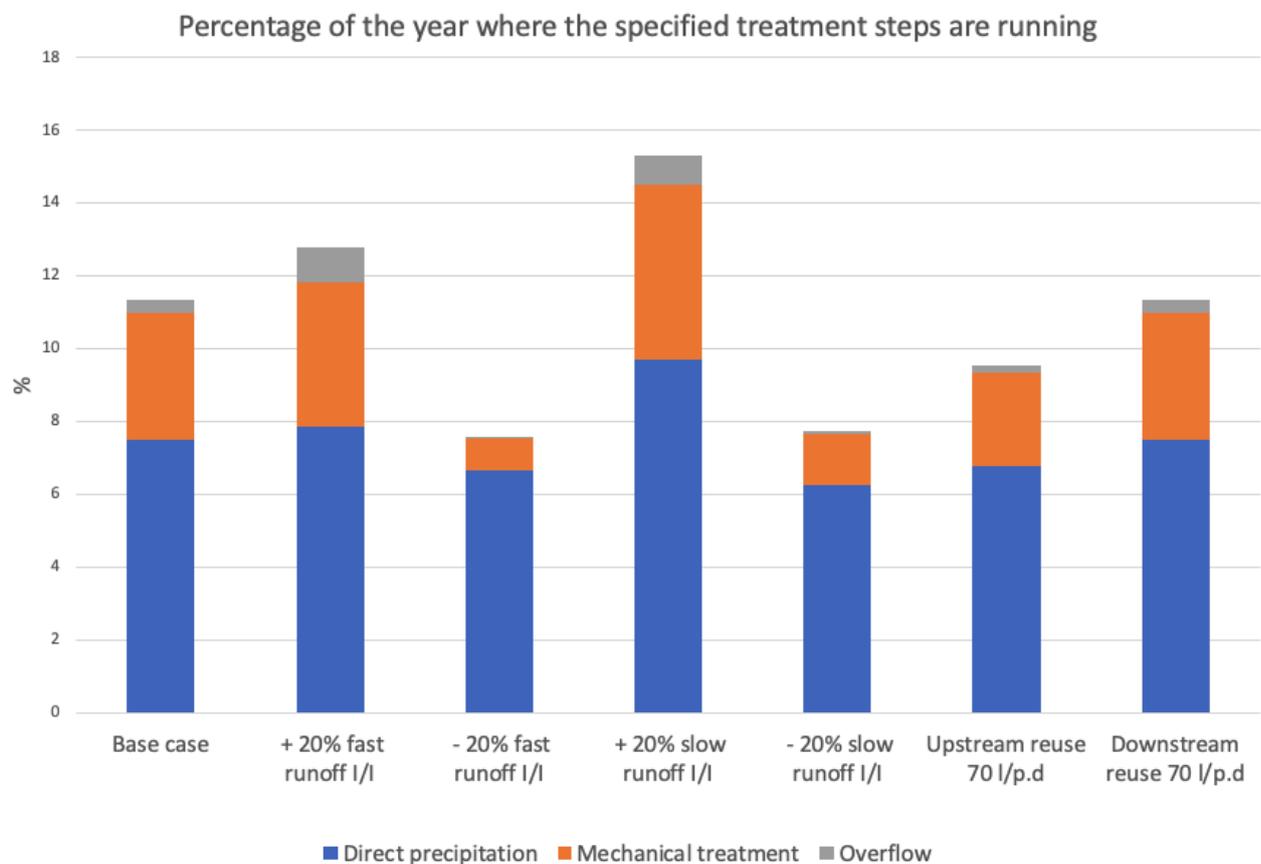
Figure 5.14: The percentage of time that the WWTP utilizes partial treatment meaning it does not utilize the biological and chemical treatments for all the wastewater inflow.

5.2   Results from grading

In Table 5.13 the grades for all criteria and scenarios are presented.

Table 5.13: Grades for all criteria and scenarios. The decimals on the Effluent quality criterion are from the grades of the phosphorus, nitrogen and BOD$_7$ under-criteria since the final grade for Effluent quality is the mean value of those three.

	Base case	+ 20% fast runoff I/I	- 20% slow runoff I/I	+ 20% slow runoff I/I	- 20% slow runoff I/I	Upstream reuse 70 l/p.d	Downstream reuse 70 l/p.d
Effluent Quality	2.6	1	3.3	1.7	3	3	2.6
Heavy metal content in sludge	2	2	3	1	3	2	2
Climate impact	1	1	2	1	2	2	1
Water use	2	2	2	2	2	5	5
Energy use	2	2	3	1	3	3	2
Sphere of action/ political support	3	1	3	1	4	2	2
Local environment quality & amenity	2	1	3	2	2	2	2
Working environment	3	2	4	1	4	4	3
Safety/risks	2	1	4	1	4	3	2
Operating costs	3	2	4	1	4	4	3
Vulnerability	2	1	4	1	4	3	2
Flexibility	3	2	5	1	5	4	3

The grade for *Effluent quality* in Table 5.13 is the mean value of the grades for total phosphorus, total nitrogen and BOD$_7$ individually that are the sub criteria for the *Effluent quality* criterion. The grades show that all the scenarios that reduces the wastewater inflow to Rya WWTP compared to the base case resulted in a grade ≥ 3, that is a future acceptable level of effluent quality. The other scenarios that did not result in a reduction of the wastewater inflow to Rya WWTP compared to the base case, including the base case, were not considered to reach a future acceptable of effluent quality resulting in grades less than 3.

The grades set by the panel on the *Heavy metal content in sludge* criterion show that reducing I/I water results in future acceptable levels of Cd/P in sludge. Reuse of water and increased fast runoff did not change the outcome compared to the base case however, increased slow runoff I/I water resulted in a lower grade compared to base case.

In the *Climate impact* criterion, no scenario achieved a future acceptable level. However, the scenarios reducing I/I and upstream water reuse got a grade 2 indicating that they contributed less to greenhouse gas emissions compared to the rest of the scenarios that got a grade 1.

Scenarios that did not have water reuse did not reduce drinking water use resulting in a grade 2 for *Water use* indicating that it was not acceptable in the future. Scenarios downstream reuse and upstream reuse reduction of 70 liters per person and day was considered close to optimal, thus they achieved grade 5.

The grades on the *Energy use* criterion show that all scenarios that reduced I/I and upstream reuse reached future acceptable levels of energy use resulting in grade 3. All the other scenarios were graded below future acceptable levels. This means that a reduction of 0.9 GWh or more would be acceptable for the future while no reduction or increased energy use is unacceptable.

The *Sphere of action/political support* criterion was graded lowest for scenarios that increased I/I because they counteract reaching the goals presented in the basis for grading. It was also graded below future acceptable level for the water reuse scenarios because of the potential requirement obstacles. The scenarios that decreased the I/I reached a future acceptable level and –20% slow runoff I/I got a grade 4 which is higher than –20% fast run off I/I but based on the information in the criterion this seems to be a deviation.

The grades set by the panel for the criterion *Local environment quality & amenity* show that only the scenario with a reduction of fast runoff I/I by 20% reached a future acceptable level (grade 3). The rest were graded below a future acceptable level, and +20% fast runoff I/I was graded 1 which was the lowest due to it having significantly more CSO compared to all the other scenarios that can be seen in Figure 5.7.

In the *Working environment* criterion, the grades set by the panel shows that the scenarios reducing I/I and upstream water reuse had a future acceptable level while increased I/I flow results in a working environment below a future acceptable level. The increased slow runoff I/I was considered significantly below future acceptable level hence the grade1 since more of the I/I reached the WWTP compared to fast runoff I/I that offloaded more as CSO. The base case resulted in a future acceptable level since the present working environment was considered on an acceptable level and that it would also be acceptable in the future. Downstream reuse was graded the same as base case since it has the same wastewater inflow and reuse was not found to add any additional effects on the working environment.

The grades for the *Safety/risks* criterion show that the high flows during the base case scenario that is a wet year was considered to frequent and therefore not acceptable in the future. When I/I was increased, it was predicted to generate additional concerns over

safety and risks these where from the equipment/machinery working for more time closer to max capacity that could wear it down quicker and cause potential break downs. Break downs or failures can be stressful to fix knowing that the longer it takes to correct the more wastewater goes untreated. The decreased wastewater inflow by upstream reuse was enough to reach a future acceptable level of risks and safety and reducing I/I was considered even better resulting in beyond future acceptable levels.

For the *Operating cost* criterion, the increased cost due to the increased wastewater inflow from fast runoff I/I to the WWTP the costs of additional electricity and direct precipitation chemical consumption put it below future acceptable level but the increased cost from +20% slow runoff I/I was considered worse. The slow runoff I/I was considered worse because less of the I/I for the scenario is offloaded as CSO compared to the fast runoff and therefore increase the consumption of electricity and dire precipitation chemicals more. All the scenarios that decreased I/I and upstream water reuse was considered better than a future acceptable level because of the reduced costs compared to the base case. The operating costs for a wet year like the base case as the WWTP is today considered to also be on a future acceptable level. It also showed that the effectiveness of lowering operating costs was similar for reducing both fast and slow runoff I/I.

For the *Vulnerability* criterion, decreased I/I and upstream reuse reduced PAC and polymer consumption to a level that the vulnerability of having a lack of these chemicals was seen as acceptable in the future with decreased I/I reducing to a more than acceptable. Downstream reuse that results is unchanged compared to the base case was considered unacceptable while increased amounts chemical consumption because of increased I/I was considered less acceptable compared to the base case.

The grades for the *Flexibility* criterion show that the capacity to open for an increased wastewater inflow to the WWTP was considered close to optimal for scenarios where I/I water was reduced, and better than a future acceptable level for upstream reuse. The reason for upstream achieving is that is reduced less of the flows above 8.5 m^3/s down below 8.5 m^3/s compared to decreased I/I. The base case and downstream reuse were considered on a future acceptable level meaning that the current capacity for partial treatment is acceptable for a wet year in the future. Increased I/I-water resulted in grades below future acceptable levels. However, increased slow runoff I/I was thought to be the worst because it did not offload as much of the I/I as CSOs.

The results after grading can be seen in Figure 5.15 as the average grade each scenario was given based on their non-weighted grades for all criteria.
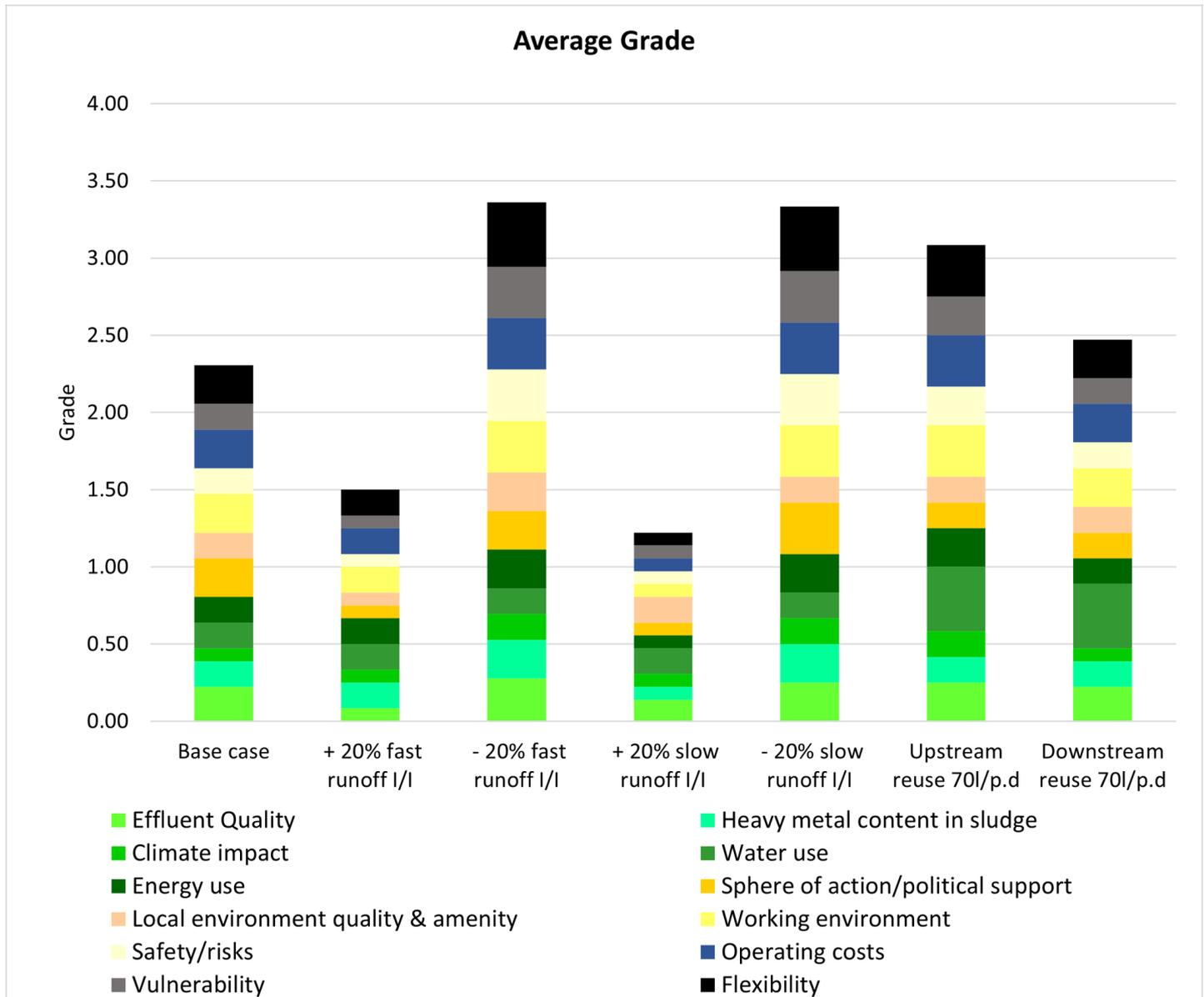
Figure 5.15: Average grades for each scenario before weighting.

On average, the –20% fast runoff I/I got the highest grades along with –20% slow runoff I/I. The increase I/I in +20% fast runoff I/I and +20 slow runoff I/I got the lowest grade on average with +20% slow runoff I/I receiving the lowest grades of all scenarios on average. The scenarios that on average got above the future acceptable level was –20% slow runoff I/I, -20% fast runoff I/I and upstream reuse.

5.3 Results from weighting

In this section, the results from the weighting session will be presented.

5.3.1 Initial weighting

The first initial weighting, that was done without comparing the relative value of a grading step to reference values, resulted in the weight distribution in Table 5.14. The most weight was distributed to the criteria *Effluent quality*, *Water use* and *Safety/risks*.

Table 5.14: The weights distributed to each criterion that were limited to 1-20 and the resulting weight distribution in percentages.

