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Evaluation of Rinse Water Recirculation Alternatives at Lackarebäck Water Treatment Plant

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

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ABSTRACT

Water treatment plants generate large volumes of residual streams during normal drinking water production. At Lackarebäck, one of two water treatment plants in Gothenburg, these streams currently amount to approximately 6,300 m^3 per day and are discharged without any reuse. This thesis evaluates three predefined alternatives for recirculation using a cost-benefit analysis (CBA), considering economic performance, climate impact, operational risks, and qualitative benefits over a 50-year analysis period.

The evaluation method monetizes changes in raw water abstraction, energy use, and wastewater discharge. Climate impacts are assessed through changes in energy consumption and greenhouse gas emissions and monetized by using a CO_2 shadow price to produce a net-present value (NPV) that includes financial costs and benefits as well as climate effects. Operational risks are evaluated qualitatively using a risk matrix, and selected benefits that are difficult to monetize reliably are assessed qualitatively alongside the economic results. Sensitivity, scenario and threshold analysis are performed to assess how uncertainties affect the results.

All three alternatives produce a negative NPV in the base case. Alternative A recirculates ultrafiltration backwash water and first filtrate, while Alternative B also includes carbon filter backwash water and clarified supernatant from sedimentation. Alternative C is the most extensive option with additional sedimentation before recirculation. Alternative B, which recirculates the second largest amount of water, stands out as the most balanced alternative based on the evaluation. It also shows a positive NPV when considered under optimistic assumptions. Alternative B is therefore recommended as a basis for further development but must be verified through sampling and more detailed cost and climate estimations.

Key words: Rinse water recirculation, cost-benefit analysis, water treatment, backwash water

Utvärdering av recirkulationsalternativ för spolvatten vid Lackarebäcks vattenreningsverk

Examensarbete inom masterprogrammet infrastruktur och miljöteknik

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SAMMANFATTNING

Vattenverk genererar stora volymer restvattenströmmar vid normal dricksvattenproduktion. Vid Lackarebäcks vattenverk, ett av två vattenverk i Göteborg, är dessa strömmar för närvarande på cirka 6 300 m^3 per dag och avleds utan någon form av återanvändning. Detta examensarbete utvärderar tre fördefinierade alternativ med hjälp av en kostnadsnyttoanalys (KNA), med hänsyn till ekonomi, klimatpåverkan, operativa risker och kvalitativa nyttor över en analysperiod på 50 år.

Utvärderingsmetoden värdesätter förändringar i råvattenuttag, energianvändning och utsläpp till avloppssystemet. Klimatpåverkan bedöms utifrån förändringar i energiförbrukning och växthusgasutsläpp och värdesätts med hjälp av ett CO_2-skuggpris för att ta fram ett nettonuvärde (NNV) som inkluderar både finansiella kostnader och nyttor samt klimateffekter. Operativa risker bedöms kvalitativt genom en riskmatris, och utvalda nyttor som är svåra att värdesätta tillförlitligt bedöms kvalitativt tillsammans med de ekonomiska resultaten. Känslighets-, scenario- och tröskelanalyser genomförs för att bedöma hur osäkerheter påverkar resultaten.

Samtliga tre alternativ ger ett negativt NNV i basfallet. Alternativ A recirkulerar backspolningsvatten från ultrafiltrering och förstafiltrat, medan alternativ B även inkluderar backspolningsvatten från kolfilter och klarfas från sedimentering. Alternativ C är det mest omfattande alternativet, med ytterligare sedimentering före recirkulation. Alternativ B, som recirkulerar den näst största vattenmängden, framstår som det mest balanserade alternativet utifrån utvärderingen. Det får även ett positivt NNV vid optimistiska antaganden. Alternativ B rekommenderas därför som grund för fortsatt utveckling, men behöver verifieras genom provtagning samt mer detaljerade kostnads- och klimatberäkningar.

Nyckelord: Recirkulation av spolvatten, kostnadsnyttoanalys, vattenrening, backspolningsvatten

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Preface

This master's thesis was carried out in collaboration with Kretslopp och Vatten, City of Gothenburg, within the Master Program Infrastructure and Environmental Engineering at the Department of Architecture and Civil Engineering at Chalmers University of Technology. The work was conducted during the spring semester of 2026. I would like to thank my supervisor Olof Bergstedt at Kretslopp och Vatten for his guidance and my examiner Andreas Lindhe for feedback during the process.

Göteborg, July 2026

Elias Jonsson

Notations

Roman upper case letters

Bt	Benefits in year t [SEK]
C	Consequence of an unwanted event [-]
Ct	Costs in year t [SEK]
E	Energy consumption [kWh/m³]
H	Pump head [m]
NPV	Net Present Value [SEK]
NPVclimate	Net Present Value of monetised climate effects [SEK]
P	Probability of an unwanted event [-]
PCO_2	CO_2 shadow price [SEK/kg CO_2-eq]
PV	Present value [SEK]

Roman lower case letters

g	Gravitational acceleration [m/s^2]
n	Number of years in the analysis period [years]
r	Discount rate [-]
t	Year index in the analysis period [-]

Greek letters

η	Pump efficiency [-]
ρ	Water density [kg/m^3]

Abbreviations

CBA	Cost-Benefit Analysis
CO_2-*eq*	Carbon dioxide equivalents
GAC	Granular Activated Carbon
MCDA	Multi-Criteria Decision Analysis
MSEK	Million Swedish kronor
NPV	Net Present Value
PFAS	Per- and Polyfluoroalkyl Substances
PV	Present Value
QMRA	Quantitative Microbial Risk Assessment
SEK	Swedish kronor
UF	Ultrafiltration
WTP	Water Treatment Plant

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1 Introduction

Sustainable water management is becoming increasingly important in a changing climate and under growing societal demands. Even in regions that have historically delivered sufficient amounts of water of high quality, the need to improve efficiency and system resilience has gained increased attention. Drinking water treatment plants play an important role in ensuring a reliable supply of safe water, and optimising internal processes is an opportunity to reduce overall water use.

This thesis investigates the economic, environmental, and operational effects of rinse-water recirculation at a municipal water treatment plant to support decision-making.

1.1 Background

Access to sufficient and safe drinking water is fundamental to human health. Despite this, water scarcity affects large parts of the world, either due to limited natural availability, insufficient infrastructure or increasing pressure on existing water infrastructure systems. In 2021, UN Water estimated that 10% of the global population lived in countries with high and critical water stress levels (FAO & UN-Water, 2024). From a global perspective, demand for freshwater is expected to continue rising due to population growth, urbanisation, and climate change.

Only about 0.5% of the water on Earth is usable and accessible for humans to use (Cullmann et al., 2021). Climate change has also brought changes in precipitation patterns, more frequent droughts, and greater variability in water supply. The result is increased pressure on existing water resources. At the same time, increasing demands from households, industry, and agriculture further pressure water systems. As a result, water is increasingly recognised as a scarce resource that requires careful management.

Challenges related to water scarcity and water management are also relevant for Nordic countries. Many of the larger Nordic cities face challenges with water resources, especially during dry summers and times of high demand. In Gothenburg, this has led to the project "Göteborg visar vägar till hållbar vattenanvändning", where the aim is to find ways to achieve more sustainable water usage. One measure under consideration is the recirculation of rinse water at the Lackarebäck water treatment plant. The aim is to treat the rinse water, reuse it and thereby reduce the overall water use.

Water treatment plants use large amounts of water to produce clean and safe drinking water. Therefore, reducing the internal water use could be important from both environmental and economic perspectives. By recirculating water, the need to use raw water is also reduced, which could increase the robustness of the supply system. Recirculation of rinse water can lead to more sustainable operations, but it requires assessment of climate impact, operational reliability, water quality, and economic implications. Since several technical options for handling residual streams exist, a comparative evaluation that considers economic, environmental, and risk-related aspects is required to support decision-making.

However, recirculation also introduces investment costs, additional treatment steps, increased energy use, climate impacts, and operational risks. Therefore, the decision cannot be based on water savings alone. This highlights the need for an integrated decision-support framework that evaluates rinse water recirculation alternatives not only in terms of economic performance, but also includes climate impacts and operational risks.

1.2 Aim and objectives

This project aims to assess and compare strategies for handling and recirculation of rinse water at the Lackarebäck water treatment plant to support informed decision-making. This will be done by evaluating a predetermined set of alternative strategies for handling and recirculation of rinse water with respect to economic, operational, climate-related, and risk-related aspects.

The following objectives are defined to achieve the aim of this thesis:

- Review existing treatment methods and solutions for rinse water treatment and reuse.
- Collect and analyze operational data related to rinse water treatment and current water use at the plant.
- Compare and assess a set of predetermined technical solutions for handling and recirculation of rinse water and residual streams.
- Evaluate the alternatives with respect to economic performance.
- Assess climate-related impacts for each alternative with a focus on energy use, water savings and increased emissions.
- Perform risk assessments for each alternative.
- Compare the alternatives using a structured assessment framework.

1.3 Limitations

The thesis is limited to evaluating predefined alternatives. The investigation of technical solutions is conceptual, and the investigation of new technical concepts regarding rinse water recirculation is outside the scope of the thesis. Therefore, the results should be interpreted as an early-stage decision support assessment rather than a detailed design or study. The main limitations of the analysis are summarized below:

- The recirculation alternatives are conceptual and not engineered in detail.
- Investment costs are based on estimates and not on actual offers.
- Water quality and volumes are based on the available data from the pre-study.
- Climate emissions related to construction are estimated at screening level and not a full life cycle analysis.

2 Theoretical background

This chapter provides the background needed to understand the study. It describes the drinking water treatment process at Lackarebäck, the residual water streams generated during normal operation, and the main principles of recirculation in water treatment systems.

2.1 Drinking water treatment plants

Drinking water treatment plants (WTPs) are designed to remove physical, chemical, and biological contaminants from raw water ensuring safe and reliable drinking water for consumers (WHO, 2022). The exact treatment configuration depends on raw water quality, requirements, and plant design. In Nordic countries, the treatment process typically includes coagulation, flocculation, sedimentation, filtration, and disinfection, although the specific process varies depending on the water quality, treatment need, and plant design.

Coagulation and flocculation are used to create larger particles in the water and to remove natural organic matter (NOM), often measured as colour or total organic carbon. NOM is a key parameter for coagulant dosing, reducing the effect of disinfection as well as adsorption to activated carbon and can cause membrane fouling. Coagulation and flocculation make removal easier during the following treatment steps. Sedimentation allows heavier flocs and particles to settle. This reduces the number of particles in the water before filtration. Filtration then removes remaining suspended solids, microorganisms and organic matter (Edzwald & American Water Works Association, 2011).

Different filtration techniques are applied depending on the plant and the raw water source. Typical filtration techniques include sand filtration, granular activated carbon (GAC) filtration or membrane filtration such as ultrafiltration (UF), microfiltration (MF) or reverse osmosis (RO)(Edzwald & American Water Works Association, 2011). Traditional granular filters depend on physical straining and adsorption and remove larger particles, while membrane filtration uses a barrier with specific small pores to remove smaller particles and microorganisms (Edzwald & American Water Works Association, 2011).

Water treatment plants generate internal wastewater streams in normal operation. These are for example residual streams from sedimentation processes and backwash water from filtration. Management of these streams influences both efficiency and overall water use. In many traditional surface water treatment facilities, the internal residual streams account for about 3-10% of the total treated water output (Edzwald & American Water Works Association, 2011). This highlights the significant impact of internal water management on overall plant efficiency and resource utilisation. Improving how these internal streams are managed might be a great way to help reduce freshwater intake.

2.2 Lackarebäck drinking water treatment plant

Lackarebäck water treatment plant is one of the two main drinking water treatment facilities supplying Gothenburg. Raw water is taken from the Göta River and pumped to Delsjöarna, where it is stored before being transported to the treatment plant (Kretslopp och vatten & Göteborgs Stad, n.d.). Together with Alelyckan water treatment plant, the other large treatment plant in Gothenburg, they produce 170 million litres of drinking water per day (Kretslopp och vatten & Göteborgs Stad, n.d.).