	Weight	Weight %
Effluent quality	20	34%
Heavy metal content in sludge	5	8%
Climate impact	2	3%
Water use	6	10%
Energy use	2	3%
Sphere of action/political support	3	5%
Local environment quality & amenity	5	8%
Working environment	3	5%
Safety/risks	6	10%
Operating costs	2	3%
Vulnerability	2	3%
Flexibility	3	5%

There was a clear consensus within the panel that *Effluent quality* should hold a high weight relative to the other criteria and therefore got the maximum weight of 20. For *Heavy metal content in sludge*, the majority of the panel members thought that it should have ¼ the weight of *Effluent quality* and was compromised as such resulting in a weight of 5.

Climate impact, *Energy use*, *Operating costs* and *Vulnerability* were considered to have been impacted less by the differences between the scenarios. The panel indicated that the differences in grades was therefore not as significant relative to differences in the other criteria hence the weight of 2.

For *Water use* there was a clear mix of opinions ranging from a weight of 1-10 and so a weight of 6 was a result of compromising. The reason was that the once arguing for a high weight argued that the decrease of drinking water was significant while the once arguing for a low grade considered other what was measured in other criteria to be more important than reducing drinking water consumption.

For *Sphere of action/political support* it was pointed out that sometimes the focus on reaching goals could be of higher consideration for Gryaab than the actual reduction of emissions connected to them as an argument for a high weight. However, this opinion was not shared for all the panel members that thought it should have less influence and that the effects of the criterion was difficult to grasp leading to a weight of 3.

The *Local environment quality & amenity* was compared to the *Effluent quality*, and it was suggested that it should hold similar value to the sub criterion of phosphorus, nitrogen and BOD$_7$ emissions. There was consensus withing the panel that the effects of CSOs experienced by humans such as smell should hold a weight of 5 giving it similar influence as to one of the three emissions considered in *Effluent quality*.

The *Working environment* and *Safety/risks* criteria were compared during weighting. It was argued that the consequences of from errors in safety of people always is of high priority at the WWTP and that the potential physical harm should put *Safety/risks* at a higher weight compared to *Working environment*. There was also emphasis from the panel that their opinion was that the working environment at the WWTP is good and that they already have sufficient guidelines for high wastewater inflow situations. The discussion led to a weight of 3 for *Working environment* and 6 for *Safety/risks* with the discrepancy mainly because of the consequences of safety failures being of higher priority than working environment.

Since *Vulnerability* considered the precipitation chemical consumption it was brought up that it, by previous measurements, had been concluded that it was possible to stay under the environmental permit limit for phosphorus, nitrogen and BOD$_7$ even without direct precipitation and therefore the panel decided that *Vulnerability* should hold a low weight, hence it was weighted with 2.

Flexibility was compared to *Vulnerability* and considered more important since maintenance of equipment or treatment step would require the WWTP to be able to run at limited capacity. Running at limited capacity for the increased I/I scenarios was considered difficult and therefore *Flexibility* was weighted higher than *Vulnerability* and got a weight of 3.

5.3.2 Weighting with cost quotas

After initial weighting, another weighting was done in where the panel was split into two groups where the cost quotas were used as guidance for weighting. The reason that all criteria did not have a cost quota is because some did not have indicators, such as the criteria *Sphere of action political support* and *Safety/risks*. In Table 5.15 cost quotas can for group 1, 2 and the combined groups can be seen. The cost quotas are calculated as stated in Equation (4.12) Weighting and the resulting cost quotas for the weighting done by group 1 and 2 separately and together is presented in Table 5.16 .

Table 5.15: Calculated cost quotas for groups 1 and two separately and together as well as the reference values to compare with.

	Group 1	Group 2	Group 1&2	Unit	Reference values
Effluent quality - Phosphorus	281441	281441	281441	kr/tonnes P	200 kr/kg P [42]
Effluent quality - Nitrogen	47336.2	23668.1	35502	kr/tonnes N	50 - 210 kr/kg [55], 40-100 kr/kg [56], 200 kr/kg [57]
Effluent quality - BOD_7	8670.72	8670.72	8671	kr/tonnes BOD_7	10-20 kr/kg BOD_7 [42]
Heavy metal content in sludge	668925	668925	668925	kr/% failed batches	10 000 kr/tonne sludge [58]
Climate impact	3364.44	2523.33	2944	kr/tonnes CO_2 eq.	7000 kr/tonne [59] 8700 kr/tonne [58], 1471 kr/kg [60]
Water use	583980	243325	364987	kr/l drinking water per p.d	0.03 kr/l [61]
Energy use	1261667	1892500	1892500	kr/GWh	4 kr/kWh [58], 0.2 kr/kWh [60]
Sphere of action /political support	-	-	-	-	14 Mkr/grade step [58], 0.5 Mkr/grade step [60]
Local environment quality & amenity	1351786	405536	811071	kr/Mm^3	
Working environment	7678.52	11517.8	7679	kr/h	27 Mkr/grade step [58], 4 Mkr/grade step [60]
Safety/risks	-	-	-	-	27 Mkr/grade step [58], 4 Mkr/grade step [60]
Operating costs	1	1	1	kr	34 Mkr/grade step [58], 27 Mkr/grade step [60]
Vulnerability	8862.44	4431.22	6647	kr/ton PAC +DF Polymer	13000 kr/tonne [58], 2566 kr/tonne [60]
Flexibility	1224127	918095	1071111	kr/% time extra treatment step is running	14 Mkr/grade step [58], 3 Mkr/grade step [60]

Since cost quotas are merely used as a guidance for the weighting, it is not necessary that the cost quotas for the scenarios are the same as the reference values. However, the groups aimed to get the cost quotas in the same magnitude as the reference values. The criteria with reference values from other studies based on millions of kr per grade step the criteria for those studies did not have the same definition as for this study, which the panel was informed of. The criteria that did not have a cost quota, or that did not have reference values, were weighted without guidance of the cost quota. The weighting with cost quotas in group 1 and 2 resulted in the weights presented in the two middle columns of Table 5.16 . The weight distribution between the criteria from the subsequent, combined group weighting can be seen to the right in Table 5.16 .

Table 5.16: Percental weight distributions for group 1 and 2, respectively and together. The weight distribution for subcategories of Effluent quality is summarized. The reason why all percentages do not add up to 100 percent is that decimals have been removed.

	Group 1 weight %	Group 2 weight %	Group 1&2 weight %
Effluent quality	32	40	36
Heavy metal content in sludge	3.2	5.3	4.2
Climate impact	3.2	4.0	3.6
Water use	19	13	16
Energy use	1.6	4.0	3.1
Sphere of action/political support	4.8	4.0	4.7
Local environment quality & amenity	16	8.0	12
Working environment	1.6	4.0	2.1
Safety/risks	9.7	8.0	9.3
Operating costs	1.6	2.7	2.1
Vulnerability	3.2	2.7	3.1
Flexibility	3.2	4.0	3.6

For *Effluent quality* the weight distribution remained like the initial weighting, and this also resulted in cost quotas that the groups considered on a similar level as the reference values. There was a difference in that group 1 considered nitrogen to be more impactful distributing more weight to it compared to phosphorus and BOD$_7$.

Utilizing the cost quotas compared to the initial weighting the *Heavy metal content in sludge* was reduced because the cost quota that was seen as appropriate resulted in a lower weight distribution compared to the initial weighting. The *Water use* cost quota that was considered appropriate based on the reference value and knowledge from the panel members of drinking water costs increased the weight distribution of *Water use* compared to the initial weighting. The valuation of *Local environment quality & amenity* was higher in group 1 than in group 2 where group 1 thought that around 1.3 SEK per m^3 of untreated wastewater was appropriate while group 2 relied mainly on the same as for initial weighting.

For *Climate impact, Energy use, Sphere of action/political support, Working environment, Safety/risks, Operating costs, Vulnerability* and *Flexibility* the discussion and resulting weight did not deviate noticeably from the initial weighting.

Overall, the final weights set by the whole panel with utilizing the guidance of cost quotas was all within the span of the weights set by the two groups separately. The weight distribution resulting from the weighting process was then multiplied with the grades set for the scenarios to get the weighted results, an example of this can be seen in Table 5.17 where the grades, weights and weighted grades for the base case are presented.

Table 5.17: Conversion of grades for the base case with the weight distribution from the combined groups utilizing cost quotas into weighted results. The weighted result for all criteria for the base case is summarized in the bottom right as the total weighted result.

Base case	Grade	Weight (%)	Weighted result
Effluent quality - Phosphorus	3	10.4	0.31
Effluent quality - Nitrogen	2	15.5	0.31
Effluent quality - BOD$_7$	3	10.4	0.31
Heavy metal content in sludge	2	4.1	0.08
Climate impact	1	3.6	0.04
Water use	2	15.5	0.31
Energy use	2	3.1	0.06
Sphere of action/political support	3	4.7	0.14
Local environment quality & amenity	2	12.4	0.25
Working environment	3	2.1	0.06
Safety/risks	2	9.3	0.19
Operating costs	3	2.1	0.06
Vulnerability	2	3.1	0.06
Flexibility	3	3.6	0.11
Total		100.0	2.30

The weighted results calculated as in Table 5.17 for all the scenarios can be seen in Figure 5.16.
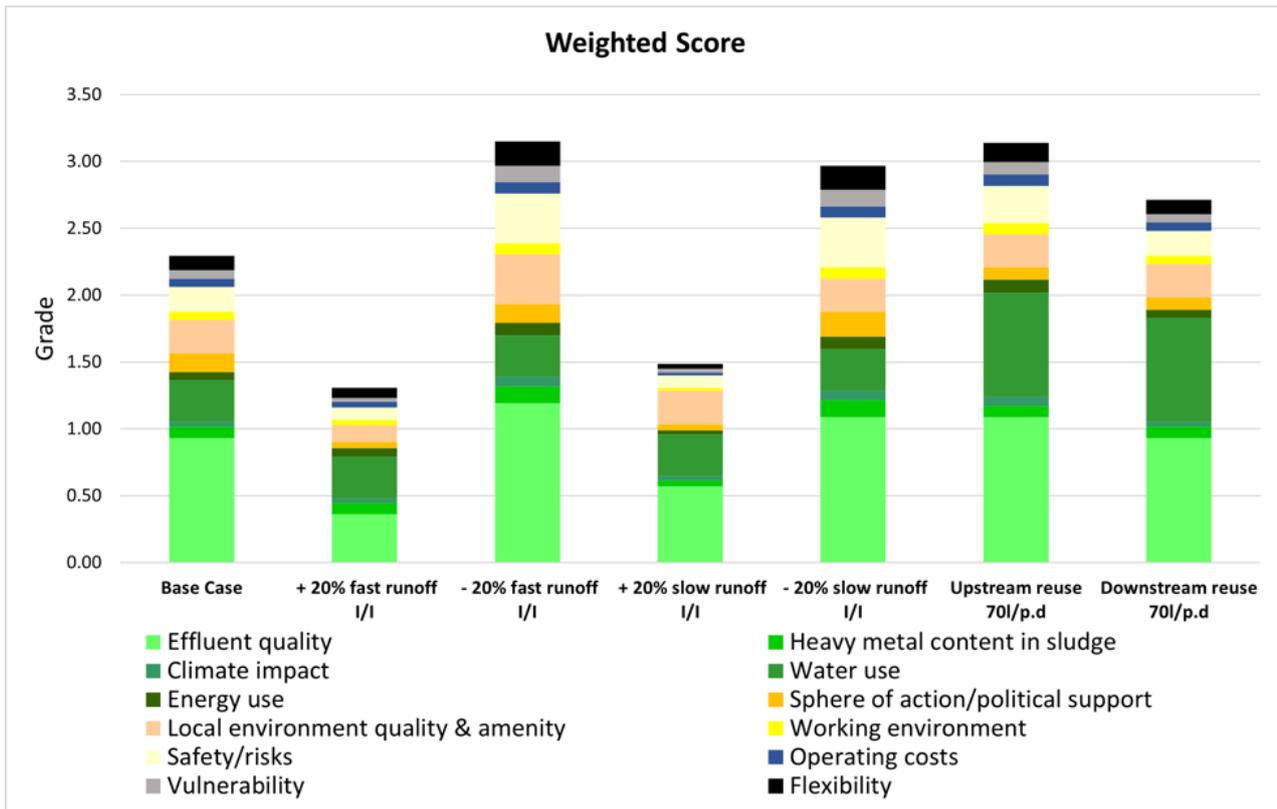
Figure 5.16: The results after weighting using the final weight distribution of the panel and the corresponding grades for each scenario on the y-axis and on the x axis the scenarios. The influence of each criterion can be seen from the colors in the bars.

A reduction of fast runoff I/I resulted in the highest score followed by upstream water reuse. Both reduction if fast runoff I/I and upstream water reuse reached a score that was above a future acceptable level. The base case, reduction of slow runoff I/I and downstream water reuse scored between future acceptable level and worse than future acceptable level. Both scenarios with increased fast and slow runoff I/I water scored lower than worse than acceptable level.

6

Sensitivity Analyses

In this chapter, five different sensitivity analyses for the results of the study will be presented.