The treatment process consists of pretreatment with pH adjustment followed by coagulation using aluminium sulphate to promote the formation of flocs (Kretslopp och vatten & Göteborgs Stad, 2016). The formed flocs are removed from the water in the sedimentation basin before the water passes through carbon filtration for the removal of remaining particles and substances causing taste and odour (Kretslopp och vatten & Göteborgs Stad, 2016).

As an additional microbial barrier, the water passes through ultrafiltration membranes, which remove bacteria, viruses, and parasites. In the final stage, pH and hardness are adjusted, and small amounts of chlorine and chlorine dioxide are added to protect the distribution network (Kretslopp och vatten & Göteborgs Stad, 2016).

A preliminary study performed by Kretslopp och Vatten in 2019 investigated the internal streams in Lackarebäck water treatment plant. The internal streams and volumes can be found in Table 1.

Table 1: Residual streams at Lackarebäck water treatment plant

Residual stream	**Volume (m^3/d)**
Ultrafiltration rinse water	3900
Rinse water carbon filtration	1900
First filtrate from carbon filtration	500
Chemical waste stream from ultrafiltration	400
Clarified supernatant from sedimentation	<300

The large volumes of ultrafiltration rinse water and carbon filtration backwash water suggest that internal water streams make up a significant share, about 7% of the production at Lackarebäcks water treatment plant. This shows that recirculation strategies could improve water use and operational efficiency, highlighting the need for further assessment.

2.3 Filter backwashing and rinse water management

Filtration of water is a key step in drinking water treatment plants. This ensures the removal of suspended solids and flocs prior to the distribution of the water. However, to maintain the performance of the filter, backwashing is used to remove accumulated particles in the filters (Edzwald & American Water Works Association, 2011). Backwashing typically involves reversing the flow of water to detach solids and particles from the filter.

This process generates water containing suspended solids, coagulant residues, organic matter, and, depending on the water source, metals such as iron and manganese. In membrane systems, backwashing also removes particles and microorganisms from the membrane. Spent filter backwash is generally the largest residual stream by volume, but it usually contains fewer solids than other residual streams (Edzwald & American Water Works Association, 2011).

Traditionally, backwash water has been discharged to the sewer system, returned to the raw water source, or treated separately before disposal. However, increasing focus on water use and resource efficiency has led to a growing interest in recirculation or reuse of rinse water within the treatment plant (Hilmersson Haag et al., 2023). At Lackarebäck the backwash water and residual streams are currently discharged as wastewater or as stormwater.

2.4 Economic evaluation of infrastructure projects

Economic evaluation is important to decision-making in infrastructure investments, and even more when public resources are involved. Cost-benefit analysis (CBA) is a decision-support tool for assessing whether a project or investment has a positive societal impact over time by comparing the total costs and benefits (Naturvårdsverket, 2003; Trafikverket, 2026). The main purpose of CBA is to determine whether the total benefit of the project exceeds the total costs of the project, seen from a societal perspective (Nas, 2018). In the case of water recirculation, CBA provides a framework for evaluating whether the reduced raw water abstraction and operational savings justify the investment and potential risks associated with a new system.

CBA differs from a business analysis as it considers costs and benefits affecting society as a whole and includes effects that are not directly reflected in market prices (Nas, 2018). This point is especially important for water treatment systems, where the environmental and risk-related impacts might not be fully captured in market prices.

In a CBA, costs and benefits could occur at different points in time. Investments typically involve a high upfront cost, while benefits, such as reduced operating costs, are realised over a longer period. To make it comparable to each other, future costs and benefits are discounted to the present value using a discount rate (Nas, 2018).

The present value (PV) of future benefits is calculated as:

$$PV = \frac{B_t}{(1+r)^t} \qquad (1)$$

B_t represents the benefits in year t, and r is the discount rate.

A project's overall economic performance is typically represented by the Net Present Value (NPV), which is defined as:

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \qquad (2)$$

A project is considered socio-economically beneficial if the NPV is positive, meaning that the total discounted benefits exceed the total discounted costs.

For the evaluation of rinse water recirculation in water treatment plants, examples of relevant cost and benefit components are presented in Table 2.

Table 2: Examples of costs and benefits

Benefits	**Costs**
Reduced raw water abstraction	Investment costs
Lower discharge fees	Operation and maintenance costs
Reduced energy use	Energy consumption
Increased robustness of the water supply	Chemical consumption
Environmental benefits e.g. decreased greenhouse gas emissions from i.e. treatment chemicals	Increased greenhouse gas emissions due to new equipment

Climate impact can be included in a CBA by identifying and monetizing changes in greenhouse gas emissions for each of the alternatives. This means first quantifying changes in electricity use, chemical consumption, or greenhouse gas emissions. To compare emissions across different units, an emission factor can be used to convert all emissions to CO_2 equivalents. To then include climate impact in a cost-benefit analysis, CO_2 equivalents must be converted into monetary terms using a shadow price.

2.5 Climate and energy assessment in water treatment

Treating drinking water requires energy and chemicals, both of which produce greenhouse gas emissions. When looking at water recirculation options, it is important to consider how each alternative affects energy use and environmental impact.

Energy consumption in water treatment plants is mainly linked to raw water abstraction and pumping, energy for filtration processes, backwashing, and handling of sludge and residuals. Including recirculation of rinse water may reduce energy consumption by reducing raw water pumping but also increase electricity consumption if additional treatment is required (Edzwald & American Water Works Association, 2011).

Greenhouse gas emissions are usually expressed as carbon dioxide equivalents (CO_2-eq). Electricity is expressed as energy consumption (kWh), which, when multiplied by an emission factor (kg CO_2-eq per kWh), can be compared directly to CO_2 equivalents (WRI & WBCSD, 2004). Other emissions, for example, from the use of chemicals or new infrastructure investment, are also relevant and should be included in the total climate evaluation of the alternative.

2.6 Risk assessment in technical systems

Implementing new infrastructure or operational changes to technical systems involves uncertainty and potential risks. In addition to the economic and climate-related impacts, risk assessment is an important part of decision-making processes.

Risk is commonly defined as the combination of the probability of an unwanted event and the consequence of the event (WHO, 2022):

$$Risk = P \times C \qquad (3)$$

Where P is the probability of the event occurring and C represents the consequence if the event occurs.

In drinking water treatment plants, there are several risks that should be considered. Both technical and operational risks are relevant to rinse water recirculation. In Table 3 some examples of risks related to the recirculation of rinse water are listed. These risks reflect common challenges associated with backwash water recirculation in drinking water treatment (Edzwald & American Water Works Association, 2011), as well as regulatory requirements for drinking water quality (WHO, 2022).

Table 3: Examples of risks

Risk category	**Examples of risks**
Operational risk	Process instability, increased maintenance needs, reduced treatment efficiency
Technical risk	Membrane fouling, clogging of filters, pump failure, increased system complexity
Water quality risk	Accumulation of contaminants, microbial regrowth, build-up of metals
Regulatory risk	Violation of quality limits

Risk assessment of technical systems is closely related to uncertainty (SIS, 2018). In water treatment plants, uncertainty can be caused by, for example, changes in raw water quality, limited operational data and history, or a lack of understanding of how the system works. Recirculating rinse water can also contribute to a buildup of contamination, and these long-term effects must be considered when making decisions on recirculation.

In infrastructure assessments, risks are usually evaluated using risk matrices. Here, risks are evaluated qualitatively or semi-quantitatively. Since quantitative methods often need detailed failure data that may not be easily available, a qualitative assessment is often a more practical used approach (WHO, 2022).

When evaluating rinse water recirculation alternatives, risk assessment works as a complement to economic and climate analyses. By identifying and comparing potential risks across different alternatives, decision-makers can consider economic and climate performance along with uncertainties and possible negative outcomes that could have an impact on the long-term performance.

2.7 Structured comparative assessment framework

Decision-making for infrastructure projects often involves multiple criteria that are hard to capture in a single evaluation method. The previous sections have established the theoretical foundations for each of the main perspectives discussed in this thesis. These perspectives use different units and methods, which makes it difficult to consider them all together. Therefore, a structured assessment framework is needed to ensure that each alternative is evaluated consistently.

Economic impacts are assessed through discounted costs and benefits. Climate impacts are measured by changes in energy use and greenhouse gas emissions. Risk-related aspects are evaluated by looking at probability and consequences. By using cost-benefit analysis (CBA), economic effects and monetised climate effects can be expressed in a common monetary unit, which allows direct comparison (Nas, 2018). Risk-related aspects and benefits that cannot be monetized reliably can be presented alongside the monetized results which allow decision-makers to weigh them separately. This makes the results more traceable and the differences between alternatives clearer. Also, adding an uncertainty analysis could highlight how different parameters affect the outcome, which is important to support informed decision-making.

Other decision support tools include Multi-Criteria Decision Analysis (MCDA). MCDA is good for decision-making when several types of criteria are involved which e.g. cannot be expressed in monetary terms (Department for Communities and Local Government, 2009). It usually involves considering each criterion carefully, which can sometimes introduce subjectivity. Since the aim of this thesis is to deliver structured and reproducible decision support, CBA has been selected.

The following chapters review existing articles and relevant information on water recirculation practices, economic assessments, and the regulatory framework to evaluate the current situation.

3 Literature review

This literature review aims to provide an overview of the existing findings from research and articles on rinse water treatment, recirculation strategies, and evaluation methods used in water treatment systems.

Scientific literature was identified through systematic searches of the Chalmers University Library search function and Google Scholar. Search strings were used to find studies addressing technical solutions, economic evaluation, climate-related impacts and risk-related considerations that were relevant to this thesis.

The Scopus AI tool was used as a support tool to improve search terms, identify relevant studies and summarise key points in the literature quickly. However, all selected literature was reviewed and manually assessed to ensure relevance and quality to this thesis.

3.1 Rinse water treatment and recirculation practices

Several studies have investigated the possibility of reusing backwash water within drinking water treatment systems. Wolska & Urbańska-Kozłowska (2023) assessed the potential for reintroducing treated backwash water into the treatment process in an article from 2023. They reported that backwash water accounts for approximately 5% of the total treated water production after analysis of two different water treatment plants, which is a considerable amount of the internal water flow. Most of this volume came from sand filters, which represented 90% of the total backwash volume.

Although the filter configuration in the article differs from that using granular activated carbon and membrane processes, the findings show that backwash water makes up a significant part of the internal flow and has potential for recirculation. However, the study also identifies several technical challenges linked with increased levels of iron, manganese, and microorganisms. These results indicate that backwashing should be pretreated in sedimentation or other separation processes and disinfected before being returned to the system. Wolska and Urbańska-Kozłowska estimate annual savings of 150,000 EUR for surface water treatment plants through reduced abstraction and discharge fees. However, the article does not include investment and operational costs associated with pretreatment processes.

A similar approach was investigated by Komorowska-Kaufman & Toczek (2022). They analyzed backwash water recirculation in a surface water treatment plant supplying a combined heat and power facility. In this case, backwash water was treated through sedimentation before being returned to the beginning of the treatment plant. The authors reported that the reduction in the annual amount of abstracted raw water was approximately 130,000 $m^{3,}$ which corresponds to an 8.3% reduction.

The treatment process included a small dose of coagulant prior to the sedimentation process which achieved high removal efficiency, including both a 96% reduction in iron concentration and 97% reduction in turbidity. This treated backwash water was found to be of similar quality, or in some parameters, better than the raw surface water being introduced to the plant. These findings demonstrate that a relatively simple sedimentation-based solution was effective. However, like the article Wolska & Urbańska-Kozłowska, this article also focuses on technical performance and less on investment costs, climate aspects and operational risks.