6.1   Group weighting

The weighed scores for group 1, group 2 and group 1 & 2 together follow the same pattern for all scenarios except for upstream reuse and –20% fast runoff I/I. Weighting by group 1 resulted in that upstream reuse got the highest weighted score while the weighting by group 2 resulted in that –20% fast runoff I/I got the highest weighted score, which can be seen in Figure 6.1. The reason for the difference is that group 1 allocated more weight to water use compared to group 2. Even though both groups had distributed the second most weight to water use that can be seen in Table 6.1.
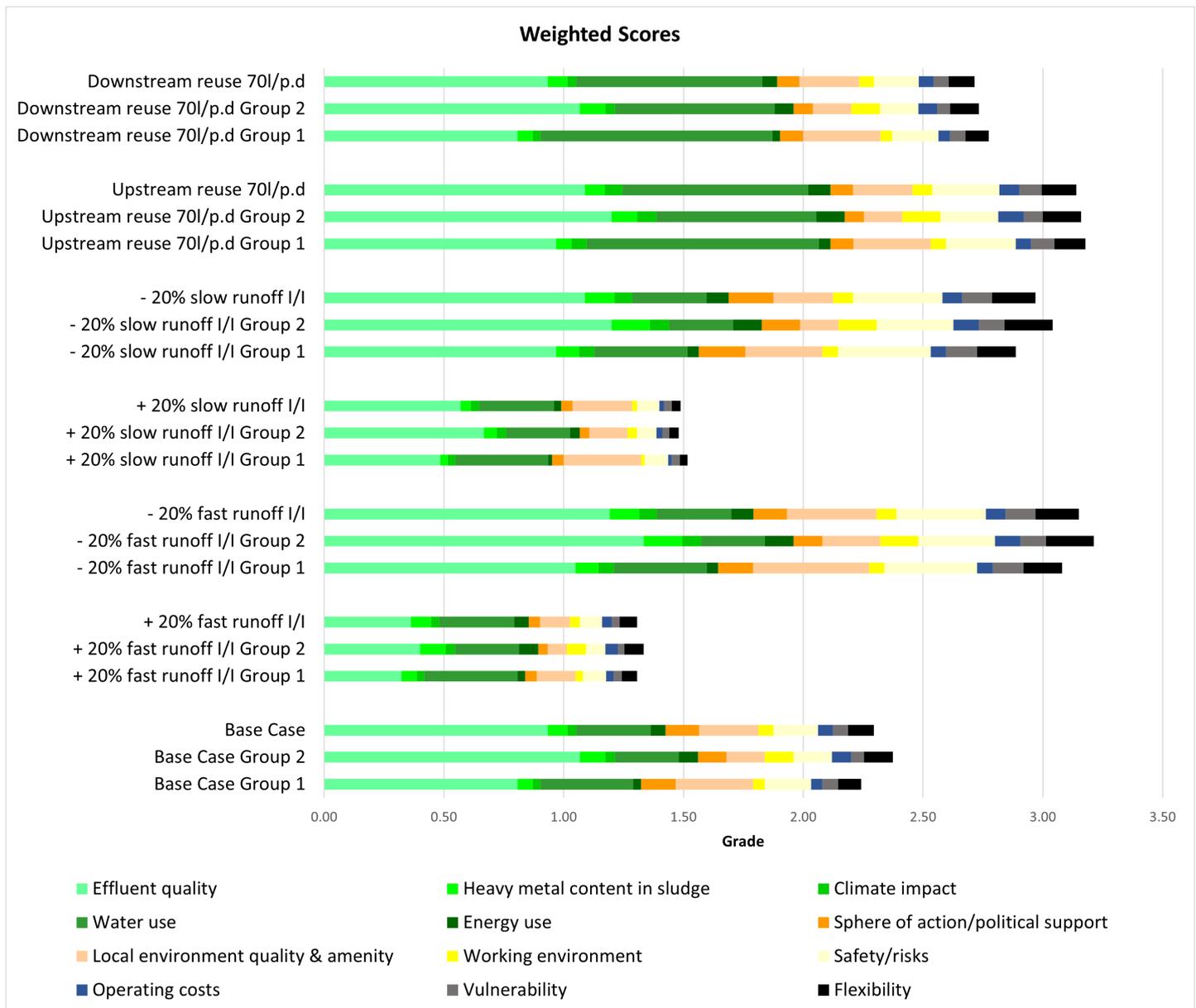
Figure 6.1: The weighted scores for the scenarios calculated for weighting done by group 1, group 2 and group 1 & 2 together.

The distribution of weight differs between the groups. The main differences in the weight distribution were for *Effluent quality* with an 8 weight % difference between group 1 and 2, *Water use* with a 6 weight % difference, and *Local environment quality & amenity* 8% as can be seen in Table 5.16. When the two groups distributed weights together, the final weight of a criterion was always in the interval of the two groups, which was seen in Table 5.16 above.

Ranking the weight distribution from highest to lowest for all the groups, which is showcased in Table 6.1, the four highest weighted criteria were the same between the groups: *Effluent quality, Water use, Local environment quality & amenity* and *Safety/risks. Heavy metal content in sludge, Sphere of action/political support* and *Climate impact* where all in the middle four for all groups. *Working environment* and *Operating costs* was on the

lower end for all group assembles.

Table 6.1: The criteria ranked from highest weight at the top to lowest on the bottom based on the weighting for group 1, group 2 and group 1&2 together.

Ranking group 1	Ranking group 2	Ranking group 1&2
Effluent quality	Effluent quality	Effluent quality
Water use	Water use	Water use
Local environment	Local environment	Local environment
quality & amenity	quality & amenity	quality & amenity
Safety/risks	Safety/risks	Safety/risks
Sphere of action/political support	Heavy metal content in sludge	Sphere of action/political support
Heavy metal content in sludge	Climate impact	Heavy metal content in sludge
Climate impact	Energy use	Climate impact
Vulnerability	Sphere of action/political support	Flexibility
Flexibility	Working environment	Energy use
Energy use	Flexibility	Vulnerability
Working environment	Operating costs	Working environment
Operating costs	Vulnerability	Operating costs

The group assembles did not seem to matter when deciding what criteria should have the highest influence on the results. Differences in the weight distributed to *Water use* between group 1 and group 2 does however change what scenario upstream water reuse or –20% fast runoff I/I that gets the highest weighted score. In this study it was not intended to compare the measure of reducing I/I with water reuse. The weighted score of –20% slow runoff for group 2 is above 3 indicating a future acceptable level but for group 1 it is below. The differences between the weighted score of the scenarios for reduced slow and fast runoff I/I is similar for both groups but because of the reduced influence of *Water use* in group 2 compared to group 1 and more influence given to *Effluent quality* both the scenarios for –20% fast and slow runoff I/I have higher scores that for –20% slow runoff I/I pushes it over the future acceptable limit of 3.

6.2   Electricity mix

Changing the electricity from wind power to EU electricity mix or Swedish electricity mix to investigate the impact of the used electricity mix on the results of the study gave the following results. In Table 6.2, the resulting carbon footprints for each scenario using the different alternatives are presented.

Table 6.2: The CO_2-equivalents for each scenario where electricity comes from wind, Swedish electricity mix or EU electricity mix and the corresponding grades according to the linear relationship from the original grading.

	Grade	CO_2eq.
Original grades − Wind		
Base case	1	14 375
+ 20% fat runoff I/I	1	14 499
- 20% fast runoff I/I	2	13 823
+ 20% slow runoff I/I	1	14 867
- 20% slow runoff I/I	2	13 810
Upstream reuse 70 l/p.d	2	13 929
Downstream reuse 70 l/p.d	1	14 375
Sensitivity analysis - Swe		
Base case	-1.0	15 844
+ 20% fast runoff I/I	-1.1	15 974
- 20% fast runoff I/I	-0.1	15 260
+ 20% slow runoff I/I	-1.7	16 364
- 20% slow runoff I/I	-0.1	15 246
Upstream reuse 70 l/p.d	-0.2	15 369
Downstream reuse 70 l/p.d	-1.0	15 844
Sensitivity analysis - EU		
Base case	-16.9	26 588
+ 20% fast runoff I/I	-17.1	26 770
- 20% fast runoff I/I	-15.7	25 778
+ 20% slow runoff I/I	-17.9	27 316
- 20% slow runoff I/I	-15.6	25 754
Upstream reuse 70 l/p.d	-15.9	25 909
Downstream reuse 70 l/p.d	-16.9	26 588

Both changes in electricity resulted in grades below 1 if the linear relationship from the grading of the original climate impact was used. With the existing grading scale where each grade corresponds to 675 tonnes CO_2-equivalents (see Section 5.1.3), a negative grade would result in the grade 1 for all scenarios. Changing the grade from 2 to 1 for the scenarios that received a grade 2 in the original grading would not affect the overall results, as can be seen in Figure 6.2 . Therefore, with the existing scale, the results would be the same if the EU electricity mix or the Swedish electricity mix were used in the climate impact calculations.
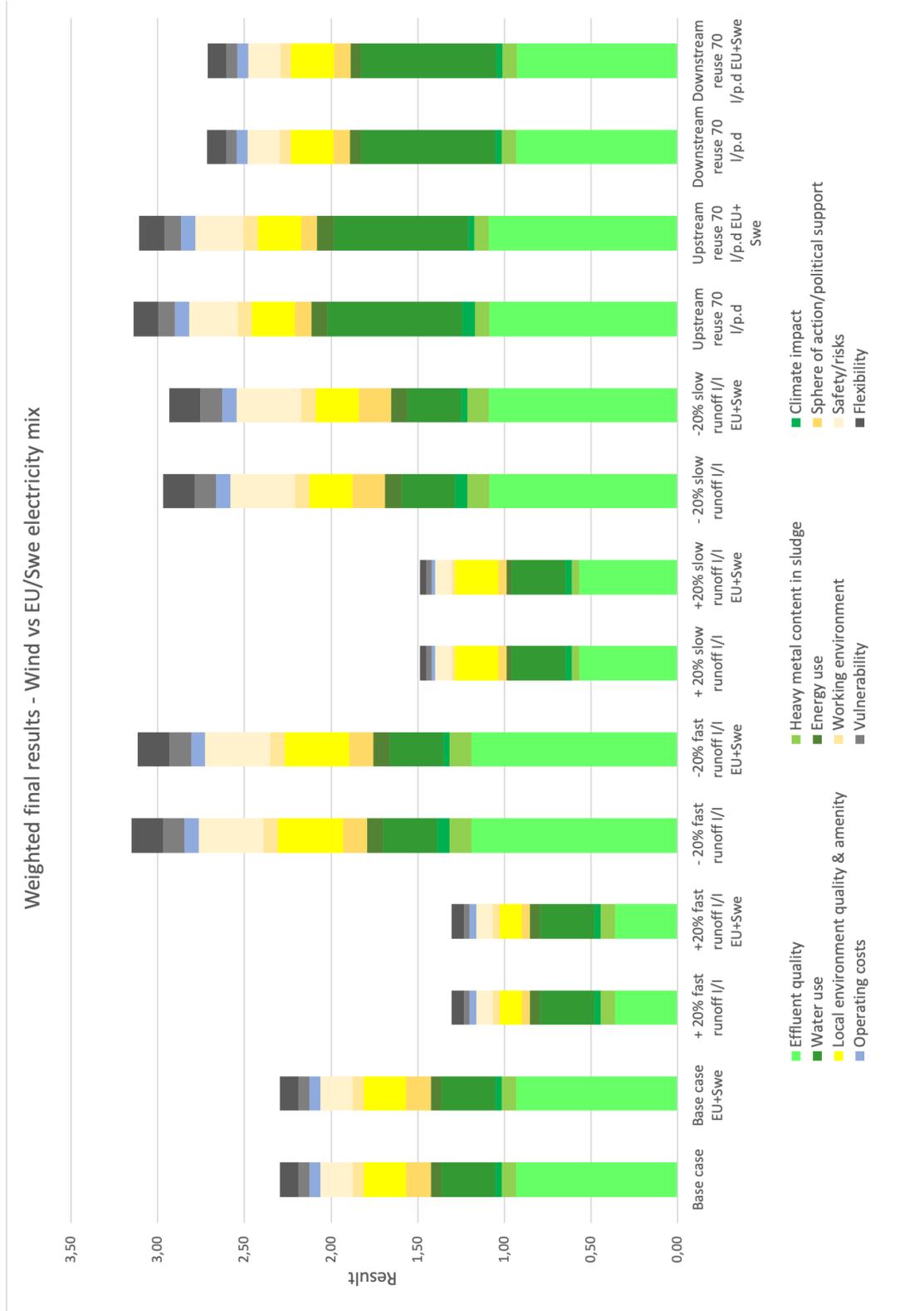
Figure 6.2: Weighted results for all scenarios when wind power is used in the carbon footprint calculations and when EU and/or Swedish electricity mix is used.

As can be seen in Figure 6.2, the weighted scores are in the same order compared to each other and the overall impression of the results remain the same for a change in electricity mix used at Rya WWTP. This can be because the weight for the *Climate impact* criterion is low, which was partly motivated by the lack of difference between the scenarios. Since the change in total climate impact is relatively large when a different electricity mix is compared to the wind electricity mix none of the scenarios would get above 1. However, the difference in climate impact between the scenarios is still similar for wind and other electricity mixes because when EU electricity is used, the difference between the lowest and highest climate impact is 1562 tonnes CO_2-eq, when Swedish electricity mix is used the biggest difference is 1118 tonnes CO_2-equivalents and when wind electricity is used the biggest difference is 1057 tonnes CO_2-equivalents. Since the differences between the scenarios was the reason that the *Climate impact* criterion was one of the main factors for its weight it's not likely to change for the other electricity mixes.

6.3 Grading allowing decimals based on current linear relationship

During the grading the scale was limited to 1-5 and decimals were not allowed. Because of these limitations some grades deviated more than others from the linear relationship generated from the grading points. To analyze if the limitation to not use decimals for grades have been favorable or unfavorable to any scenarios, the grade that the scenarios would have got based on the linear relationship can be seen in Table 6.4 and the linear relationship can be seen in Table 6.3. The predicted effects of the grading with decimals using the linear relationship are showed in Table 6.5 that shows the difference between the predicted decimal grades and the set grades on the weighted score.

Table 6.3: The linear relationship for the grades of each criterion.

Criterion	Linear relationship
Effluent quality - Phosphorus	$y = -20.173x + 98.231$
Effluent quality - Nitrogen	$y = -239.88x + 1695.2$
Effluent quality - BOD	$y = -654.79x + 3453$
Heavy metal content in sludge	$y = -3.395x + 33.375$
Climate impact	$y = -675x + 15204$
Water use	$y = 23.333x - 46.667$
Energy use	$y = -0.9x + 1.8$
Sphere of action /political support	-
Local environment quality & amenity	$y = -8.4x + 22.429$
Working environment	$y = -147.88x + 3329.6$
Safety/risks	-
Operating costs	$y = -1.1355x + 3.0126$
Vulnerability	$y = -256.25x + 1775.9$
Flexibility	$y = -1.8552x + 16.907$

Table 6.4: The grades set by the panel and the grades with decimals (denoted (D)) set according to the linear relationships limited within the interval 1-5.

Criterion	Base Case	Base Case (D)	+20% fast runoff I/I	+20% fast runoff I/I (D)	-20% fast runoff I/I	-20% fast runoff I/I (D)	+20% slow runoff I/I	+20% slow runoff I/I (D)
Effluent quality	2.7	2.6	1.0	1.0	3.3	3.2	1.7	1.9
Heavy metal content in sludge	2.0	2.0	2.0	1.9	3.0	3.0	1.0	1.1
Climate impact	1.0	1.2	1.0	1.0	2.0	2.1	1.0	1.0
Water use	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Energy use	2.0	2.0	2.0	1.8	3.0	3.0	1.0	1.1
Sphere of action /political support	3.0	3.0	1.0	1.0	3.0	3.0	1.0	1.0
Local environment quality & amenity	2.0	2.3	1.0	1.0	3.0	2.5	2.0	1.9
Working environment	3.0	2.5	2.0	2.3	4.0	4.1	1.0	1.1
Safety/risks	2.0	2.0	1.0	1.0	4.0	4.0	1.0	1.0
Operating costs	3.0	2.7	2.0	2.1	4.0	4.4	1.0	1.2
Vulnerability	2.0	2.1	1.0	1.4	4.0	4.1	1.0	1.0
Flexibility	3.0	3.0	2.0	2.2	5.0	5.0	1.0	1.0

	-20% slow runoff I/I	-20% slow runoff I/I (D)	Up-stream reuse 70l/p.d	Up-stream reuse 70l/p.d (D)	Down-stream reuse 70l/p.d	Down-stream reuse 70l/p.d (D)
Effluent quality	3.0	3.1	3.0	3.1	2.7	2.6
Heavy metal content in sludge	3.0	3.1	2.0	2.0	2.0	2.0
Climate impact	2.0	2.1	2.0	1.9	1.0	1.2
Water use	2.0	2.0	5.0	5.0	5.0	5.0
Energy use	3.0	3.1	3.0	3.0	2.0	2.0
Sphere of action /political support	4.0	4.0	2.0	2.0	2.0	2.0
Local environment quality & amenity	2.0	2.3	2.0	2.3	2.0	2.3
Working environment	4.0	4.2	4.0	4.2	3.0	2.5
Safety/risks	4.0	4.0	3.0	3.0	2.0	2.0
Operating costs	4.0	4.3	4.0	3.7	3.0	2.7
Vulnerability	4.0	3.9	3.0	3.0	2.0	2.1
Flexibility	5.0	4.9	4.0	4.0	3.0	3.0

Table 6.5: The change in the weighted score of each criterion for the scenarios as well as the total change in weighted result for the scenarios.

Criterion	Base Case	+20% fast runoff I/I	-20% fast runoff I/I	+20% slow runoff I/I	-20% slow runoff I/I	Upstream reuse 70l/p.d	Down-stream reuse 70l/p.d
Effluent quality	-0.01	0.00	-0.03	0.08	0.04	0.03	-0.01
Heavy metal content in sludge	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Climate impact	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Water use	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy use	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Sphere of action /political support	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Local environment quality & amenity	0.03	0.00	-0.06	-0.01	0.04	0.04	0.03
Working environment	-0.01	0.01	0.00	0.00	0.00	0.00	-0.01
Safety/risks	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operating costs	-0.01	0.00	0.01	0.00	0.01	-0.01	-0.01
Vulnerability	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Flexibility	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Total	0.01	0.02	-0.08	0.08	0.09	0.06	0.01

In Figure 6.3 the weighted scores of the scenario and the changes in the weighted scores between the grading and decimal grading. What stands out is that upstream reuse is now scored higher than –20% fast runoff I/I, despite that the order remains the same. It can also be seen that the limited grading has favored –20% fast runoff I/I and been unfavorable to the –20% slow runoff and if the decimal grades would have been used the –20% fast runoff would still be scored higher, but the difference would be 0.01 instead of 0.18 in the weighted score. The difference is mainly due to the change in grading between decimal and set grades for Effluent quality, that had the most weight, and Local environment quality & amenity, that had third highest weight.
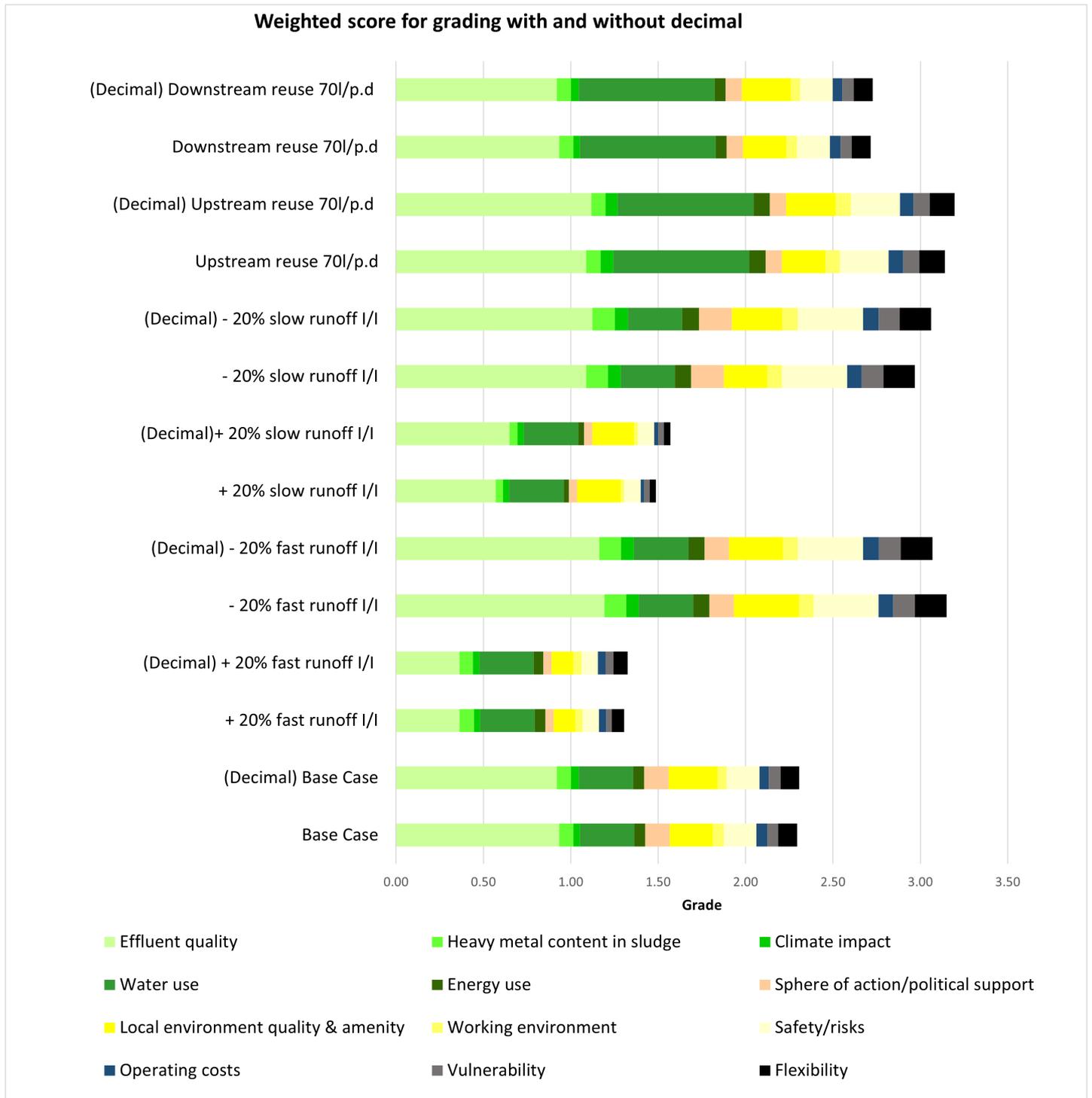
Figure 6.3: The weighted results of the scenarios with the grades set from grading and grades set according to the linear equations allowing decimals.

6.4 Linear grading with extended grading scale for extreme values

During the grading session, there were discussions about the grading of the Effluent quality criteria and the Local environment quality & amenity criteria regarding the fact that the data for the +20% fast runoff I/I scenario was deviating a lot from the rest of the scenarios. The difference between the second highest data result and +20% inflow was much larger than the difference to the third highest result. This led to that the group expressed that they would have needed a lower grade than 1 to be able to set a grade linearly proportional to the amounts of nutrient emissions and combined sewer overflow.

As a sensitivity analysis, the grade 1 for +20% fast runoff I/I was therefore changed according to the linear relationship between the rest of the scenarios, which were more reasonably graded according to the group. This resulted in a grade change from one to a lower grade for +20% fast runoff I/I, see Table 6.6 below.

Table 6.6: Grades on the Effluent quality and Local environment quality & amenity criteria when an extended grading scale is used

Criterion	Grade with extended grading scale
Effluent quality - P	0.4
Effluent quality - N	0.6
Effluent quality - BOD_7	-1.2
Local environment quality & amenity	-4.4

In Figures 6.4 , 6.5, 6.6 and 6.7 below, the linear relationships for the initial grades are shown beside the linear relationship when the +20% fast runoff I/I grade is set proportional to the other scenarios.

(a) Regular grading scale

(b) Extended grading scale for extreme values
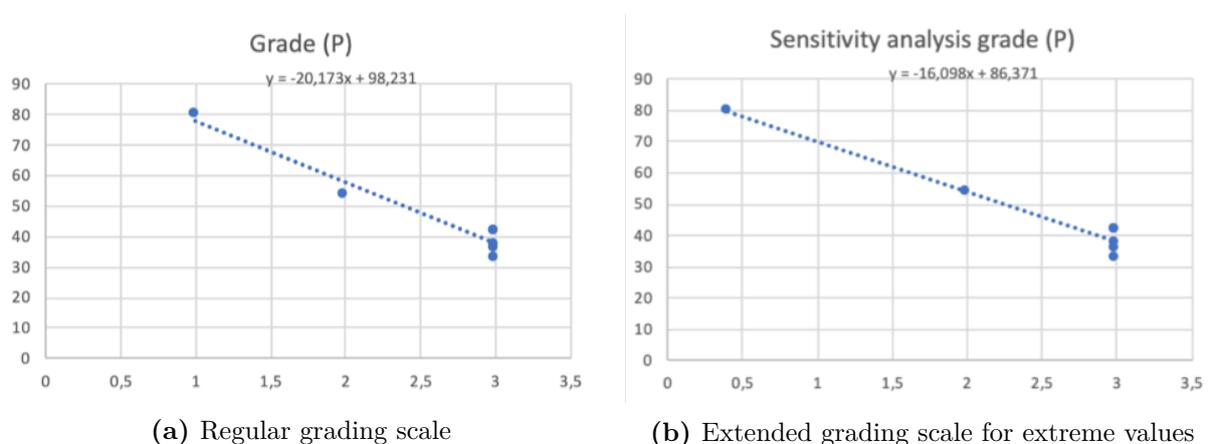
Figure 6.4: Linear relationships for grades in relation to data for phosphorus with regular grading scale (left) and extended grading scale (right).
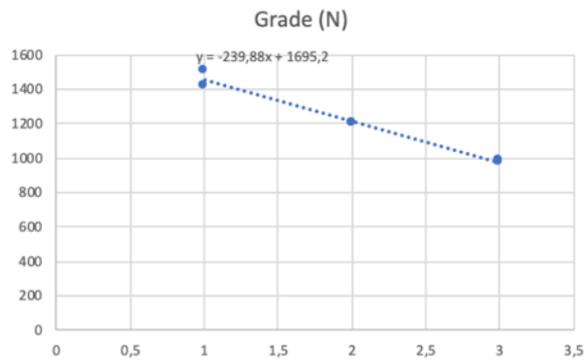
(a) Regular grading scale
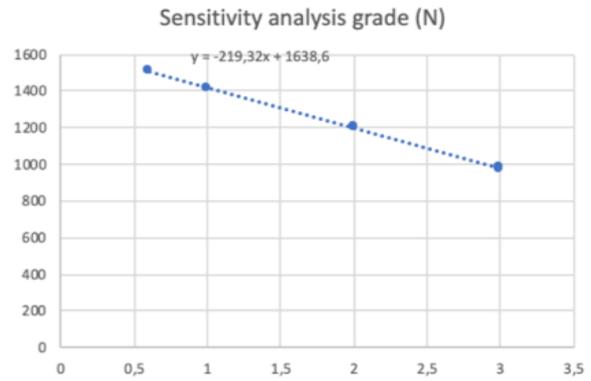
(b) Extended grading scale for extreme values

Figure 6.5: Linear relationships for grades in relation to data for nitrogen with regular grading scale (left) and extended grading scale (right).
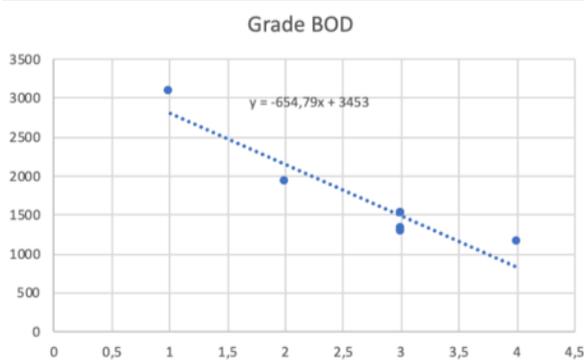
(a) Regular grading scale
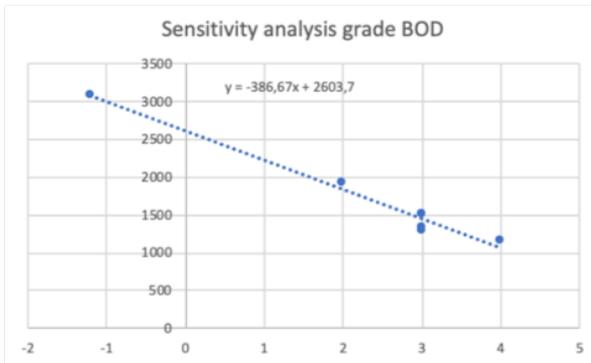
(b) Extended grading scale for extreme values

Figure 6.6: Linear relationships for grades in relation to data for BOD_7 with regular grading scale (left) and extended grading scale (right).
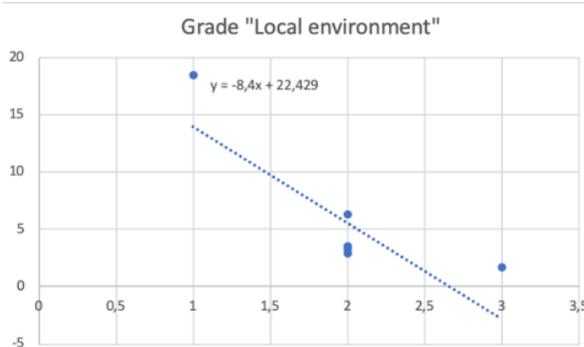
(a) Regular grading scale
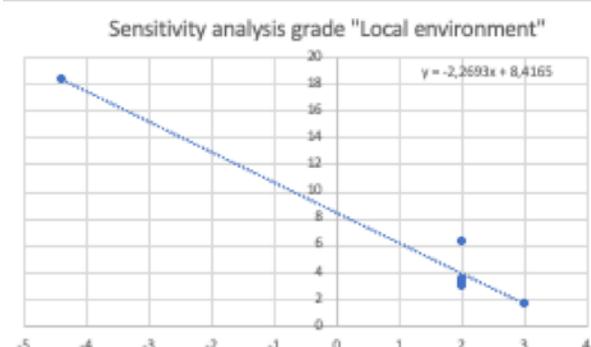
(b) Extended grading scale for extreme values

Figure 6.7: Linear relationships for grades in relation to data for CSOs with regular grading scale (left) and extended grading scale (right).

It can be seen that the linear relationships follow the pattern of the grade points more closely for the scenarios when the grade scale is expanded and the grade for +20% fast runoff I/I is set based on the relationship between the rest of the scenarios. This could

indicate that the results would have had larger differences between the scenarios if a more
generous grading scale were to be used.