Gora and Walsh (2011) investigated a different approach by mixing 10% of ultrafiltration backwash water directly with raw water in a treatment train consisting of flocculation and ultrafiltration (UF) without any pretreatment of the recycled water. Their results demonstrated no deterioration in water quality, and one of the two treatment plants investigated showed improved removal of organic matter. However, the authors advise that further studies are needed to investigate the effects on membrane cleaning frequency and potential fouling of the ultrafiltration membrane.

In contrast to direct recirculation with raw water Wolska et al. (2025) evaluated ultrafiltration as a pretreatment step prior to recirculation of backwash water from the sand filter. Two different membrane types were compared: 200 kDa and 80 kDa. Of these two, the 80 kDa membrane generally proved more efficient, showing effective elimination of microorganisms, iron, and manganese. The authors estimated that implementing this system would increase the cost of water treatment by less than 5% of the current water price, while at the same time enable significant reduction in water abstraction. However, water price typically reflects distribution and renewal costs rather than marginal treatment costs. The reported percentage from this study is therefore not directly comparable to the estimates used in this thesis.

To reduce microbial contamination in backwash water, Wolska et al. (2024) investigated disinfection as a stabilisation method for the reuse of backwash water. They demonstrated that both chlorination and UV radiation can significantly reduce microbial contamination in backwash water from sand filters to levels comparable to those in the raw water source. However, high doses of disinfectant were needed, and chemical disinfection led to the formation of trihalomethanes (THMs). This shows potential trade-offs between microbial safety and the formation of by-products.

The article also reports investment costs of 50,000 or 60,000 EUR for chlorine and UV disinfection, respectively, and operating costs of 0.02-0.05 EUR/m^3, depending on the disinfection method. Reuse of backwash water accounted for approximately 5% of the total treated water volume, while total treatment costs increased by 1.5-4.5%. The findings from Wolska et al. show that recirculation may require additional treatment to ensure microbiological safety. Although around 5% of treated water can be reused, this comes with higher operational and investment costs and increased system complexity. This indicates that both economic and operational aspects must be considered together with the actual water savings.

Along with technical and operational considerations, health risks need to be evaluated. Mahdavi et al. (2024) looked into potential health risks associated with the reuse of treated backwash water at the Saveh Water Treatment Plant. The study uses assessment models, like quantitative microbial risk assessment (QMRA), to evaluate the health risks associated with treating backwash water through sedimentation and coagulation processes. The results showed that hazard risk index values stayed below the critical limits. This indicates that reuse did not present major health risks under the conditions studied.

However, Mahdavi et al. (2024) emphasized that risk levels depend on the efficiency and proper operation of the system. Overall, it highlights the importance of considering risks when evaluating recirculation strategies for drinking water systems.

The reviewed articles demonstrate that several different technical approaches to rinse water recirculation exist. They range from reintegration of recycled water directly into the treatment train without any pretreatment to processes that use sedimentation, disinfection, or membrane technologies. The required treatment level of the rinse water depends on the raw water characteristics, plant configuration and the desired risk tolerance. While some studies indicate that existing treatment barriers may be sufficient, others emphasize that additional stabilization measures are needed to ensure reliability and desired water quality.

Although several studies report reductions in freshwater abstraction of approximately 5-8%, energy use and climate-related impacts are given less attention. Implementing new treatment steps for rinse water may increase energy consumption and could offset some of the benefits of reducing water abstraction. This indicates that climate-related aspects remain unexplored in the literature.

3.2 Economic evaluations of rinse water or similar industrial systems

Economic feasibility is an important aspect in decision-making processes. Molinos-Senante et al. (2011) show that in the water reuse projects examined, using cost-benefit analysis often focused on internal cost and revenues, while external impacts such as environmental benefits were addressed qualitatively or not monetised. The framework proposed in the article distinguishes between internal benefits, such as investment and operational costs, and revenues from reclaimed water, and external benefits related to the reduction of discharged pollutants and improved environmental quality.

Molinos-Senante et al. (2011) demonstrate that several water reuse projects were considered not economically viable when only considering internal benefits. However, when external benefits were monetised and considered, the project became feasible. This highlights the importance of using a wide economic perspective when evaluating water reuse strategies.

A cost-benefit analysis of wastewater reuse in Puglia, Italy by Arborea et al. (2017), found that economic feasibility strongly depends on local conditions. It compared different reuse scenarios and found that project feasibility varied based on plant size, infrastructure needs, and water demand in the region. Larger plants had lower per-unit water costs, while smaller plants had higher per-unit costs.

The results from Arborea et al. (2017) showed that economic results were affected by aspects like discount rates and the expected environmental benefits. This means that economic results for water reuse projects must fit the specific technical and regional context of each water treatment plant. These insights are relevant to drinking water treatment plants, where the total economic benefits might not be large compared with large-scale wastewater reuse projects. However, operational reliability and regulatory compliance can be important in decision-making.

From the literature, it can be concluded that the use of recirculated rinse water can help reduce the use of fresh water. There are many technical options available. However, most of these studies have focused either on technical aspects or economic results, fewer have considered economic effects, operational risks, climate impact and qualitative benefits within the same assessment. This indicates a need to explore how cost-benefit analysis can be used to provide a more comprehensive assessment including both positive and negative effects associated with rinse water recirculation and thereby support more informed decision-making.

3.3 Examples of implementation in Nordic water treatment plants

Numerous studies have examined technical and economic aspects of rinse water recirculation as presented in the previous sections. Fewer have documented examples of full-scale implementations. However, in this section, some examples from Denmark and Norway will be presented to illustrate how regulations and site-specific conditions influence practical solutions of internal reuse.

In Denmark, multiple waterworks have implemented internal reuse of filter backwash water. At Farum Waterworks, they treat around 500,000 m^3 of water yearly through open sand filters (EUROWATER, n.d.-b). To remove iron precipitation from the filters, backwashing is essential to achieve sufficient treatment levels. The backwash water is collected and later treated using pressure filters and UV disinfection. After quality control, it is released into the raw water and becomes clean drinking water. They report that 96% of the backwash water is reused, and estimations show that this represents a yearly saving of 67,000 euros (EUROWATER, n.d.-b).

Another example is a small water treatment plant in Ulfborg, Denmark, that produces 60 m^3 of water per hour (EUROWATER, n.d.-a). High wastewater discharge fees motivated the implementation of internal backwash water reuse. Instead of discharging it directly to the sewer system, they installed a separate pressure filtration unit to treat water from a settling tank. The entire backwash volume is reused in the process, reducing abstraction fees and eliminating discharge fees. As an extra safety measure to prevent microbial growth, UV disinfection was installed in the settling tank (EUROWATER, n.d.-a).

In Norway, there are fewer documented examples. One, however, is the Oset water treatment plant, which serves as the main water treatment plant in Oslo, and was built in 2007 and is designed with strict discharge limitations(Enander & Sveen, 2006). At the time of construction, the treatment plant was limited to discharging 10 l/s to the downstream sewer network due to capacity constraints. This influenced the treatment plant design and made handling of backwash water, sludge streams and residual flows a must. This example shows that infrastructure limitations also affect water management strategies.

These examples illustrate the importance of local regulations, economy and infrastructure limitations. The Danish examples were economically driven, but the Norwegian example showed how regulations affect design. This difference highlights the need to assess recirculation strategies in their specific settings.

3.4 Regulatory differences between the EU and the USA

The rules for recycling of backwash water are different in the United States compared with European nations. In the US, the Environmental Protection Agency (EPA) created the Filter Backwash Recycling Rule (FBRR) to help manage the reuse of waste streams like filter backwash water from treatment plants (EPA, 2002). The rules state that recycling streams, like backwash water, must go back through the existing treatment processes or an approved alternative site. These regulations were introduced after several reported outbreaks of waterborne diseases linked to poor treatment of recycling streams.

In contrast, there is a lack of specific regulations in the European Union regarding filter backwash recycling. Drinking water safety in the European Union is regulated by the EU Drinking Water Directive (EU) 2020/2184, which takes a preventive approach based on risk management by requiring water suppliers to conduct risk assessments and implement control measures across the supply chain (EU, 2020).

Nordic countries implement the EU directive through national requirements. In Sweden, the EU directive is given through *Livsmedelsverkets föreskrifter om dricksvatten* (LIVSFS 2022:12), which emphasizes risk assessment, hazard control and requirements related to documentation (Livsmedelsverket, 2022). Similarly, in Norway, *Drikkevannsforskriften* requires water suppliers to find hazards and ensure that water treatment processes are sufficient to prevent health risks (Helse- og omsorgsdepartementet, 2016).

As a result, US regulations specifically address backwash recycling in the FBRR, while in the EU and Nordic countries, there are mainly performance and risk-based regulations. In Europe, reusing rinse water internally is not strictly regulated. But a risk assessment must be performed to ensure it meets drinking water quality standards.

These regulatory differences can affect both the design and documentation needed for recirculation systems. In risk-based frameworks like those in the EU and Nordic countries, water suppliers have a greater responsibility to prove that internal reuse does not threaten drinking water safety, which could influence how complicated the implementation is.

In summary, the literature suggests that rinse water recirculation can lower raw water intake, but most studies mainly examine technical feasibility and economic impacts. There is relatively limited research that combines economic evaluation, operational risks, climate effects, and other qualitative benefits into one single comprehensive assessment. This thesis aims to fill this gap by using a cost-benefit analysis framework on a predefined set of recirculation scenarios.

4 Methodology

This study evaluates different strategies for the management of residual streams at the Lackarebäck water treatment plant using a structured comparative assessment framework. The main method for evaluation is cost-benefit analysis (CBA). The CBA is used to compare the costs and benefits of three predefined recirculation alternatives relative to the current handling of residual streams. In addition to the direct economic costs and benefits, monetized climate effects are included in a climate-adjusted NPV, while operational risks and selected benefits are assessed qualitatively.

This approach is a standard way to look at the social and economic impacts of infrastructure projects. Three recirculation alternatives are evaluated against the current operation at Lackarebäck. By examining the costs and benefits of each alternative, CBA provides a clear way to determine if an investment is beneficial or not.

This study does not limit the assessment to only direct costs and benefits for the water utility. Instead, it applies a broader socio-economic perspective by also considering risks, qualitative benefits, and climate-related impacts. Climate-related impacts are assessed based on changes in energy consumption and greenhouse gas emissions. Operational risks are considered qualitatively to take uncertainties related to system performance, treatment reliability, and water quality into account. Some benefits are also assessed qualitatively because of the large uncertainty related to monetizing them.

4.1 Analytical framework

To ensure clarity and a systematic approach, the analysis follows a step-by-step framework based on cost–benefit assessments typically used in infrastructure planning. In the guidelines for socio-economic analysis of environmental projects made by the Swedish Environmental Protection Agency a similar approach is also recommended (Naturvårdsverket, 2003).

The evaluation consists of the following main steps:

1. Definition of reference scenario and alternatives
2. Estimation of flow volume and changes
3. Cost estimation
4. Benefit estimation
5. Climate impact assessment
6. NPV and climate-adjusted NPV calculation
7. Qualitative risk assessment
8. Qualitative benefit assessment
9. Sensitivity, scenario, and threshold analysis
10. Comparative evaluation of alternatives

This method allows a consistent and clear evaluation of technical performance, economic impacts, and risk considerations among the different alternatives.

4.2 Residual streams included in the analysis

This study analyses four residual streams produced during treatment at the Lackarebäck water treatment plant: ultrafiltration backwash water, carbon filter backwash water, clarified supernatant from sedimentation and the initial filtrate from carbon filtration. These streams were chosen because they are the largest internal water flows being discharged and have the best potential for water recovery through recirculation.

Backwash water from the ultrafiltration (UF) system is the largest residual stream in this study, with an estimated flow of about 3,900 m^3 per day. The treatment plant consists of two parallel halves which each have eight chemical precipitation lines and eight UF lines. UF backwashing occurs independently in the different UF lines and due to frequent backwashing, the resulting flow is close to being continuous. This backwash mainly consists of permeate used to clean the membrane surface, along with particles retained during ultrafiltration. These particles are mostly from previous treatment steps and are materials that the membranes normally remove during operation. Water analyses show that most parameters are within acceptable limits, although some samples have variations in pH and higher aluminum concentrations.