In Figure 6.8 and 6.9 below, the final weighted scores in the study are shown as well as
the weighted scores for when the grade scale was extended on the *Effluent quality* and
Local environment quality & amenity criteria.
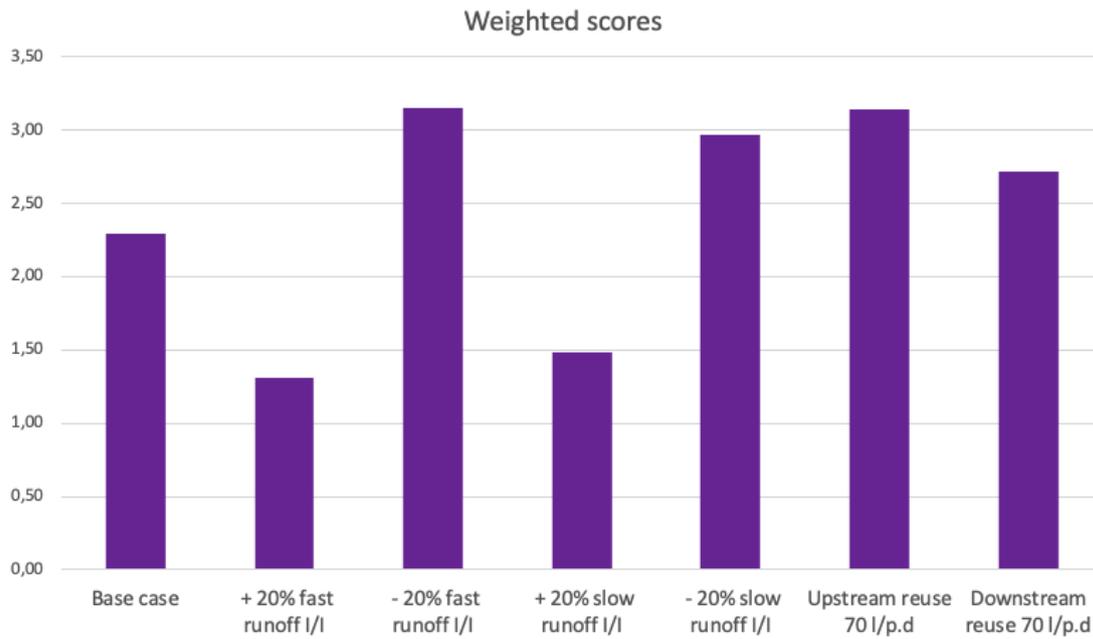
Figure 6.8: The original weighted scores that were presented in Section 5.3, presented as purple bars.

Figure 6.9: Weighted scores when the grading scale is extended for extreme values, presented as purple bars.

When the grading scale is extended to fit the linear relationship between the other scenarios for the Effluent quality and *Local environment quality & amenity* criteria, the final weighted result for +20% fast runoff I/I is lower than when grading was limited to 1-5. This means that the negative effects of +20% fast runoff I/I could have been suppressed in the grading compared to if the grading group would have had the opportunity to set a lower grade where they expressed that they needed it. An extended grading scale could have given larger differences between scenarios in the overall result. However, if the grading scale would be extended, other grades could also possibly change which would affect the results, so the effects of an extended grade scale is not possible to determine in retrospect. However, the +20% fast runoff I/I scenario is likely the scenario with the greatest grade changes with an extended grading scale because the data for many criteria is so deviant compared to other scenarios.

6.5   Data error

For the scenario with 20% increased fast runoff I/I, the pattern of increased wastewater inflow from fast runoff I/I for January 1st to November 25th for the scenario and for November 25th to December 31st had noticeable differences. The deviation is that the wastewater inflow to the WWTP is consistently lower than for the base case and there are CSOs at times were the flows to the WWTP that are withing the WWTP capacity and therefore does not warrant combined sewer overflow for the November 25th to December 31st period, which can be seen in Figure 6.10. For the period January 1st to November 25th the +20% fast runoff I/I the wastewater inflow was never lower than the base case and generated increased flow peaks referring to mainly high wastewater inflows. A zoomed in figure of the deviating area for November 25th to December 31st can be seen in Figure 6.11.
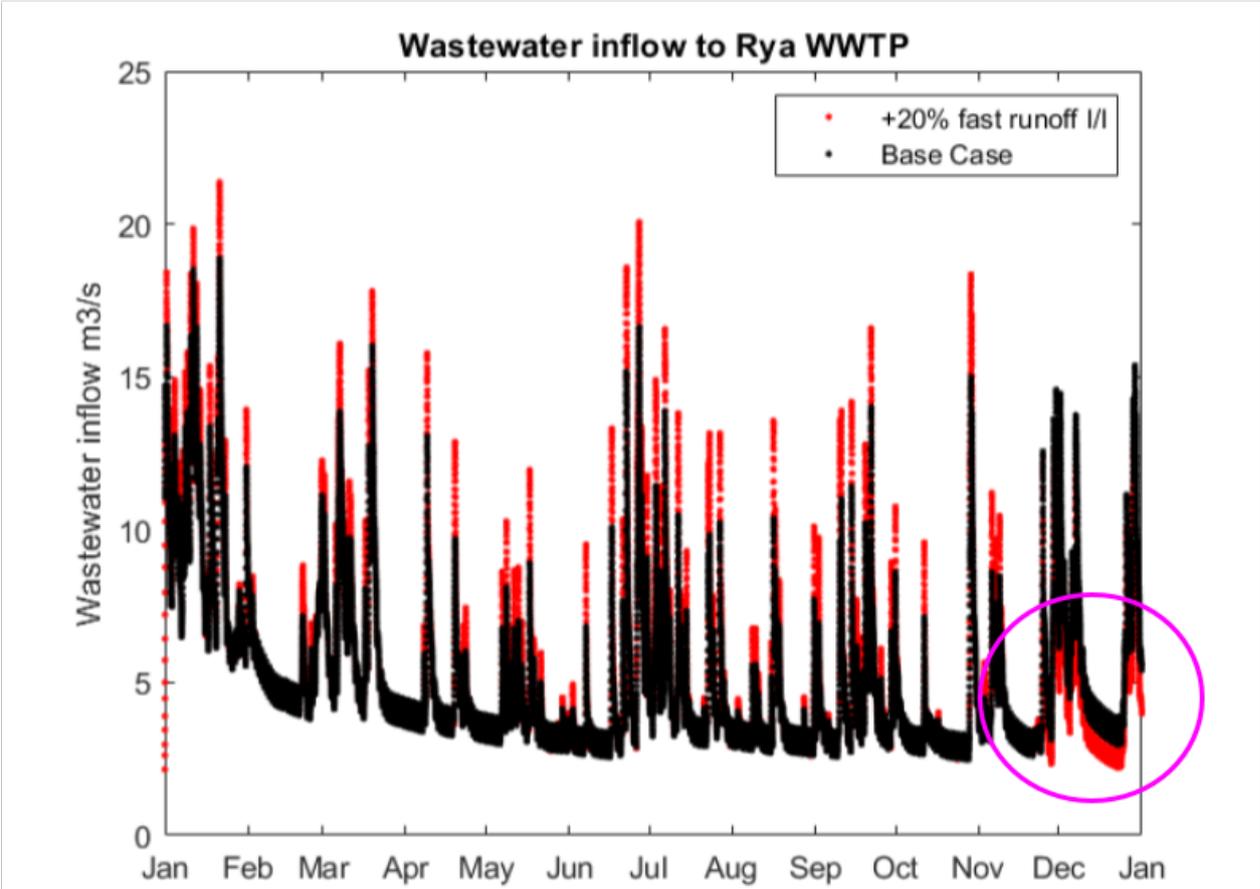
Figure 6.10: The +20% fast runoff I/I wastewater inflow and the deviation from 25 November to 31 December is highlighted with a purple ring.
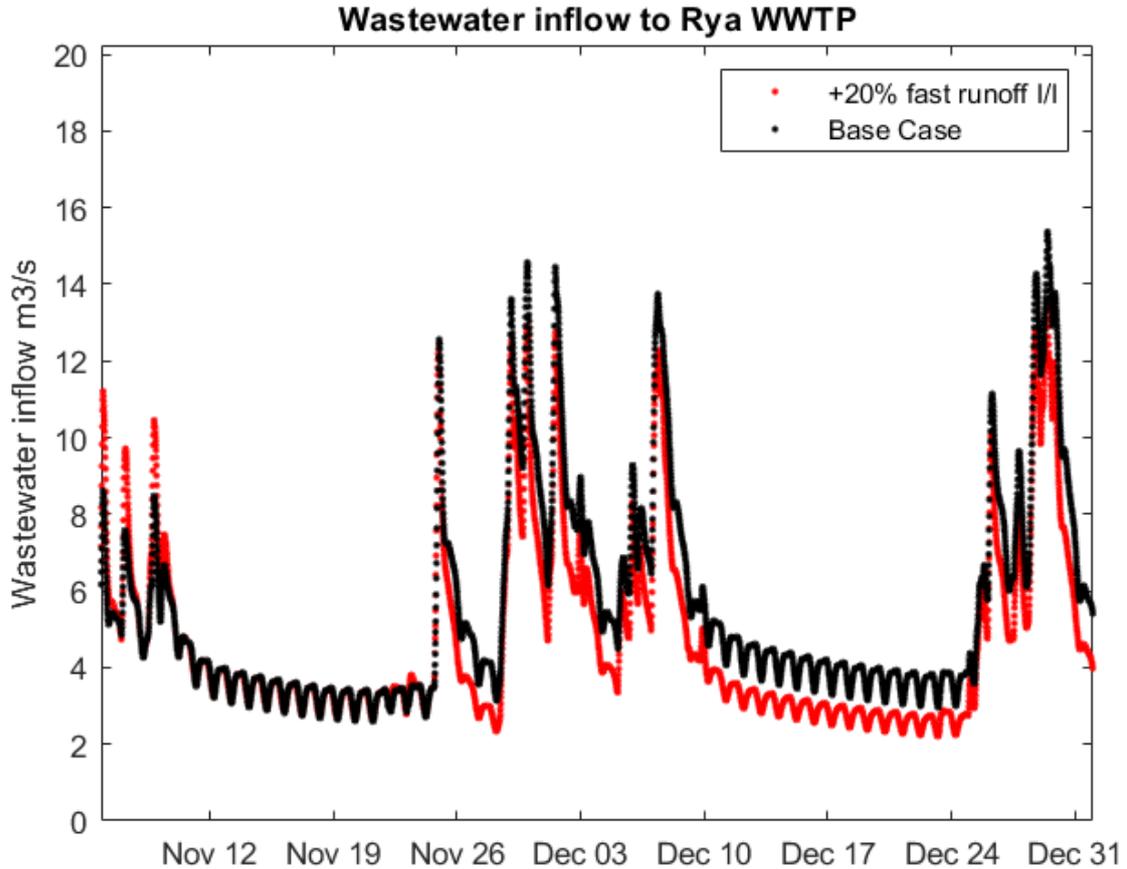
Figure 6.11: The wastewater inflow for +20% fast runoff I/I for the period 5 November to 31 December.

Because the flow seemed to be consistently lower for +20% fast runoff I/I compared to the base case during the November 25th to December 31st period and it had never been lower for any of the other wastewater inflows during the rest of the +20% fast runoff I/I scenario a new scenario was created to see how the deviation has affected the weighted results. For the new +20% fast runoff I/I scenario the period November 25th to December 31st was modified to fit the pattern of the period January 1st to November 25th. This was done by comparing the difference between the base case and the +20% fast runoff I/I over the period January 1st to November 25th for the wastewater inflow. It was calculated that on average the +20% fast runoff I/I scenario had 4.6% more volume flowing to the Rya WWTP compared to the base case for the period January 1st to November 25th and this was calculated as in Equation (6.1).

$$Wf_{Diff} = \frac{TotalWf_{+20(Jan1-Nov25)}}{TotalWf_{BC(Jan1-Nov25)}} \tag{6.1}$$

Wf_{Diff} is the difference in wastewater inflow, $TotalWf$ is the total wastewater inflow, $+20$ is the +20% fast runoff I/I scenario, BC is the base case scenario and $(Jan1-25Nov)$ refers to the time interval from January 1st to November 25th.

The difference between the wastewater inflow of +20% fast runoff and the base case for the period November 25 to December 31 was that the base case had 20% more wastewater inflow and was calculated as in Equation (6.2) . It was calculated the same as the difference in wastewater inflow for the period January 1st to November 25th but for the period November 25th to December 31st instead.

$$Wf_{Diff} = \frac{TotalWf_{+20(Nov25-Dec31)}}{TotalWf_{BC(Nov25-Dec31)}} \qquad (6.2)$$

If the pattern for +20% fast runoff I/I would have continued for November 25th to December 31st then the wastewater inflow volume would have been around 4.6% more than the wastewater inflow volume of the base case. The volume of a 4.6% increase compared to the base case was calculated as in Equation (6.3) to 21 Mm³ while the volume for +20% fast runoff I/I scenario was 16 Mm³.

$$Est.Wf_{(+20)} = TotalWf_{BC(Nov25-Dec31)} \times 1.046 \qquad (6.3)$$

$Est.Wf_{(+20)}$ is the estimated wastewater inflow that the +20% fast runoff I/I should have had for the period November 25th to December 31st.

To get a new flow series without deviation for increased fast runoff it was calculated that the wastewater inflows should be increased by 31% for the +20% runoff I/I scenario in the deviated period from November 25th to December 31st. This was calculated by dividing the total amount of wastewater inflow volume for the estimated volume of 21 Mm³ with the volume of 16 Mm³ for the +20% fast runoff I/I scenario.

A new scenario for 20% increased I/I from fast runoff was created by increasing the +20% fast runoff scenario data entries from November 25th to Decemberst 31 by 31% the resulting wastewater inflow series can be seen in Figure 6.12 and the changed period can be seen in more detail in Figure 6.13.