Recycling this stream could significantly reduce raw water intake and discharge due to its high flow rate. However, the presence of concentrated particles and membrane-cleaning residue may require additional treatment before it can be recirculated.

Backwash water from the carbon filters is another major residual stream, with an estimated flow of around 1900 m^3 per day. It is generated during backwashing of the carbon filters. This stream includes particles accumulated in the filter beds during operation, as well as water that is comparable in quality to the carbon filter effluent. Most of the particles are aluminum hydroxide precipitates that come from residual flocs left behind after the sedimentation. As a result, there may be a high particle load and a high level of aluminum in the stream. Due to the particle load, there may be problems with recirculation without proper treatment. Some samples showed PFAS levels higher than those in the incoming raw water, however, these results will be verified through repeated sampling to confirm the results. The feasibility study recommends additional treatment, such as sedimentation or membrane filtration, before recirculating the water within the process. PFAS are persistent compounds that do not break down in traditional water treatment processes. If elevated concentrations are confirmed in this stream, it could cause gradual accumulation within the treatment process, which in turn could affect the water quality.

The initial filtrate from the carbon filtration process is a smaller residual stream, estimated at around 500 m^3 per day. It occurs during the start-up phase after backwashing of the carbon filters. Although the initial filtrate is generally more similar in quality to standard carbon filter effluent than to backwash water, it still contains particles that must be flushed out before stable filtration can continue. These particles are mostly made up of leftover floc material, like aluminum hydroxide from earlier coagulation and sedimentation steps.

The initial filtrate has a relatively low level of contamination when compared with other residual streams in this study. Therefore, it is a suitable candidate for recirculation within the treatment process, needing little or no additional treatment. Together, these streams represent a combined flow of approximately 6,300 m^3 per day, showing a strong potential to reduce raw water intake.

In addition to these streams, clarified supernatant from the sedimentation basins is considered beneficial for recycling. The clarified supernatant from sedimentation occurs during emptying of the basin, which occurs at most once per week. Preliminary assessments conclude that the volume during emptying can reach up to 2500 m^3 (Hilmersson Haag et al., 2023). Exactly how this stream should be handled for recirculation is not clear, as it depends on ongoing decisions about local sludge handling at the treatment plant. An idea is to directly recirculate only the upper part of the basin. Another option is to recirculate the entire stream from the basin, but this would probably require more extensive treatment before recycling.

It should also be noted that reducing the volume of residual streams may be an alternative to recirculation. For example, the volume of the first filtrate has already been reduced, and improved sludge withdrawal from the sedimentation basin could further reduce the need to recirculate clarified supernatant. Measures like these, therefore, represent an alternative strategy to recirculation.

For all the streams, there is uncertainty related to the sampling done for the pre-study. Additional sampling has been carried out, but the results are not yet available.

4.3 Residual streams excluded in the assessment

Other residual streams involved in the treatment process include chemical-cleaning wastewater from cleaning the ultrafiltration process. This is a small volume of water and is expected to have a limited impact on the plant's overall water balance. According to the preliminary assessment, this stream is expected to be discharged into the stormwater system (Hilmersson Haag et al., 2023). The same procedure is also being followed at the Alelyckan treatment plant, indicating that this handling method should be technically feasible.

Water quality tests from the preliminary study showed that the stream has low pH levels, probably due to cleaning chemicals used during membrane maintenance(Hilmersson Haag et al., 2023). Because of these chemicals and the limited safe recirculation options within the treatment process, this stream is excluded from the current analysis. The study instead concentrates on residual streams that offer better opportunities for treatment and reuse within the water treatment plant.

4.4 Current scenario

The reference scenario is the current situation at the treatment plant. There is currently no internal recirculation of water streams, as they are either discharged to the wastewater system or to the nearby Mölndalsån as stormwater. Figure 1 shows an overview.

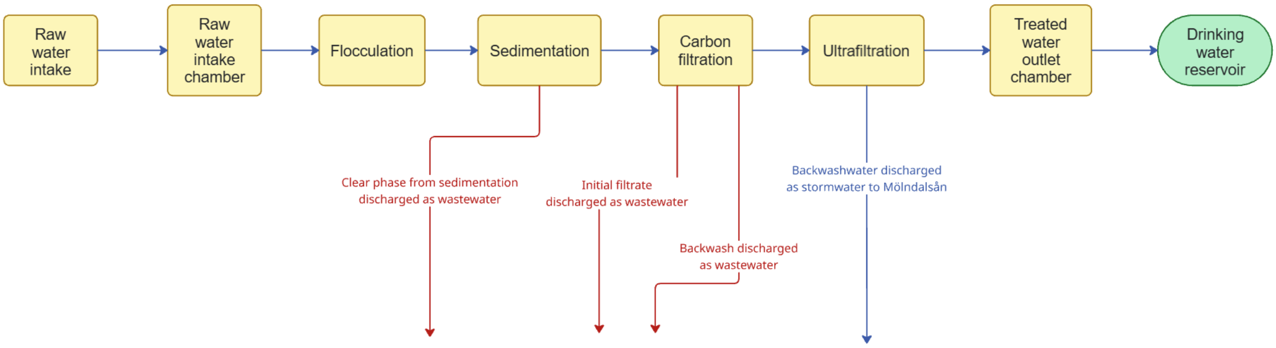

Figure 1: Current handling of relevant backwash water and residual streams

4.5 Definition of alternatives

The study assesses a predefined set of options for managing backwash water and residual streams at Lackarebäck water treatment plant. The baseline is the current situation. Therefore, costs and benefits in alternatives A, B, and C represent changes compared with the current situation and not total plant-level costs and benefits. Water streams that are considered are the backwash water from ultrafiltration and carbon filtration, the initial filtrate from the carbon filter and clarified supernatant from the sedimentation basin. The existing volumes and handling methods are detailed in Table 4.

Table 4: Assessed residual streams

Residual stream	**Flow [m³/day]**	**Current handling**	**Characteristics**	**Main challenge for recirculation**
Ultrafiltration backwash	3900	Discharged as stormwater to Mölndalsån	Concentrated particles, possible chemical residues	Risk of particle accumulation and membrane/process load
Carbon filter backwash	1900	Discharged as wastewater	High particle load, aluminum hydroxide	High solids content, may require pretreatment
Initial filtrate carbon filter	500	Discharged as wastewater	Lower contamination, but contains residual particles	Uncertain water quality during early filtration phase
Clarified supernatant from sedimentation	<300	Discharged as wastewater	Low particle load, chemical residue from flocculation	Quality depends on the mixing during emptying of the basins

The alternatives differ in terms of which residual streams that are recirculated, the pre-treatment process used before recirculation and where in the treatment process the streams are returned. Alternative A represents the least extensive solution and focuses on recirculation of ultrafiltration backwash water and first filtrate from carbon filtration. Alternative B includes additional recirculation of carbon filter backwash water and clarified supernatant from sedimentation. Alternative C is the most extensive solution and includes higher degree of treatment before recirculation. The alternatives were developed to represent increasing levels of water recirculation, investment needs, complexity and potential risks.

Table 5: Recirculation alternatives

Stream	Alternative A	Alternative B	Alternative C
UF backwash water	Secondary UF, returned before primary UF	Secondary UF, returned before primary UF	Secondary UF, returned before coagulation
Carbon filtration backwash water	Handled as today	Secondary UF, returned before coagulation	Sedimentation + UF, returned before UF
First filtrate from carbon filtration	Returned without pre-treatment before primary carbon filtration	Returned before coagulation	Sedimentation, returned before primary UF
Clarified supernatant	Handled as today	Upper phase returned before coagulation	New sedimentation + UF, returned before coagulation

Alternative A is the simplest and least extensive of the alternatives being assessed. It recirculates ultrafiltration backwash water after a secondary ultrafiltration treatment process and returns first filtrate from carbon filtration without any additional treatment. Carbon filter backwash water and clarified supernatant from sedimentation are handled as in the current operation. This alternative therefore has relatively low investment cost and complexity, however it also recirculates the least amounts of water compared with alternatives B and C.

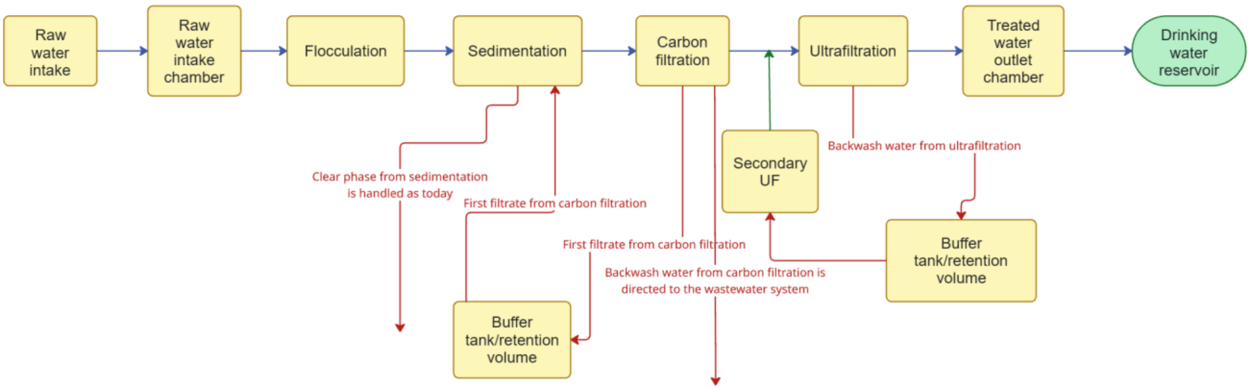

Figure 2: Alternative A

Alternative B increases the degree of recirculation by including carbon filter backwash water and the upper clarified supernatant from the sedimentation. The carbon filter backwash water goes through secondary UF before it is returned to the raw water side. In contrast, the first filtrate and clarified supernatant are returned with no pre-treatment. This improves water recovery but also adds complexity to flow management and raises the risk of particle buildup.

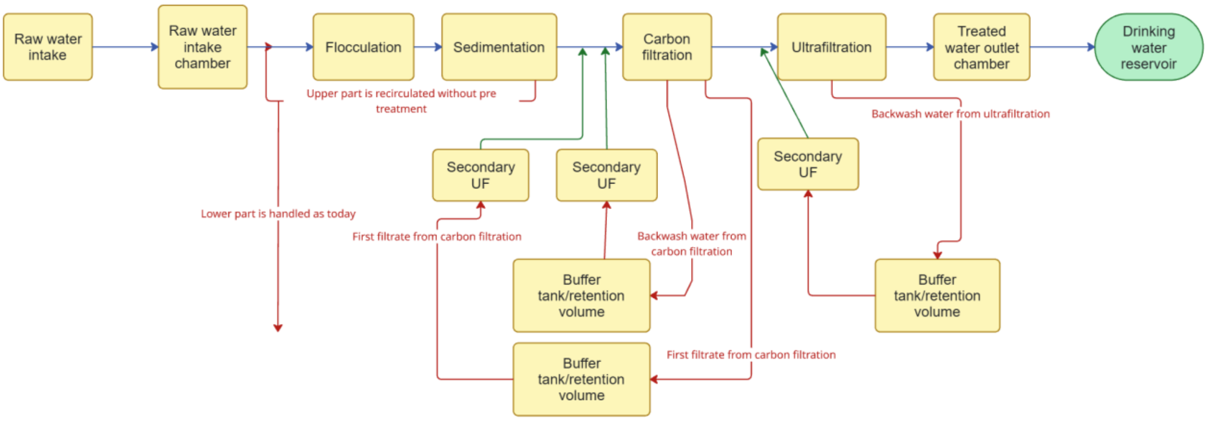

Figure 3: Alternative B

Alternative C is the most advanced and extensive option. It involves recirculating all the streams considered and adds extra sedimentation treatment before clarified supernatant is returned to the treatment process. This alternative offers the best water recovery but also requires the most investment, more infrastructure, and greater operational complexity.

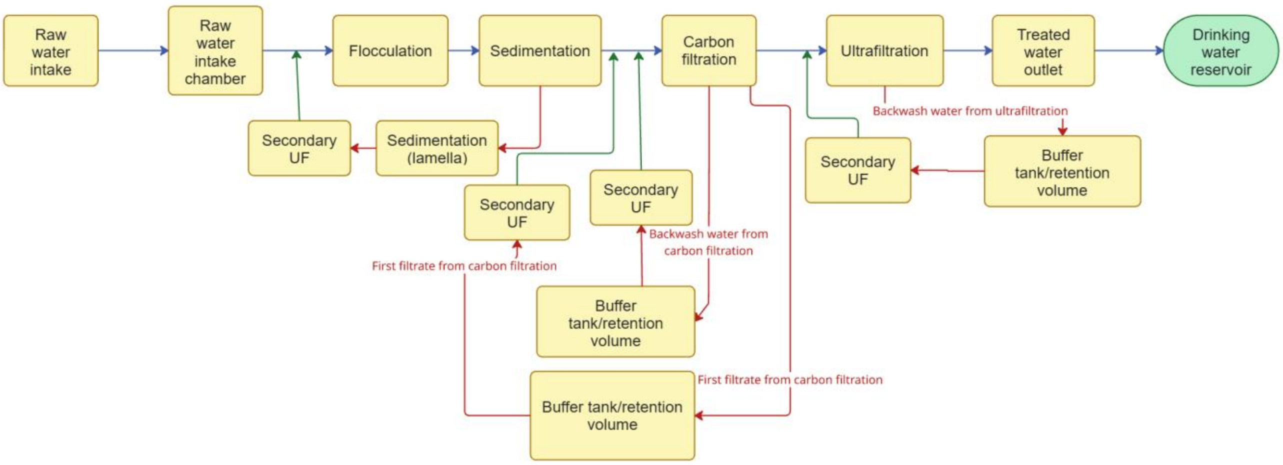

Figure 4: Alternative C

4.6 Cost-Benefit Analysis Framework

A cost-benefit analysis (CBA) is used to evaluate the economic feasibility of different alternatives for handling residual streams at Lackarebäck water treatment plant. The analysis compares the costs of implementing and operating each alternative with its potential benefits. Climate impacts were identified and monetized using a CO_2 shadow price. In this study, the NPV that includes both direct economic costs and benefits for the water utility and monetised climate impacts is referred to as the climate-adjusted NPV. Meanwhile, risks and benefits that could not be quantified were evaluated through a qualitative approach. The CBA was done by estimating costs and benefits relative to the current handling of residual streams. Investment costs and emissions from construction were assumed to occur in year 0, while annual benefits and operating costs were assumed to remain constant over the analysis period.

Prior to the estimation of costs and benefits, several inputs were needed to perform the CBA. One primary driver of benefits is the reduction in the amount of water pumped from the raw water intake to Lackarebäck and the reduction in water directed to the wastewater and stormwater system. This has been based on the identified flows from the pre-study. These volumes create the basis for estimating both economic benefits from reduced pumping costs and the climate benefits from reduced wastewater treatment emissions. The volumes are found in tables 6 and 7.

Table 6: Water savings due to internal recirculation

Treatment processes	**Alternative A**	**Alternative B**	**Alternative C**
Ultrafiltration	3900	3900	3900
Carbon filtration	0	1900	1900
First filtrate	500	500	500
Clarified supernatant	0	150	300
Sum (m^3/d)	4400	6450	6600

Table 7: Annual reduction of water being discharged to wastewater and stormwater, respectively

Reduction of water to stormwater and wastewater in m^3/year	**Alternative A**	**Alternative B**	**Alternative C**
Stormwater	1 423 500	1 423 500	1 423 500
Wastewater	182 500	930 750	985 500

4.7 Cost estimation

The cost estimation includes both investment and operational costs associated with the different alternatives. Investment costs include the infrastructure required for implementing the alternatives, such as tanks, pipelines, pumps and treatment equipment.

Operational costs include additional electricity used for internal recirculation pumping, labour, membrane cleaning chemicals for secondary UF, and annualized membrane replacement, where relevant. In alternatives where additional treatment steps are introduced, such as sedimentation or secondary ultrafiltration, operational costs include chemical consumption and membrane operation.

Investment costs were based on the preliminary estimations provided by the supervisor at Kretslopp och Vatten. These estimates cover the main infrastructure components needed for each alternative, including secondary UF, buffer and equalization volumes, piping, installation, and sedimentation. Additional energy use was calculated from the required pumping due to internal recirculation in each alternative using flow volume, pump head and pump efficiency.

Table 8: Cost components

Cost component	**Included in CBA**	**Estimation method**	**Comment**
Investment cost	Yes	Based on supervisor-provided estimates for each alternative.	Includes secondary UF, buffer/equalization tanks, piping and sedimentation where relevant.
Additional pumping energy	Yes	Calculated from flow, pump head and pump efficiency.	Converted to annual electricity cost using electricity price.
Operating cost	Yes	Based on estimated annual operating costs from supervisor.	Includes labour and membrane cleaning chemicals.
Maintenance and membrane replacement	Yes	Annualized from the estimated membrane replacement cost provided by supervisor.	Based on 700,000 SEK every seventh year.
Engineering and design cost	Included in investment cost.	Included in investment cost.	Not added separately to avoid double-counting.
Pumps and control system	Included in investment cost.	Included in investment cost.	Not added separately to avoid double-counting.

4.8 Benefit estimation

The economic benefit estimations were based on the reduction in raw water abstraction and the reduction in discharge to the wastewater system. Reduced raw water abstraction was estimated based on the annual volume recirculated in each of the alternatives and was monetized by multiplying the volume reduction by the raw water pumping intensity and electricity price. The economic benefit of reduced discharge to the wastewater system was estimated using a unit value per cubic meter which represents the avoided wastewater treatment cost.

Benefits such as reduced stormwater discharge, increased supply robustness, and reduced pressure on freshwater resources were not monetized due to the lack of reliable unit values and economic effects. Instead, they were qualitatively assessed on what impact they would have compared with the current situation.

Table 9: Benefit components

Benefit component	Included in CBA	Estimation method	Comment
Reduced raw water pumping energy	Yes	Reduced volume × pumping energy intensity × electricity price	Direct energy saving from the reduction in raw water abstraction
Reduced discharge to sewer	Yes	Reduced sewer discharge × unit value per m^3	Represents avoided wastewater treatment cost
Reduced discharge to stormwater	No, qualitative	Assessed qualitatively	Not monetised due to uncertain direct unit value
Increased supply robustness	No, qualitative	Assessed qualitatively	Not monetised due to uncertainty
Reduced pressure on freshwater resources	No, qualitative	Assessed qualitatively	Not monetised to avoid overstating benefits

4.9 Input parameters and assumptions

The cost-benefit analysis requires a set of input parameters to estimate costs, benefits and climate effects. These are included in Table 10 and are described shortly below.

The analysis period is set to 50 years. This reflects the expected lifetime of the infrastructure. The discount rate is set to 3.5 %, which is in line with recommendations from Naturvårdsverket and Trafikverket for socio-economic assessments of infrastructure projects (Trafikverket, 2026; Naturvårdsverket, 2008).

Raw water is first pumped from the intake to Delsjöarna, where it is stored in intermediate reservoirs before being transported to Lackarebäck. Pumping energy was based on the hydraulic energy equation using flow volume, pump head, and pump efficiency found in equation 4. The calculated energy use per cubic meter of water was found to be 0.233 kWh/m^3. However, 0.01 kWh/m^3 is recovered by the turbine at Lackarebäck when the water is transported there from Delsjöarna. Based on this, and after recommendations from the supervisor, the raw water pumping energy was set to 0.200 kWh/m^3. This was then multiplied with the electricity price to estimate the cost of water abstraction per cubic meter.

$$E = \frac{\rho * g * H}{\eta * 3.6 * 10^6} \qquad (4)$$

The value assigned to reduced discharge to the wastewater system was based on the values from a PM on the cost-benefit analysis of infiltration and inflow water (Saletti, 2025). While the residual streams from Lackarebäck do not fit the traditional definition of infiltration and inflow water, they still add extra hydraulic load when discharged into the wastewater system. Therefore, the values from (Saletti, 2025) served as estimates for the avoided marginal cost of reducing this load. Following guidance from (Saletti, 2025), the economic value was set at 3 SEK/m^3. In this, 1.8 SEK/m^3 is due to internal operation and maintenance and 0.24 SEK/m^3 represents internal pumping. Also, 1 SEK/m^3 was added to include the investment needed in the wastewater treatment plant due to increased flow. Environmental and climate costs are not included in this value, as climate effects were calculated separately.

Electricity price and the emission factor for the specific electricity mix used at the water treatment plant were provided by the supervisor from Kretslopp och Vatten. The emission factor for reduced wastewater treatment was also based on the PM by Saletti. The base value was set at 0.17 kg CO_2e/m^3, which included 0.12 kg CO_2e/m^3 for wastewater treatment and 0.05 kg CO_2e/m^3 for pumping. This value replaced Ryaverket's average carbon footprint of 0.31 kg CO_2e/m^3 for treated wastewater. The average represents the total emission of the plant, rather than the marginal effect of reducing small and stable flows.
Emission factors for chemicals is taken from the climate calculation tool published by Svenskt Vatten. The CO_2 shadow price of 5.9 SEK/kg CO_2-eq represents the midpoint of the range 4.4–7.4 SEK/kg recommended by Göteborgs Stad based on a report by Anthesis Enveco AB (Söderqvist & Wallström, 2017). The emission factor for raw water abstraction is derived from the pumping energy requirement of 0.200 kWh/m^3 multiplied by the emission factor for electricity, giving 0.001 kg CO_2-eq/m^3.

Table 10: Input parameters

Parameter	Value	Unit	Used for	Comment
Analysis period	50	years	NPV	Analysis period used for NPV calculations.
Discount rate	3.5	%	NPV	Discount rate used for NPV calculations.
Raw water cost	0.140	SEK/m^3	Benefits	Cost of abstracting 1 m^3 of raw water only based on pumping/energy cost.
Discharge handling value	3.000	SEK/m^3	Benefits	Value of reducing discharge to wastewater treatment.
Electricity price	0.70	SEK/kWh	Benefits and costs	Average electricity cost.
Raw water pumping energy	0.200	kWh/m^3	Benefits	Energy needed to abstract 1 m^3 raw water.
Emission factor: Raw water abstraction	0.001	kg CO_2-eq/m^3	Climate benefits	Climate factor linked to raw water abstraction/raw water pumping.
Emission factor: Wastewater treatment	0.170	kg CO_2-eq/m^3	Climate benefits	Climate factor linked to discharge to wastewater treatment/sewer handling.
Emission factor: Electricity	0.004	kg CO_2-eq/kWh	Climate costs	Emission factor for electricity use.
Emission factor: Chemicals	0.459	kg CO_2-eq/kg	Climate costs	Climate factor for chemical production and use.
Cost of CO_2 equivalents	5.9	SEK/kg CO_2-eq	Climate costs	CO_2 shadow price

4.10 Climate impact assessment

The climate impact assessment was conducted to estimate the change in greenhouse gas emissions associated with each of the three alternatives. Operational climate effects were estimated by multiplying the changes in activity level by the relevant emission factor. Emission reduction was calculated for reduced raw water abstraction and reduced discharge to the wastewater system. At the same time, increased emissions occur due to energy use and increased use of chemicals. These effects were calculated into annual climate effects.