For the whole time period the new +20% fast runoff I/I scenario was calculated to have increased the wastewater inflow volume to Rya WWTP by 3% by dividing the total wastewater inflow volume for the two +20% fast runoff scenarios over the whole time period.
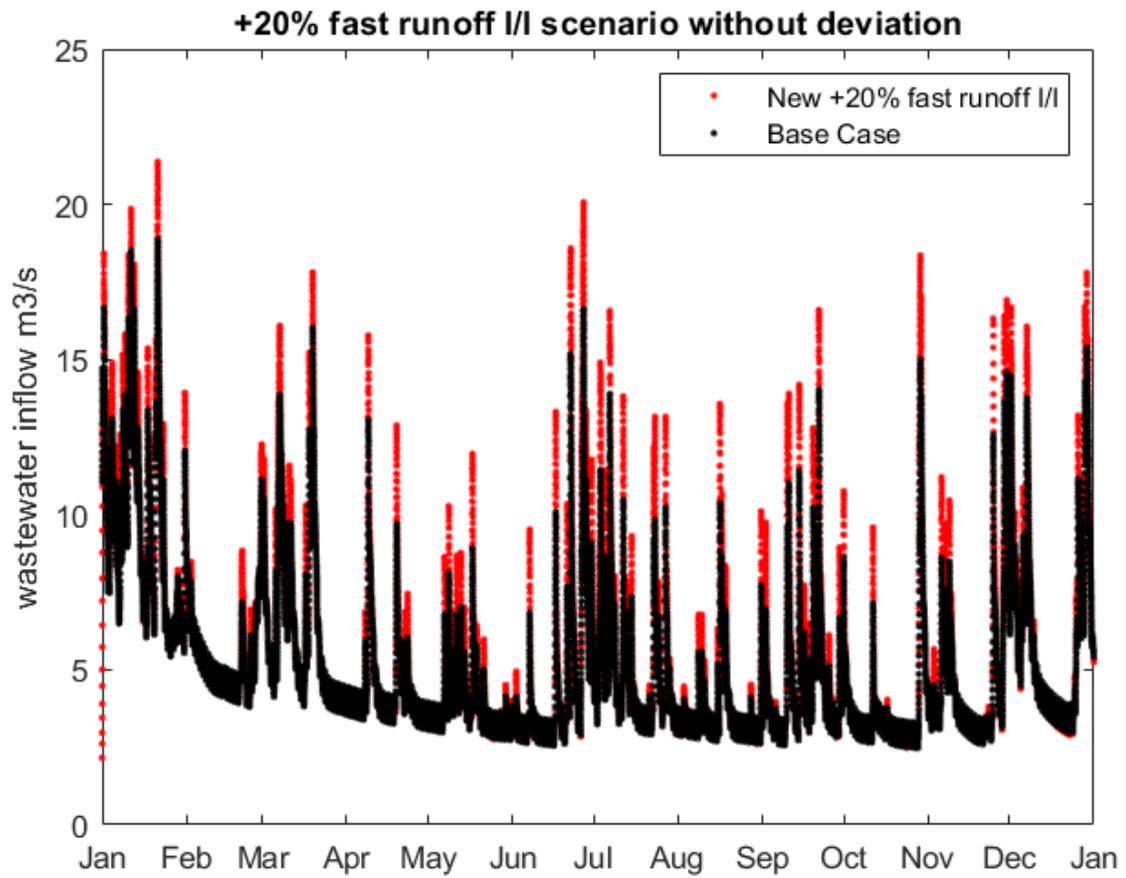
Figure 6.12: The wastewater inflow for the new +20% fast runoff I/I scenario.
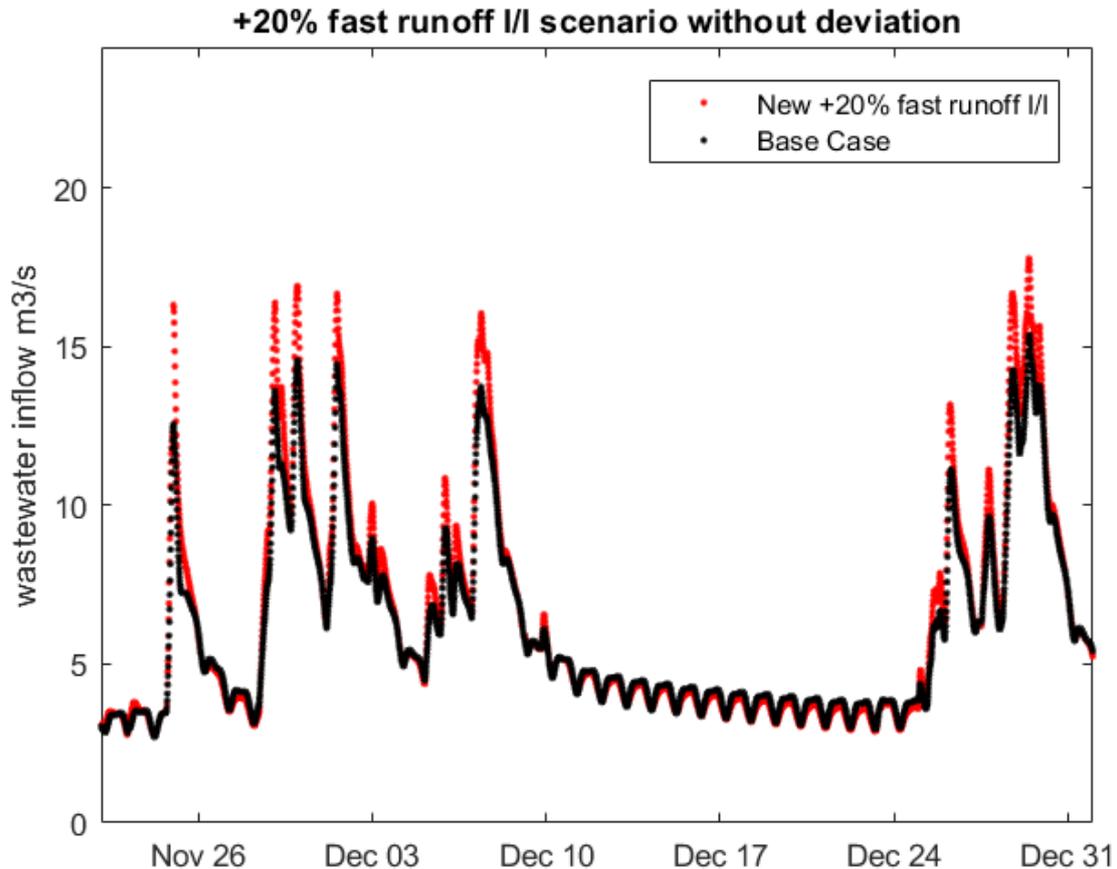
Figure 6.13: The modified part of the wastewater inflow for the new +20% fast runoff I/I scenario.

It is believed that decrease in wastewater inflow that was for the November 25th to December 31st period was because wastewater inflow was instead offloaded as CSOs in the simulation tool. It was confirmed by DHI, the developers of the FCF tool, that there were CSOs when there should not have been. Because of this it was assumed that the wastewater inflow difference of 16 Mm^3 and 21 Mm^3 of 5 Mm^3 mean that there was a 5 Mm^3 increase of CSOs that should be deducted for the November 25th to December 31st period. This would have resulted in a total CSO for the +20% fast run off scenario of 13.4 Mm^3 instead of 18.4 Mm^3.

The next step in the sensitivity analysis was to use the new +20% fast runoff I/I wastewater inflow series and total CSOs and see what the results would have been using the same methods as in the method section. Then using the linearity equations from the grading that can be seen in Table 6.3 to see what grades that were affected by the deviation.

The new wastewater inflow series and total CSO for +20% fast run off to calculate the results of the data in each criterion the expected change in grading can be seen in Table 6.7. In *Climate impact*, *Safety/risks* and *Vulnerability*, the effect of the new increased wastewater inflow would have a decreasing effect on the grades and because they already had the lowest possible grade of 1 they would not change. The criteria *Water use* and *Sphere of action/political support* does not change for the new +20% fast runoff I/I wastewater inflow series and CSO so the grade would remain the same.

The new CSO volume of 13.4 Mm^3 instead of 18.4 Mm^3 would correspond to a grade 1 according to the linearity equation from the grading of *Local environment quality & amenity* rendering the grade unchanged. For *Energy use* the electricity consumption was calculated as 0.4 GWh instead of 0.2 GWh this puts the grade at 1.5 meaning it could be rounded off to 2 or 1.

For PAC, the consumption would increase from 1408 tonnes to 1534 tonnes and polymer consumption from 5.3 tonnes to 5.7 tonnes. This together with the increased electricity consumption would increase the operational cost with 0.67 million Swedish kronor. This would put the operational costs of the new scenario at 1.27 million Swedish kr more than the base case that corresponds to a grade 1, which is a decrease in grade. The number of failed sludge batches in the new scenario was calculated to 27.9% which compared to the previous 27.11% would not change the grade of the H*eavy metal content in sludge* criterion.

Phosphorus emissions from CSOs were calculated to 32 tonnes for the low estimate and 57 tonnes for the high estimate, while it was previously 44 for the low and 80 for the high estimate. The phosphorus emissions from the WWTP were increased from 35.6 tonnes to 36.9. So, for the low estimates that was used in the grading the decrease of phosphorus emissions would from the WWTP and CSO combined be 10.7 tonnes of phosphorus with a total phosphorus emission of 68.9 tonnes. This would result in grade 1, meaning that the grade would remain unchanged.

For BOD, the new low and high estimates of CSO emissions was 1392 and 2758 tonnes respectively and the previous estimations for low and high was 1917 and 3797 tonnes respectively. The emissions of BOD from the WWTP were calculated to 1188 tonnes while it had previously been 1152 tonnes. Combining the low estimations for CSOs and the emissions from the WWTP the combined emission for the new scenario is 2580 and was previously 3069. This decrease in emissions would not increase the grade.

Nitrogen emissions for the new scenario from CSOs were, for low estimates, 267 tonnes and for high estimates 474 tonnes. Emissions from the WWTP increased from 1139 tonnes to 1182 tonnes for the new scenario. The combined emissions from the WWTP and the low estimate for the new scenario is 1449 and for the previous 1508 tonnes. This decrease would not increase the grade. On-call hours would increase from 2987 hours to 3045 hours, this would result in a grade 2, meaning no grade change for the *Working environment* criterion. The amount of time using partial treatment would increase from 12.8% to 14% this would not reduce the grade from 2 to 1, so the grade for *Flexibility* would remain the same at 2.

Table 6.7: The grades set by the panel on the +20% fast runoff I/I scenario with deviation at the grading and the predicted grades if the new +20% fast runoff I/I scenario would be used

	Grade + 20% fast runoff I/I	Grade Changed
Effluent quality - Phosphorus	1	1
Effluent quality - Nitrogen	1	1
Effluent quality - BOD$_7$	1	1
Heavy metal content in sludge	2	2
Climate impact	1	1
Water use	2	2
Energy use	2	1.5
Sphere of action/political support	1	1
Local environment quality & amenity	1	1
Working environment	2	2
Safety/risks	1	1
Operating costs	2	1
Vulnerability	1	1
Flexibility	2	2

From Table 6.7 it can be stated that the criteria that could be affected by the deviation were *Energy use* and *Operating costs*. Since both grades for these criteria would have decreased by 1 step and the +20% fast run off scenario was already had the lowest weighted score this deviation seems to have made the difference in weighted score between +20% fast runoff I/I and +20% slow runoff I/I scenarios closer than it should have been. The weighted result using the weight distribution of the panel for cost quotas would be 1.25-1.28 depending on if *Energy use* is rounded down or up, this is a decrease of 0.03-0.06.

6.6   Compilation of sensitivity analyses

In Table 6.8 below, the weighted results for all scenarios in the different sensitivity analyses are presented.

Table 6.8: Average grades and weighted results for all scenarios including the results in sensitivity analyses.

	Base case	+ 20% fast runoff I/I	- 20% fast runoff I/I	+ 20% slow runoff I/I	- 20% slow runoff I/I	Upstream reuse 70 l/p.d	Down-stream reuse 70 l/p.d
Grading	2.31	1.50	3.36	1.22	3.33	3.08	2.47
Weighting	2.30	1.31	3.15	1.49	2.97	3.14	2.72
Sensitivity analyses							
Weighting group 1	2.24	1.31	3.08	1.52	2.89	3.18	2.77
Weighting group 2	2.37	1.33	3.21	1.48	3.04	3.16	2.73
Changed electricity mix	2.30	1.31	3.11	1.49	2.93	3.10	2.72
Grading with decimals	2.31	1.32	3.07	1.57	3.06	3.20	2.73
Extended grading scale	2.30	0.28	3.15	1.48	2.97	3.14	2.72
Increased fast runoff I/I data error	2.30	1.25-1.28	3.15	1.49	2.97	3.14	2.72

All the scenarios got scores consistent with their weighted result for all sensitivity analyses except for the -20% slow runoff I/I scenario and the +20 fast runoff I/I. The sensitivity analyses showed that the scenario with –20% slow runoff I/I was always the third highest but it the score fluctuated between just above 3 and below indicating that that the scenario could be considered on a future acceptable level. The scenario that stands out the most is the +20% fast runoff I/I scenario, which would go down an entire grade step if an extended grading scale would have been used. The order scenarios for the results from lowest to highest was consistent except that the highest score that was a mix between upstream reuse and –20% fast runoff I/I. This indicates that the results are stable for comparing the I/I scenarios and the water reuse scenarios separately.

7

Discussion

This chapter presents discussion on the overall results and the details of how the results were developed. There is also discussion regarding accuracy of data, limitations and assumptions. In the end, recommendations for future research are presented.

7.1   Overall results

Overall, the results show that scenarios that decreased wastewater inflow to the WWTP, meaning the scenarios with decreased I/I or water reuse, improve the sustainability. Meanwhile, scenarios that increased wastewater inflow, meaning the scenarios with increased I/I, have a negative effect on sustainability at the WWTP. These results were to be expected since more incoming wastewater means more water that is treated, and the treatment consumes resources at the WWTP. However, there were other effects of increased I/I that were discovered other than resource use at the WWTP such as increased stress for employees, increased CSOs and a less flexible treatment process due to capacity issues.

The results of the study showed that none of the future scenarios would be on a level of sustainability that is better than a future acceptable level. This implies that even if wastewater inflow to the WWTP is lowered by decreasing the I/I by 20% or by upstream water reuse 70 liters per person and day, complementary measures at the WWTP would be required to reach beyond a future acceptable level. Only a reduction of fast runoff I/I and upstream reuse got results corresponding to a future acceptable level, while all other scenarios were considered unacceptable in the future. However, the –20% slow runoff I/I scenario could be considered on a future acceptable level since, in the sensitivity analyses, it fluctuated from being on a future acceptable level and just below.

Increased I/I resulted in sustainability levels that are considered below a future acceptable level. For the WWTP this implies that more leakage into pipes and/or an increased stormwater runoff collected in the sewer system by either increased levels of precipitation in the future due to climate change or an expansion of the sewer system that Rya WWTP is connected to would be detrimental for the sustainability at the WWTP. This is assuming the treatment process and the capacity are unchanged. To be able to handle an increased wastewater inflow from I/I, the WWTP would have to increase the capacity of the existing treatment process.

Water reuse generally increased the sustainability compared to the Base case, but since downstream reuse does not change the wastewater inflow to the WWTP it does not have as many sustainability benefits as upstream reuse for the WWTP. However, since upstream reuse must be installed outside of the WWTP, this requires that Gryaab pushes collaboration between other actors if Gryaab wants the benefits of upstream reuse. Downstream reuse, on the other hand, is performed by direct collaboration between Gryaab and another actor/industry and might therefore be easier for Gryaab to implement.

7.2 Result development

Effluent quality was given the most weight out of all criteria in all the different weightings, meaning that a grade step differences for effluent quality has the most influence on the results of the MCDA compared to a grade step difference in any other criteria. This is reasonable since the main purpose of the WWTP is to protect people and ecosystems by avoiding deterioration of the water quality and harmful emissions from wastewater. This is further supported by local environment quality and amenity having the third-highest weight distribution since it is connected to people's perception of the environment at points for CSOs.