In addition to operational emissions, emissions from new infrastructure and equipment were estimated. This was done using a simplified component-based approach and should only be used as a screening-level estimate. These included the emissions from secondary UF equipment, new buffer tanks/equalization volumes, piping, and sedimentation. They were calculated individually for each alternative and assumed to occur in year 0. Therefore, they were kept separate from the annual operational climate effects. The net annual climate effect was calculated as avoided operational emissions minus the additional operational emissions.

In addition to reporting climate effects in kg CO_2e per year, the net climate effect was monetised to assess how the alternatives performed when climate impacts were included to the pure economic assessment. This was done separately from the base NPV in order to distinguish the difference between the direct economic cost and benefits and societal value of greenhouse gas emissions reductions.

The NPV of climate effects was calculated by combining the monetised annual operational climate effect with the climate impact from construction occurring in year 0. Annual operation effects were discounted over the analysis period using the net present value formula.

$$NPV_{climate} = -\left(E_{construction} \times P_{CO_2}\right) + \left(E_{annual} \times P_{CO_2}\right) \times \frac{1-(1+r)^{-n}}{r} \qquad (5)$$

The climate-adjusted NPV was calculated by adding the NPV of climate effects to the base NPV:

$$Climate\text{-}adjusted\ NPV = Base\ NPV + NPV\ climate\ effects \qquad (6)$$

The base NPV therefore represents the direct economic results, while the climate adjusted NPV shows the result when monetised climate effects are included.

Table 11: Cost components included in climate-adjusted NPV

Cost component	Included in CBA	Estimation method	Comment
Increased emissions from energy use	Yes, in climate adjusted NPV	Extra energy use due to pumping × emission factor	Included in climate-adjusted NPV, not base NPV
Increased emissions from chemical use	Yes, in climate adjusted NPV	Based on the increase in needed chemicals estimated from Lackarebäcks chemical budget 2026	Included in climate-adjusted NPV, not base NPV
Emission from construction and equipment	Yes, in climate adjusted NPV	Component based approach based on the investment in new infrastructure/equipment	Included in climate-adjusted NPV, not base NPV

Table 12: Benefit components included in climate-adjusted NPV

Benefit component	Included in CBA	Estimation method	Comment
Emission reduction from decreased raw water abstraction	Yes, in climate adjusted NPV	Reduced volume × emission factor	Included in climate-adjusted NPV, not base NPV
Emission reduction from reduced discharge to wastewater treatment	Yes, in climate adjusted NPV	Reduced volume × emission factor	Included in climate-adjusted NPV, not base NPV

4.11 Risk assessment

A qualitative risk assessment was performed as a complement to the net present value of economic and climate effects. Since several potential consequences of recirculation are difficult to quantify in monetary terms, the risk assessment was used to identify and compare new technical, operational, water quality, and regulatory risks introduced by the different alternatives.

The assessment was carried out in comparison with the current situation at the water treatment plant. The focus was therefore on new risks that are introduced by the recirculation alternatives, as well as existing risks that may increase compared with the current situation. The risks that were considered vary depending on the alternatives but include membrane fouling and reduced performance, process failure, water quality deterioration, accumulation of contaminants, variability in sedimentation performance, and regulatory risks.

The qualitative risk assessment was based on the general principle that risk is a function of likelihood and consequence, commonly applied in technical risk assessment. Likelihood refers to how probable the risk is under normal operating conditions, while consequence refers to the severity of the impact if the risk occurs. Both were assessed using a scale consisting of three levels, low, medium and high. The overall risk was determined using a qualitative risk matrix as shown in Table 13 below. The risk matrix follows the approach used in risk assessment for drinking water systems (WHO, 2022). The likelihood and consequence criteria were adapted to reflect the operational situation at a drinking water treatment plant.

Table 13: Risk matrix

Consequence/Likelihood	**Low**	**Medium**	**High**
Low	Low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	High

The matrix shows that risks with both low likelihood and low consequences are seen as low. Risks with high consequences and medium or high likelihood are viewed as high. Risks that have low likelihood, but high consequences are categorized as medium, they may be unlikely, but they could have serious effects if they happen.

Table 14: Description of likelihood and consequence

Criteria	**Low**	**Medium**	**High**
Likelihood	Unlikely under normal operation	May occur under certain operating conditions	Likely to occur or requires active management
Consequence	Limited operational impact	Noticeable operational or process impact requiring monitoring or adjustment	Significant operational, water quality or regulatory impact

The assessment considered all the available information, along with the characteristics of the residual streams in each alternative, and also considered the expected complexity of the necessary treatment and recirculation system. Alternatives that include more internal recycling, more varied streams, increased complexity, or less effective treatment barriers were generally seen as carrying a higher risk profile. For example, the risks related to buildup of contaminants and decline in water quality become more important when more residual streams are sent back into the treatment process, and especially if there are fewer treatment steps involved.

The risk assessment was not included directly in the NPV calculation. Instead, it served as a helpful tool to point out risks that are hard to measure in monetary terms. The resulting risk levels should be viewed as screening-level assessments rather than as precise probabilities of failure. Along with the economic and climate results, the risk assessment offers a broader foundation for comparing the alternatives.

4.12 Qualitative benefits

In addition to the monetized benefits included in the CBA, a qualitative assessment was performed to highlight benefits that are important for decision-making but difficult to assign a reliable monetary value to.

The qualitative benefit criteria were defined before the alternatives were compared and were applied to all three alternatives to allow a consistent comparison between them. They were selected because they represent potential system and environmental effects that are not captured directly by the cost-benefit analysis. The qualitative benefit criteria included in the analysis are presented in Table 15.

Table 15: Qualitative benefit criteria included in the assessment

Benefit criteria	**Relevance for assessment**
More stable and predictable inflow water quality	Recirculation of treated water may reduce fluctuations in raw water characteristics, resulting in a more stable and predictable inflow to the treatment process.
Reduced pressure on freshwater resources	Reduced abstraction may decrease pressure on freshwater resources.
Increased supply robustness	May improve system resilience by reducing reliance on raw water sources.
Reduced stormwater discharge	Reduced discharge to Mölndalsån and the stormwater system may reduce environmental impact and the risk of overflow during heavy rainfall events.

Each benefit was evaluated against the current operations at Lackarebäck. The impact was classified using a qualitative scale from negligible to limited, moderate, or high. The assessment focused on the expected changes from each of the alternatives, especially the amount of water recirculated, the decrease in raw water withdrawal, the reduction in stormwater discharge, and the potential contribution to overall water supply robustness.

Table 16: Impact level interpretation

Impact level	Interpretation
Negligible	No clear or only very minor benefit compared with current operation.
Limited	Small positive effect, but unlikely to strongly influence decision-making alone.
Moderate	Positive effect that is relevant for operation or environmental performance.
High	Significant positive effect that may be important in the overall evaluation.

The qualitative benefit assessment was not directly included in the NPV calculation. Instead, it was used to complement the economic, climate, and risk results in the overall comparison of the alternatives.

4.13 Sensitivity and uncertainty analysis

Several input parameters in the cost-benefit analysis are uncertain because the alternatives are conceptual and not based on detailed designs. To see how these uncertainties affect the results, a sensitivity and uncertainty analysis was conducted. The goal was to identify which assumptions or input parameters have a large impact on the climate-adjusted NPV and to assess if the ranking of alternatives changes under different assumptions.

The sensitivity analysis used a one-at-a-time approach. This means that one input parameter was changed while keeping all other parameters at their base-case values. This approach was selected because it shows how changes in one parameter affect the outcome.

The parameters in the sensitivity analysis were chosen based on their expected impact on the outcome and the uncertainty linked to the input values. The parameters tested included investment cost, operating cost, discharge handling value, electricity price, discount rate, analysis period, emission factor for wastewater treatment, and CO_2 shadow price. These parameters influence either the annual net operating result, the value of climate effects, or the discounting of future costs and benefits. For each parameter, a low, a base, and a high value were assigned. The base value is the one used in the main analysis, while the low and high values show variations from the base case. The sensitivity analysis was only performed on the climate-adjusted NPV value.

A scenario analysis was also performed to assess the combined effect of several uncertain assumptions. The scenarios aimed to illustrate both more optimistic and more pessimistic conditions compared with the base case. This allows an evaluation of whether the alternatives stay economically unattractive under favorable assumptions or if the results mainly depend on a few uncertain input values.

In addition to the sensitivity analysis, a threshold analysis was done for chosen parameters. Each parameter was changed individually to find the value needed for the climate-adjusted NPV to reach zero. This illustrated how much the key assumptions would need to shift for the alternatives to be economically favorable. The threshold analysis gives a clearer and simpler understanding of the negative NPV results.

The analysis that was performed should be seen as a basic uncertainty assessment and is not a probabilistic uncertainty analysis. Unlike probabilistic cost-benefit analysis methods that use probability distributions and Monte Carlo simulation, this study relies on fixed low, base, and high values due to limited data availability and the conceptual nature of the alternatives. This approach is suitable for identifying key uncertainties during the early planning stage and still ensures transparency in the calculations.

In addition to the sensitivity, scenario and threshold analyses, an uncertainty assessment was performed for the key parameters used in the CBA. This assessment documented the low, base, and high estimates, the confidence in the data source, and recommended actions to improve the input data. The goal was to clarify the robustness of the underlying assumptions. Parameters that come from well-documented sources or specific plant data are considered more reliable and given higher confidence. Those based on estimates or limited documentation are treated with more caution and assigned lower confidence. The assessment is summarized in Table 17.

Table 17: Uncertainty analysis for selected parameters

Parameter	**Low estimate**	**Base estimate**	**High estimate**	**Confidence**	**Source**	**Main uncertainty**
Investment cost	-20%	Estimate from Kretslopp och Vatten	+20%	Low	Design estimates from Kretslopp och Vatten	Preliminary estimate. Detailed engineering and are needed
Discharge handling value	1 SEK/m^3	3 SEK/m^3	5 SEK/m^3	Medium	PM on CBA of infiltration and inflow water and guidance from Saletti	Value for avoided marginal wastewater system cost
Wastewater emission factor	0.10 kg CO_2e/m^3	0.17 kg CO_2e/m^3	0.31 kg CO_2e/m^3	Medium	PM values and Ryaverket environmental report as upper-bound value	Marginal emission factor uncertain. 0.31 represents average plant-level footprint
Discount rate	2.0%	3.5%	5.0%	*	Naturvårdsverket guidelines/common practice	Well-documented, but affects long-term valuation
CO_2 shadow price	4.4 SEK/kg CO_2e	5.9 SEK/kg CO_2e	7.4 SEK/kg CO_2e	High	Göteborg Stad/Anthesis Enveco	Well-documented range
Operating cost	-20%	Estimated annual cost	+20%	Medium	Plant data and literature-based estimates	Limited operational experience with the proposed systems
Electricity emission factor	0.004 kg CO_2e/kWh	0.004 kg CO_2e/kWh	0.013 kg CO_2e/kWh	Medium	Kretslopp och Vatten	Low impact on results, but electricity mix may vary
Residual stream volumes	-20%	2019 pre-study volumes	+20%	Medium	Hilmersson Haag et al. (2023)	Flow volumes and water quality need verification through new sampling
Construction emissions	-20%	Component-based estimate	+20%	Low	Literature-based emission factors	Screening-level estimate not a full LCA
Analysis period	30 years	50 years	70 years	*	Kretslopp och Vatten/assumed infrastructure lifetime	Long-term performance and component lifetime uncertain

*Fixed based on guidelines. Ranges reflect alternative assumptions for the sensitivity analysis.

5 Results

In the following chapter, the results of the comparative assessment of the three recirculation alternatives will be presented. All results are presented relative to the reference scenario which represents the current handling of residual streams at Lackarebäck water treatment plant, where no internal recirculation takes place. The results are structured according to the main evaluation criteria used in the analysis, flow recovery, economic performance, climate effects, risk and qualitative benefits. The sensitivity, scenario and threshold analysis are presented in section 5.7 followed by an overall comparison in section 5.8

5.1 Flow recovery and reduction in discharge

The three alternatives differ in the volume of water recovered and how much the discharge volumes are reduced. Table 18 shows the yearly reductions in volume for each alternative compared with the reference scenario.