Since both *Effluent quality* and *Local environment quality & amenity* were given high weights and considered important for sustainability at the WWTP, it is important to understand how CSOs increased and decreased in the scenarios and how to it affects the wastewater inflow. Increased fast runoff I/I has more CSOs compared to slow runoff I/I which means that the wastewater inflow is lower for increased fast runoff I/I compared to slow runoff I/I. This is also the reason that increased slow runoff I/I caused most emissions of P, N and BOD_7 from the WWTP but increase fast runoff I/I caused the most emissions from the WWTP and CSOs combined. This indicates that an increase in increase in slow runoff I/I is less preferred compared to fast runoff I/I for Gryaab to keep emissions from the WWTP under the environmental permit limit. However, since the total emissions are higher when fast runoff I/I is increased, it indicates that the perspective of the current environmental permit that only accounts for the emissions from the WWTP does not capture whole picture. Since precipitation is predicted to increase, CSOs are also expected to increase in the future if the capacity remains the same at the WWTP. Therefore, it could be argued that an environmental permit should account for all emissions and not only the ones from the WWTP.

For the *Local environment quality & amenity* criterion, the data analysis was relatively straightforward since all CSO flows were given by the simulation in the FCF model. However, as mentioned in the sensitivity analysis in Section 6.5, there was a data error for the period November 25th until December 31st for the +20% fast runoff I/I scenario where the volume of CSO water was overestimated. This did, however, not affect the weighted result order of the scenarios as it was concluded that the scenario still got the lowest weighted score out of all the scenarios.

A criterion that stood out in the weighting process was *Water use*. It was not predicted to influence the MCDA results as much as it did. It was pointed out during grading

that saving 70 liters per person and day was considered almost unrealistic since the total drinking water use in Sweden is 140 liters per person and day and 200 in Gothenburg. However, the scenarios for water reuse were constructed to match the volume of water increased and decreased in the I/I scenarios and not from a perspective of what a realistic amount of saved drinking water is.

The *Operating cost* criterion got the lowest weight distributed out of all criteria. This was due to the differences between scenarios being considered low in relation to the total operating cost at the WWTP. The cost criterion would probably or potentially have been given more weight if the limitations had been set differently and included costs such as installation and processing of upstream reuse and measures taken to achieve reductions in I/I by separating and sealing pipes.

The increased CSOs for increased fast runoff I/I scenario because of the capacity constraints at the WWTP could have affected the results for the Cd/P ratio in the *Heavy metal content in sludge* criterion. Because if the capacity at the WWTP was higher, then according to the relationship in Figure 4.15 it is likely that increased fast runoff I/I would instead lead to a higher percentage of failed batches due to the increased wastewater inflow. However, it needs further work to say if this is the case since it is unknown if the composition of the I/I is what increases the Cd/P quota or if the limited capacity of certain treatment steps are the reason that failure probability increases with increased wastewater inflow. Also, as will be discussed below in the discussion about assumptions the composition of different types of I/I-water were not distinguished between. If slow or fast, I/I have composition differences that impacts the Cd/P quota to different extents then the results could be overestimating one of the scenarios and underestimating the other.

In the *Climate impact* calculations, only the emissions of nutrients from the WWTP were accounted for, not the emissions from CSOs also reaching recipients. As previously discussed about the Effluent quality criterion, increased fast runoff I/I results in more CSO than increased slow runoff I/I does. Therefore, when only emissions from the WWTP and not emissions from CSOs are accounted for, the resulting carbon footprint might underestimate the total carbon footprint of the scenarios. Furthermore, since there were also other parameters that were not changed in the carbon footprint calculation tool that might have been affected, such as the biogas produced or different sludge-related parameters, there could possibly be a difference between the results and the reality if the scenarios would occur that could not be predicted in this study.

7.3   Data, limitations and assumptions

Historical data for high wastewater inflow in the interval of 10 to 16 m^3/s was scarce compared to flows around the average wastewater inflow 4 m^3/s. Wastewater inflows above 16 m^3/s were not at all found in the historical data. This means that scenarios with more data entries with higher wastewater inflows are less certain because the polynomial relationships based on wastewater inflow are less reliable for the higher flows due to data being scarcer or non-existent.

The data used in the preparation of the basis for grading varied in resolution some were weekly averages, which are less accurate and makes the results "flatter" since the average flow during a week is never as high as the peaks that can occur during a day or hour. Weekly averages were used when calculating on-call hours for the *Working environment* criterion, inflow concentrations of nitrogen, phosphorus and BOD_7 and BOD_7 outflow concentration. This was also the reason that emissions from CSOs were calculated utilizing mean values and standard deviation since data for incoming concentration of P, N and BOD did not have high enough resolution to determine if there was a pattern or not. There were also some data given for each hour, and some as daily averages. This could have affected the results since hourly data would give more accurate polynomial relationships while data given as daily, or even weekly averages would give less precise polynomial relationships. However, over the course of one year, which is the time-span of each scenario, the total amounts are assumed to be accurate enough to give results that shows the trend of how the different future scenarios would affect the sustainability at the WWTP.

The grades for the *Effluent quality* criteria were set in relation to the results for the low estimate because it was reasoned that mixing of I/I is higher when CSOs occur compared to when there is no CSOs and that the water would therefore be more diluted for the concentration of P, N and BOD_7. If instead the high estimate would have been taken into consideration, the grades could possibly have been affected. However, it is unlikely that the CSO water has this concentration due to the dilution with I/I. It is even possible that the CSO water concentration is lower than the low estimate since no measurements of concentrations in CSO water were found.

Since it was not possible to get data from FCF for the upstream reuse scenario, the amount of CSOs were estimated to be in the interval between the base case and the decreased slow runoff I/I scenario. Since the calculated wastewater inflow data series for upstream reuse causes an overestimation on the lowering of wastewater inflow and an underestimation of the decrease in CSOs, further work should be done to simulate more accurately how upstream water reuse affects the wastewater inflow and the CSOs. It is however expected that the CSOs are similar to that of decreased slow runoff I/I because it is expected to have similar continues decrease of water entering the sewer system.

Another thing that could have affected the results in the *Heavy metal content in sludge* criterion is that the Cd/P ratio is only one of the parameters deciding if a batch of sludge can be Revaq-certified. Therefore, when the "70% approved batches"-goal was used as support for the grading, it could have been misleading since even if a batch is approved based on Cd/P ratio, it can be failed because of another parameter which is not accounted for in this study.

Because drinking water is not reduced at the WWTP but rather in industries, households and the drinking water production plant it can be argued that the *Water use* criterion is outside of the system boundary of the study. Removing the *Water use* criterion would put the MCDA result of downstream reuse closer to the base case and lower the result of upstream reuse.

When calculating the changes in amounts of chemicals used in the WWTP process for the *Vulnerability* criterion, data for other chemicals than PAC and polymer for direct

precipitation was also analyzed. However, no relationship between wastewater inflow to the WWTP and amounts consumed could be found for the other chemicals, which were methanol, FeSO4 and polymer for secondary settling. These were therefore assumed to be unchanged in amounts for the scenarios in this study. Some chemicals used at the WWTP were not plotted based on the assumption that the amounts of those chemical would not change depending on wastewater inflow. Sodium hypo chloride is a chemical used at the WWTP which was not deemed to change in amounts depending on wastewater inflow. Communication with engineers at the Rya WWTP indicated that this chemical is not regulated based on wastewater inflow. There are more chemicals used at the WWTP that were not taken into consideration here as well, since they are used in amounts that were considered negligible. In reality, some of these chemicals that were neglected might be affected by changes in wastewater inflow to the WWTP which could not be predicted by the data analysis.

Another limitation of this study is that in the event of separation of pipes, the pollutants in stormwater are led away to nearby water bodies this could affect the recipients in these water bodies however, it was not accounted for in this study. Since the changes needed for each scenario were not accounted for either, such as separation of pipes or installation of an upstream reuse facility, all effects from these actions were not accounted for either, including the costs. Also, the operation of reuse systems that takes place outside of the WWTP could contribute to energy use, chemical use and release of emissions for example, is not included in the study. To get a better understanding of the whole picture, the system boundary would have to be wider and include other actors besides Gryaab and Rya WWTP.

7.4 Future recommendations

During the study and the report writing, useful areas of future research were identified:

- Including drinking water production to get a more detailed understanding of the impact of reusing water in terms of reducing resource use. This could give a more nuanced understanding of sustainability effects of water reuse that was not possible with the system boundaries of this study.

- Further work on answering why there is an increase in failed sludge batches for higher wastewater inflows. Specifically, it could be investigated if the capacity of the WWTP is the problem and if so, what treatment steps are the most important to achieve Revaq quality. It could also be the composition of I/I or the composition of I/I mixed with sewer water that is the problem. Investigating this further could help to understand how to adapt the WWTP to avoid batches that does not get approved by Revaq.

- Studying the costs of the measures needed to achieve reductions of I/I, such as pipe separation and reparation and also the implementation of water reuse. This is needed to be able to compare the costs of implementation to the sustainability benefits.

- Increasing the system boundary of the study to analyze the sustainability effects on a larger scale in relation to the sustainability effects for the WWTP that were found in this study.

8

Conclusions

From the results and discussion of the study, the following conclusions could be drawn.

- The most important sustainability criteria for the study at the WWTP were, based on the literature study and evaluation of criteria, the ones that can be seen in Table 4.1. The other criteria that were found to be commonly included in sustainability assessments can be seen in Table 3.1.

- Sustainability effects for the WWTP from downstream reuse were mostly unchanged compared to the base case. The differences were lower drinking water use, potential legal and regulatory issues and potentially increased political support. The effects of upstream water reuse were lower drinking water use and less wastewater inflow to Rya WWTP. Less wastewater inflow to the WWTP was found to have a positive effect on the overall sustainability.

- The preferred water reuse strategy based on the results is upstream reuse. This is due to the benefits of reducing the wastewater inflow to the WWTP which are not generated from downstream reuse.

- Increased I/I has a negative effect on the effluent water quality, and the results for the *Local environmental quality & amenity* criterion indicated a negative effect on the water quality in CSO areas because of increased CSOs. Increased I/I also entail increased safety risks for people and equipment, and potentially also generates less sludge that can be used in agriculture. The effects were the opposite for decreased I/I.

- The impact on the wastewater inflow to the WWTP from increased or decreased fast runoff I/I was spread out less over time compared to changes in slow runoff I/I. More wastewater inflow during shorter intervals caused by increased fast runoff I/I showed to be more impactful compared to the more spread-out effect of slow runoff I/I on the WWTP. The results also showed that decreased fast runoff I/I was more favorable compared to decreased slow runoff I/I. Fast runoff I/I affects combined sewer overflow more than slow runoff I/I and the total wastewater inflow to the WWTP was more impacted by slow runoff I/I compared to fast runoff I/I because less wastewater was redirected to CSOs. However, an increased total volume of wastewater inflow to Rya WWTP was not necessarily a problem if the flow did not exceed capacities such as the full chemical and biological treatment, direct precipitation and mechanical treatment.