Table 18: Volume reductions

Parameter	Alt A	Alt B	Alt C
Reduced raw water abstraction	1,606,000 m^3/year	2,354,000 m^3/year	2,409,000 m^3/year
Reduced wastewater discharge	183,000 m^3/year	931,000 m^3/year	986,000 m^3/year
Reduced stormwater discharge	1,424,000 m^3/year	1,424,000 m^3/year	1,424,000 m^3/year

Alternative A reduces the raw water abstraction by approximately 1,606,000 m^3/year, this is driven by the recirculation of ultrafiltration backwash water and first filtrate from carbon filtration. Because carbon filter backwash is not recirculated in Alternative A, the reduction in wastewater discharge is limited to approximately 183,000 m^3/year. Alternative B increases the total volume recovered to approximately 2,354,000 m^3/year by also recirculating carbon filtration backwash water and the upper clarified supernatant from sedimentation. This results in a large reduction in wastewater discharge. Alternative C has the highest total recovery as the entire clarified supernatant from sedimentation is recirculated. However, the difference compared with Alternative B is small and only at approximately 55,000 m^3/year or 2%. The reduction in stormwater discharge is identical for all the alternatives as they all handle the ultrafiltration backwash water in the same way.

5.2 Economic results

Table 19 summarizes the key economic results for all three alternatives over the 50-year analysis period.

Table 19: Economic results

Parameter	Alt A	Alt B	Alt C
Estimated total investment cost	30.55 MSEK	115.85 MSEK	135.95 MSEK
Net annual operating result	-0.55 MSEK/year	1.48 MSEK/year	1.20 MSEK/year
Base NPV	-43.50 MSEK	-81.17 MSEK	-107.83 MSEK

All three alternatives result in a negative NPV. This means that the total discounted costs exceed the total discounted benefits under the given assumptions. Alternative A has the lowest investment cost at 30.55 MSEK but is also the only alternative with a negative annual operating result. This is because the reduction in wastewater discharge, which is the main driver of economic benefits, is small when carbon filter backwash water is not recirculated. Alternatives B and C both produce a positive net annual operating result of 1.48 and 1.20 MSEK/year respectively, this is primarily due to larger reductions in wastewater discharge. However, the investment cost is large for these alternatives, 115.85 and 135.95 MSEK respectively and the annual operating benefits are too small to recover the cost over the analysis period. To sum up Alternative A has the least negative NPV at -43.50 MSEK, followed by Alternative B at -81.17 MSEK and Alternative C at -107.83 MSEK. It is also notable that despite Alternative C recirculating larger volumes of water than Alternative B, Alternative C produces lower annual operating results than Alternative B. This is caused by higher operational costs due to more advanced treatment steps in Alternative C.

5.3 Climate impact results

Table 20 shows the climate impact results for each alternative, including emissions from construction and equipment, as well as the net annual operational change in greenhouse gas emissions. Negative values indicate a reduction compared with the current scenario.

Table 20: Climate impact

Parameter	Alt A	Alt B	Alt C
Construction emissions	47,000 kg CO_2e	146,000 kg CO_2e	238,000 kg CO_2e
Net annual operational emission change	-5,000 kg CO_2e/year	-105,000 kg CO_2e/year	-87,000 kg CO_2e/year

All three alternatives result in a net annual reduction in greenhouse gas emissions compared with the reference scenario. This means that the avoided emissions from reduced raw water abstraction and reduced wastewater discharge exceed the additional emissions from increased energy use and chemical consumption. Alternative B achieves the highest net annual climate reduction at approximately 105,000 kg CO_2e/year followed by Alternative C and A at approximately 87,000 and 5,000 kg CO_2e/year. The higher climate benefit of Alternative B compared with C reflects the higher consumption of chemicals and more energy-demanding treatment in Alternative C. Construction emissions increase with the complexity of the alternative and range from approximately 47,000 to 238,000 kg CO_2e from Alternative A to C. All construction emissions are assumed to occur in year 0.

5.4 Climate-adjusted NPV

Table 21 shows the climate-adjusted NPV for each alternative. This is calculated by adding the monetised NPV of climate effects to the base NPV.

Table 21: Climate-adjusted NPV

Parameter	Alt A	Alt B	Alt C
Base NPV	-43.50 MSEK	-81.17 MSEK	-107.83 MSEK
NPV of climate effects	0.40 MSEK	13.72 MSEK	10.69 MSEK
Climate-adjusted NPV	-43.10 MSEK	-67.45 MSEK	-97.13 MSEK

When including the monetised value of climate effects the NPV for all three alternatives is improved. The improvement is most significant for Alternative B where the NPV of climate effects is 13.72 MSEK which reduces the climate-adjusted NPV to -67.45 MSEK compared with the base NPV of -81.17 MSEK. For Alternative C, the improvement is 10.69 MSEK, improving the climate adjusted NPV to -97.13 MSEK. For Alternative A, the improvement is small, only 0.40 MSEK. Despite the improvement when including climate effects, the ranking of the alternatives does not change, and all three remain negative.

5.5 Risk assessment

Table 22 presents the results of the qualitative risk assessment for each alternative. The risks assessed are new risks introduced by recirculation and existing risks that may increase as a result of implementing recirculation and are performed relative to the reference scenario.

Table 22: Risk assessment

Risk	Alt A	Alt B	Alt C
Membrane fouling and reduced performance	Medium	Medium	Medium
Process failure/downtime	Low	Low	Medium
Water quality deterioration	Medium	Medium	Low
Regulatory non-compliance	Medium	Medium	Medium
Contaminant accumulation	–	Medium	Medium
Sedimentation variability	–	Low	Low

The risks differ between the alternatives. Membrane fouling and reduced performance over time is rated as medium for all alternatives as secondary ultrafiltration is present in all cases. The risk of process failure and downtime due to increased system complexity is rated as low for alternatives A and B but increases to medium for Alternative C which includes more treatment steps. It is noteworthy that the risk of water quality deterioration is rated as medium in Alternative A, and low for alternatives B and C. This reflects that in Alternative A, the first filtrate from carbon filtration is returned without pre-treatment, which introduces a greater risk compared with B and C where the first filtrate is treated before being returned. Regulatory non-compliance is rated as medium for all alternatives due to the absence of specific regulations on backwash recycling in Sweden. Contamination accumulation and sedimentation variability is only seen as relevant to alternatives B and C as Alternative A does not recirculate carbon filter backwash water or clarified supernatant.

5.6 Qualitative benefits

In addition to the monetised benefits that were included in the cost-benefit analysis, four qualitative benefits were assessed for each alternative. Table 23 presents the results using the impact interpretation scale defined in section 4.12.

Table 23: Qualitative benefits

Benefit	Alt A	Alt B	Alt C
More stable/predictable process inflow	Negligible	Limited	Limited
Reduced pressure on freshwater resources	Limited	Moderate	Moderate
Increased supply robustness	Limited	Moderate	Moderate
Reduced stormwater discharge	High	High	High

The benefit of a more stable and predictable inflow stream is rated as negligible for Alternative A and limited for B and C. In Alternative A, only backwash water from ultrafiltration and the first filtrate are recirculated, and these streams are already relatively predictable. For alternatives B and C, the additional recirculation of carbon filter backwash water introduces a more controlled return flow to the treatment process. However, since the recirculated volumes only are a small part of the raw water intake the overall effect is limited. The reduction in pressure on freshwater resources and increased supply robustness is rated as limited for Alternative A, and moderate for alternatives B and C, as they provide a larger reduction in freshwater abstraction. The reduction in stormwater discharge to Mölndalsån is rated as high for all alternatives. This is based on the large volume of ultrafiltration backwash water (1,423,500 m^3/year) redirected from stormwater discharge across all three alternatives. This significantly reduces the load on the stormwater system, regardless of which alternative is implemented.

5.7 Sensitivity, scenario, and threshold analysis

The following sections present the results of the sensitivity, scenario and threshold analysis that were performed to assess how uncertainty in some of the input parameters affects the results. All analyses in this section are performed on the climate-adjusted NPV as this is considered to be the final result.

5.7.1 Sensitivity analysis

The sensitivity analysis was completed by varying one parameter at a time while keeping all other parameters at their base value. The results are presented in tornado diagrams in Figures 5 to 7. The diagrams show the range of change in the climate-adjusted NPV for each alternative for the selected parameters. It should be noted that the tornado diagrams use different x-axis scales, and each figure should therefore be interpreted individually, and the bar width should not be compared directly with the other alternatives.