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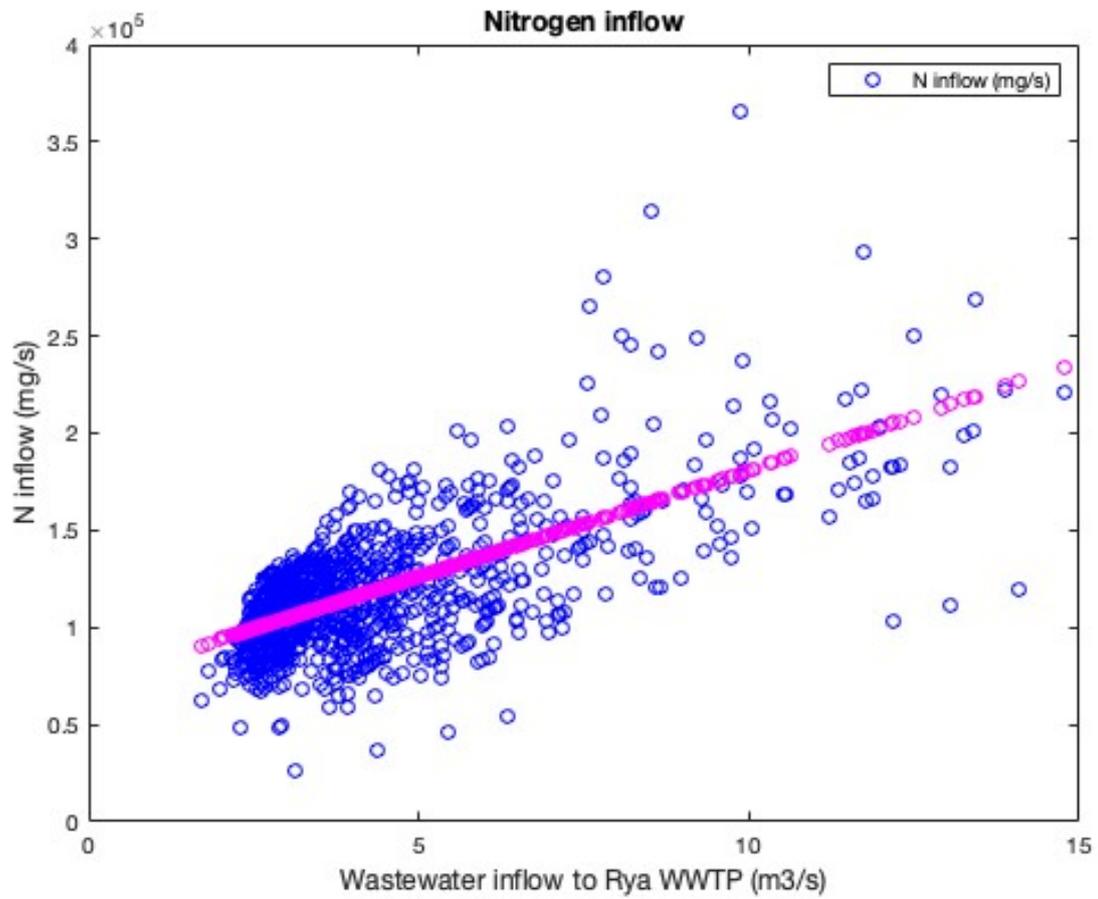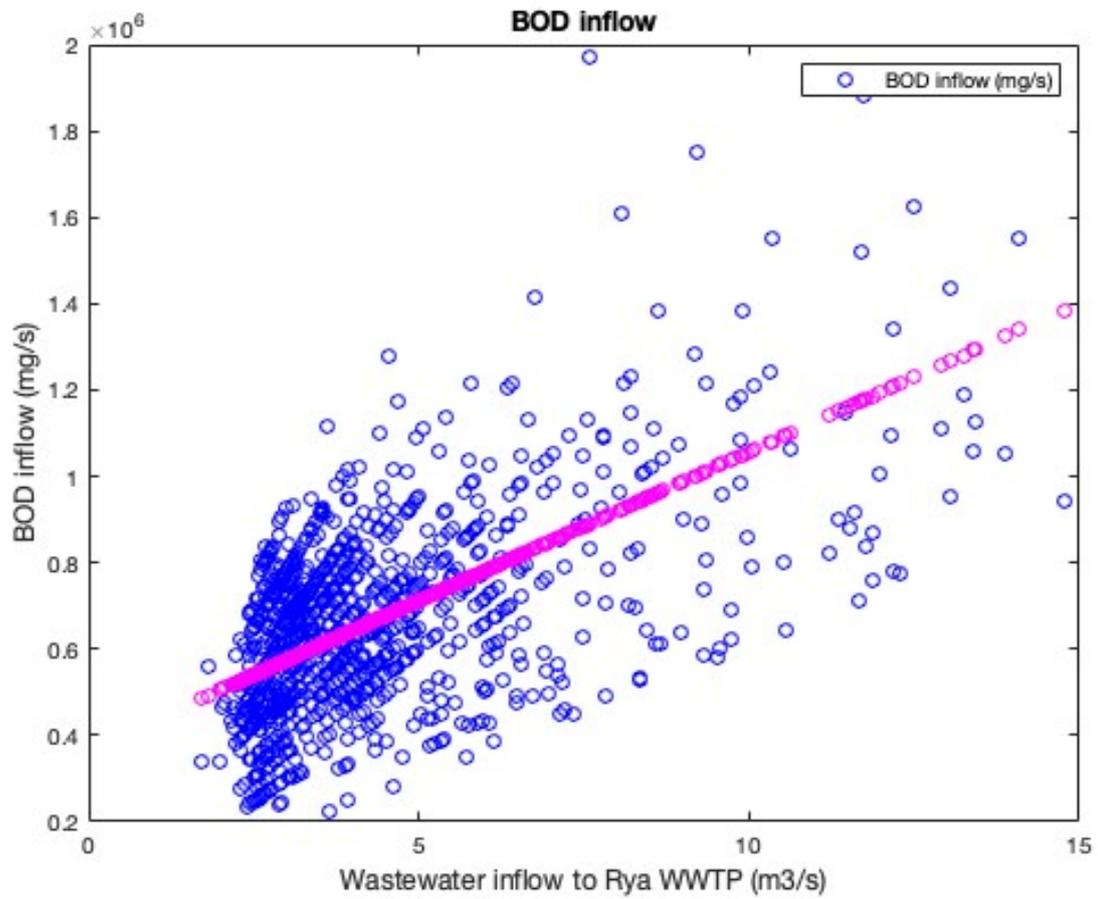
Appendix A
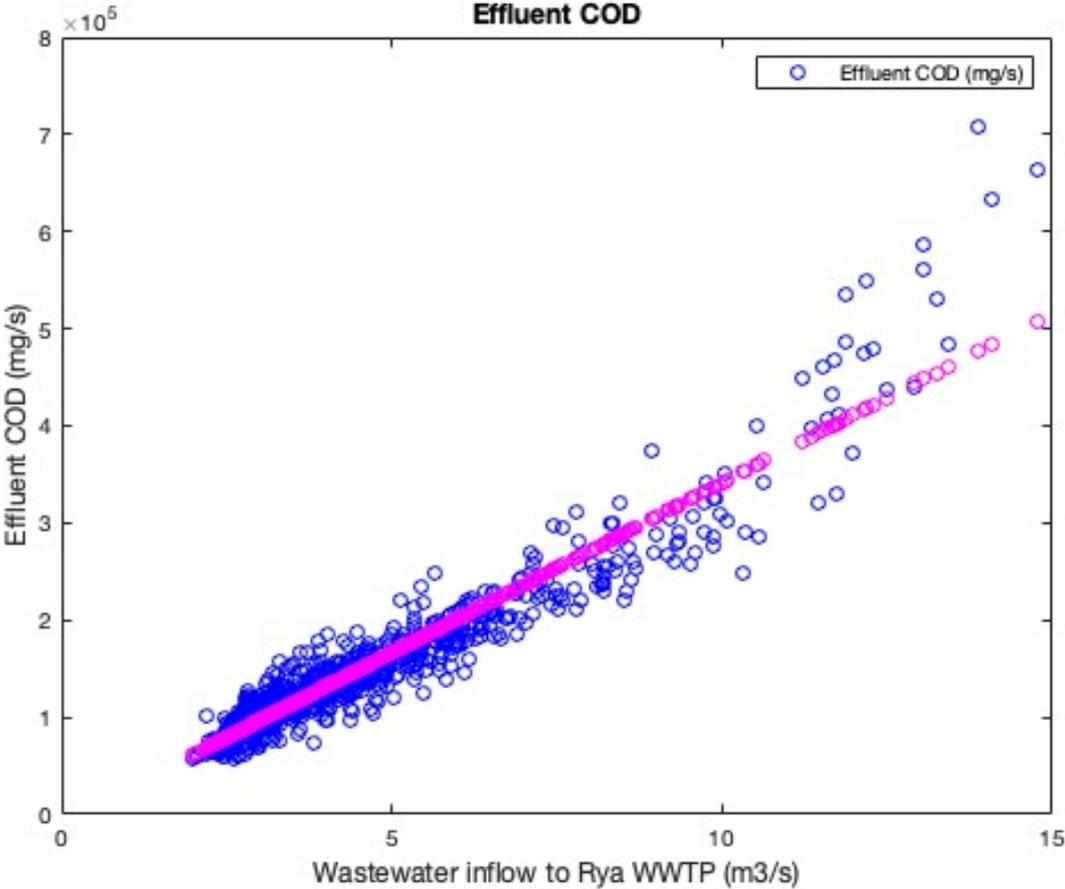
Figure 1: Effluent COD in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink). The linear equation for COD (mg/s) was y = 34949.0769*x - 8149.0413. Outliers with deviation more than 20 mg/s from average were removed
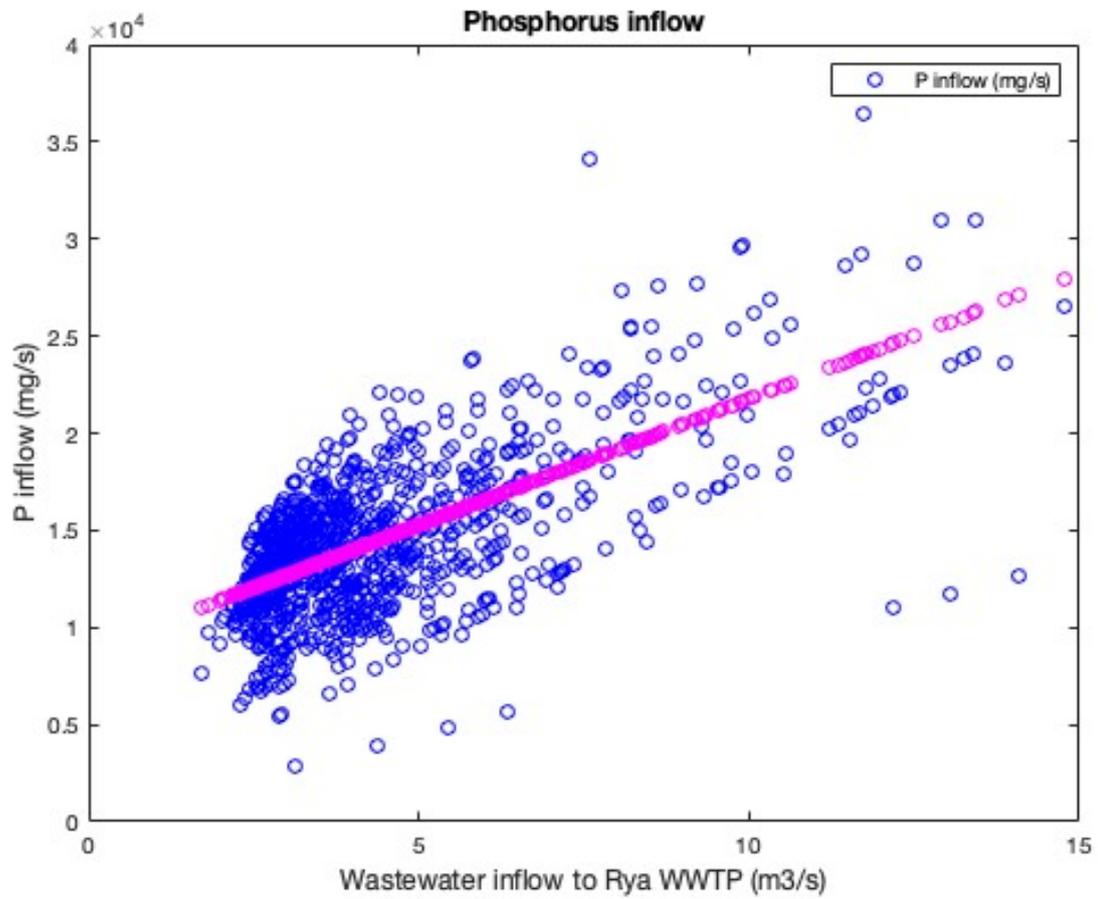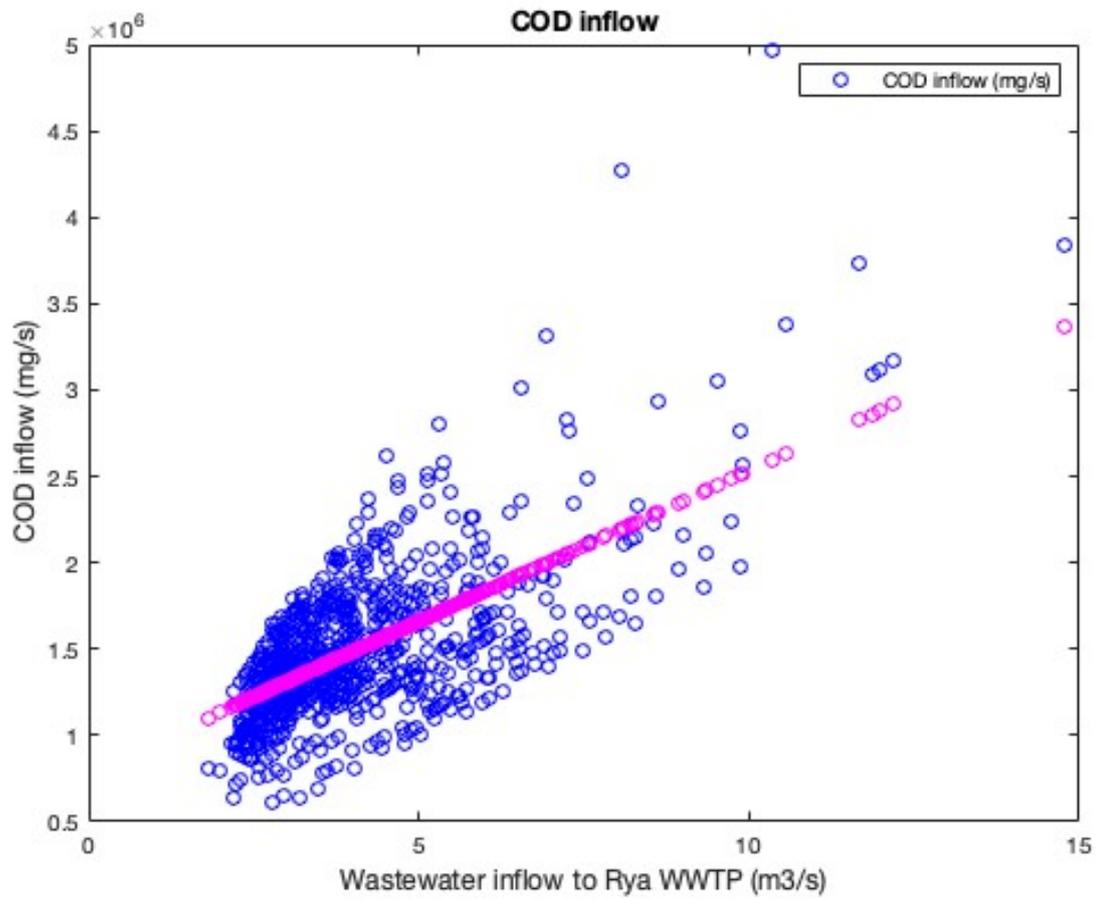
Figure 2: Phosphorus inflow in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink).The linear equation for Phosphor (mg/s) was y = 0.71198*x^2 + 1288.1295*x + 8813.5466. Outliers with deviation more than 2 mg/s from average were removed

Figure 3: Nitrogen inflow in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink). The linear equation for Nitrogen (mg/s) was $y = 26.6147 \cdot x^2 + 10526.3307 \cdot x + 72963.0502$. Outliers with deviation more than 20 mg/s from average were removed

Figure 4: BOD inflow in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink). The linear equation for BOD7 (mg/s) was y = 68965.8822*x + 367331.8503. Outliers with deviation more than 100 mg/s from average were removed

Figure 5: COD inflow in relation to wastewater inflow to the WWTP (blue) and the polynomial relationship (pink). The linear equation for COD (mg/s) was y = 174608.1138*x + 787197.235. Outliers with deviation more than 200 mg/s from average were removed

Appendix B

Interview questions

Working environment

1. Finns det några märkbara skillnader i arbetsmiljö vid höga flöden jämfört med lägre/vanliga flöden? (Skillnad när man har mer delvis behandlat och direktfällning eller andra konsekvenser av högt flöde?)

2. Sker det mer eller mindre ofta att ni behöver gå ut i processen och lösa ett problem (underhåll) (tex filter som satt igen, extra pump som behöver övervakas etc) när det är högt/lågt flöde?

3. Påverkar olika flöden ljudnivå, smuts (skvätt etc) eller andra trivsel-aspekter?

4. Påverkar olika flöden stressnivån på jobbet (mycket att göra kanske, krävs det mer kommunikation)?

5. Infektionsrisk - Finns det tillfällen där risken är större att de som arbetar exponeras mer än "vanligt" av vattnet som behandlas? När kan detta vara (vilken typ av arbetsuppgift)? Har flödet någon påverkan (Görs detta arbete oftare vid något typ av flöde)?

6. Vi har kollat lite på beredskapstimmar och jämfört med flödet och det verkar finnas ett samband som visar att beredskapstimmarna är högre vid höga flöden. Vad skulle detta kunna bero på?

7. Finns det andra arbetsuppgifter som oftare görs vid höga/låga flöden? Är arbetsmiljön bättre/sämre när dessa arbetsuppgifter utförs?

8. Övriga tankar, något arbetsmiljö/flödesrelaterat som kan vara bra att veta?

Safety/risks

1. Skiljer det sig i säkerhetsrutiner mellan höga flöden och lägre?

2. Har ni observerat några risker som uppstått på grund av höga/låga flöden?