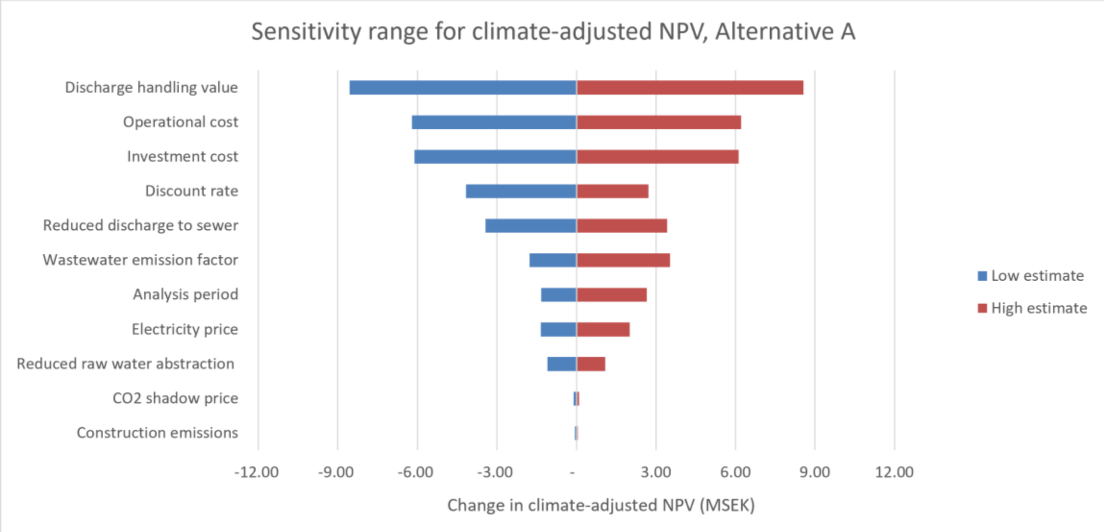

Figure 5: Tornado chart Alternative A

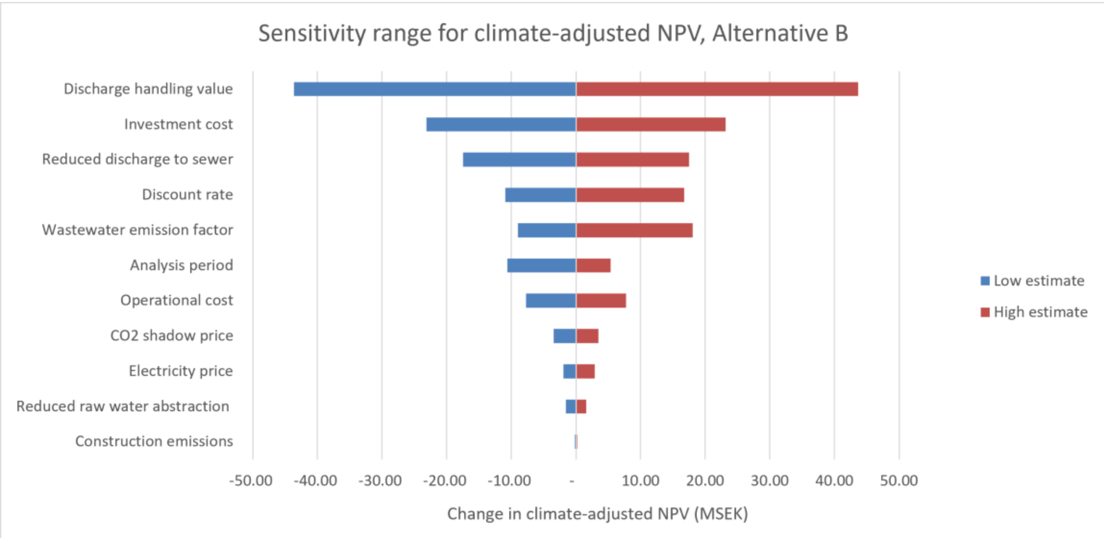

Figure 6: Tornado chart Alternative B

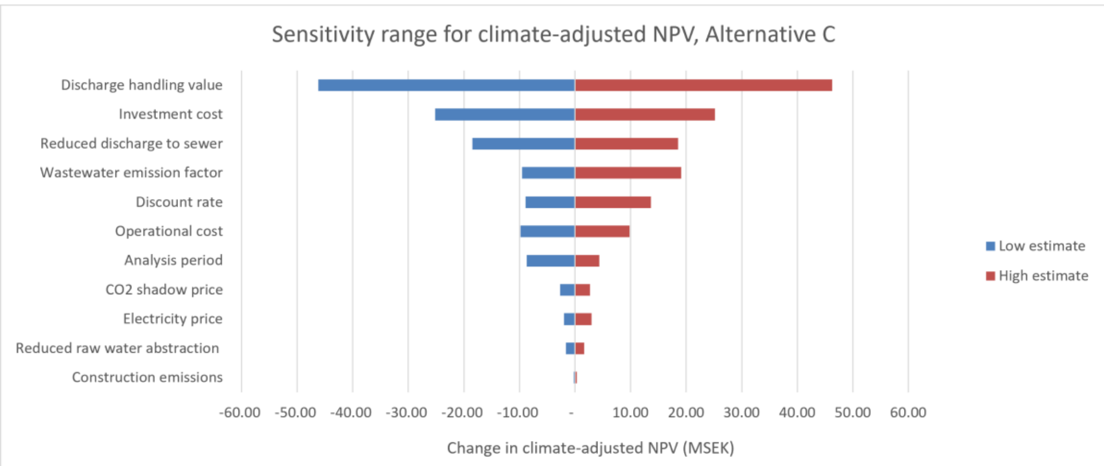

Figure 7: Tornado chart Alternative C

The tornado diagrams show clear differences in sensitivity patterns between the different alternatives. For Alternative A, the three most influential parameters are the discharge to wastewater handling value, operational cost and investment cost. These three parameters change the NPV in a range of 17.1, 12.4 and 12.2 MSEK respectively. For Alternative A there is not one single parameter that dominates the results. It is notable that the discharge handling value has a more limited effect on the NPV in Alternative A compared with B and C which reflects the lower reduction in volume of wastewater discharge in this alternative.

For alternatives B and C, the discharge handling value is the standout parameter with NPV ranges of 87.3 and 92.5 MSEK respectively. This is almost the double of the second most influential parameter. This reflects the large volumes of wastewater discharge that are reduced in these alternatives, which makes the economic results sensitive to changes of the discharge handling value. The second and third most influential parameters are investment cost and reduced discharge to wastewater. The wastewater emission factor also has a meaningful influence on the NPV with a range 27 to 28 MSEK for alternatives B and C.

The discount rate and analysis period have a moderate effect on the NPV across all alternatives. Electricity price and reduced raw water abstraction has a small influence on the NPV with a range below 5 MSEK for all alternatives. The CO_2 shadow price has a small effect on alternatives B and C, with a range of around 6 MSEK, while for Alternative A, it has a negligible effect. Construction emissions have no visible effect on the results for any alternative.

5.7.2 Scenario analysis

Four different scenarios were defined to assess how the combined effects of multiple uncertain parameters affected the results. The scenarios and the assumptions are summarized in Table 24, and the results are presented in Table 25.

Table 24: Scenario analysis assumptions

Scenario	**Main assumption**
Base case	Current base estimates
Pessimistic	Higher investment and operating costs, lower benefits, shorter analysis period and higher discount rate
Optimistic	Lower investment and operating costs, higher discharge value, higher climate valuation and lower discount rate
Climate focus	Higher wastewater emission factor and higher CO_2 shadow price

Table 25: Scenario analysis results

Scenario	**Alt A climate-adjusted NPV**	**Alt B climate-adjusted NPV**	**Alt C climate-adjusted NPV**
Base case	-43.1 MSEK	-67.5 MSEK	-97.1 MSEK
Pessimistic	-56.4 MSEK	-149.1 MSEK	-182.5 MSEK
Optimistic	-13.4 MSEK	79.0 MSEK	57.4 MSEK
Climate focus	-38.6 MSEK	-41.3 MSEK	-70.5 MSEK

In the pessimistic scenario where costs get higher, benefits lower, the analysis period shorter and the discount rate higher, all three alternatives get a more negative climate-adjusted NPV. Alternative A is the least affected, dropping to -56.4 MSEK, while alternatives B and C reach -149.1 MSEK and -182.5 MSEK. Alternative A is the least affected because it relies less on the discharge handling value. In the climate focus scenario, which uses the high CO_2 shadow price and the high wastewater emission factor, the climate-adjusted NPV improves for all the alternatives. The biggest improvement is for Alternative B where the climate-adjusted NPV gets to -41.3 MSEK.

The most notable finding is in the optimistic scenario. In this scenario, alternatives B and C shift to a positive climate-adjusted NPV of 79.0 MSEK and 57.4 MSEK, respectively. This indicates that economic feasibility is possible if favourable conditions occur at the same time. However, Alternative A remains negative at -13.4 MSEK. It should be noted that the optimistic scenario assumes several favourable conditions occurring at the same time, which is discussed in section 6.6.

Overall, the scenario analysis shows that alternatives B and C are more sensitive to changes than Alternative A, but also, that they have a greater potential for becoming economically favourable. The range of outcomes shows the importance of reducing uncertainties before making a decision.

5.7.3 Threshold analysis

A threshold analysis was performed to identify how much some selected parameters would need to change for the climate-adjusted NPV to reach zero and therefore make the alternative economically feasible. The analysis does not represent expected values but illustrates how far off the current parameters are from economic feasibility.

Table 26: Threshold analysis results

Threshold parameter	Alt A	Alt B	Alt C	Base value
Required wastewater discharge handling value	13.07 SEK/m^3	6.09 SEK/m^3	7.21 SEK/m^3	3 SEK/m^3
Required investment cost reduction	Not possible	67.5 MSEK or 58%	97.1 MSEK or 72%	Current investment cost
Required CO_2 shadow price	645 SEK/kg CO_2e	34.95 SEK/kg CO_2e	59.50 SEK/kg CO_2e	5.9 SEK/kg CO_2e
Additional annual raw water reduction required	12.8 Mm^3/year	19.9 Mm^3/year	28.6 Mm^3/year	Current reduction varies
Additional annual wastewater discharge reduction required	0.46 Mm^3/year	0.72 Mm^3/year	1.03 Mm^3/year	Current reduction varies

For discharge handling value, the threshold is 13.07 SEK/m^3 for Alternative A, 6.09 SEK/m^3 for Alternative B, and 7.21 SEK/m^3 for Alternative C. The threshold for Alternative A is more than four times the base value and is seen as unlikely to be reached. Alternatives B and C would need a doubling of the discharge handling value. This is significant, but it is within a range that could be affected by future changes in wastewater policies or regulatory requirements.

For the investment cost, it is not possible to define a threshold value for Alternative A, because the annual operating result is negative and a change of investment cost alone cannot bring the NPV to zero. For alternatives B and C, a 58% and 72% reduction in investment costs, respectively, would make the alternatives economically feasible. This is not considered to be realistic.

The necessary CO_2 shadow prices are much higher than the base value of 5.9 SEK/kg CO_2e. Alternative A would need an unreasonably high CO_2 price. Alternatives B and C would need lower prices than Alternative A, but would still be significantly higher than the base level. This indicates that the monetary value of climate benefits alone is not enough to make the alternatives economically feasible under the current assumptions.

The volume thresholds show that the alternatives need much larger water savings or reductions in wastewater to break even. The extra reductions in raw water needed are from 12 to 29 million cubic meters per year, larger than the current estimates. This means that just reducing raw water pumping cannot justify the investments. The required reductions in wastewater discharge are smaller, from 450,000 to 1,000,000 cubic meters per year. However, finding these volumes in the facility is currently not realistic. But this highlights how important the wastewater discharge value is to the economic outcome.

5.7.4 Cost per user interpretation

As an additional practical interpretation, the economic results for all alternatives can be expressed as annual cost per person. This is not a proposed tariff increase, but a way to illustrate the investment needed if it were distributed across the connected water users. Detailed calculations are shown in Appendix E.

Table 27: Theoretical annual cost per water user

Alternative	**Base NPV**	**Annualized net cost**	**Cost/person/year, 600,000 users**	**Cost/person/year, 300,000 users**
Alternative A	-43.50 MSEK	1.85 MSEK/year	3.1 SEK	6.2 SEK
Alternative B	-81.17 MSEK	3.46 MSEK/year	5.8 SEK	11.5 SEK
Alternative C	-107.83 MSEK	4.60 MSEK/year	7.7 SEK	15.3 SEK

The calculations are based on the base NPV, not using the climate-adjusted NPV, and show that the annualized net cost per connected user is relatively small when distributed across all water users. For 600,000 users, the theoretical annual cost ranges from 3.1 to 7.7 SEK per user per year, while for 300,000 users, the cost is from 6.2 to 15.3 SEK per user per year. As a practical example, this would correspond to approximately 0.02-0.15% of the expected annual VA cost for a typical villa household which is expected to pay 12,639 SEK per year in 2027 (Göteborgs stad, 2026). This calculation is only indicative as the VA-tariff is not charged per person, but it provides an additional perspective on the scale of the economic results.

5.8 Overall comparison

Table 28 provides an overall comparison of the three alternatives across the evaluation criteria used in this study.

Table 28: Comparison of alternatives

Criterion	Alt A	Alt B	Alt C
Total investment cost	30.6 MSEK	115.9 MSEK	136.0 MSEK
Net annual operating result	-0.55 MSEK/year	1.48 MSEK/year	1.20 MSEK/year
Base NPV	-43.5 MSEK	-81.2 MSEK	-107.8 MSEK
Climate-adjusted NPV	-43.1 MSEK	-67.5 MSEK	-97.1 MSEK
Net annual climate effect	-5,000 kg CO_2e/year	-105,000 kg CO_2e/year	-87,000 kg CO_2e/year
Overall risk level	Medium	Low-medium	Low-medium
Stable process inflow	Negligible	Limited	Limited
Reduced freshwater pressure	Limited	Moderate	Moderate
Supply robustness	Limited	Moderate	Moderate
Stormwater discharge reduction	High	High	High

From an economic perspective, all three alternatives result in a negative base NPV and climate-adjusted NPV. This means that none of the alternatives are economically favourable under the base case assumptions when evaluated against the current situation. Alternative A has the least negative climate-adjusted NPV at -43.1 MSEK, mostly driven by the lower investment cost compared with the other alternatives. Alternatives B and C have an even more negative climate-adjusted NPV despite having a positive annual operating result. This means that the investment costs are too high to be recovered over the 50-year analysis period. However, the scenario and threshold analysis showed that alternatives B and C shifts to a positive NPV in favourable situations.

From a climate perspective Alternative B is the alternative with the largest reduction in greenhouse gas emissions per year. Alternative C has a smaller reduction despite recirculating a higher total amount of water. This reflects the higher energy and chemical demand in Alternative C given its more advanced treatment step.

The risk assessment shows that the alternatives have different risk profiles. Alternative A has a higher water quality concern because the first filtrate is returned without pre-treatment. Alternatives B and C introduce additional risks caused by increased system complexity and more residual streams.

The qualitative benefits show that the reduction in stormwater discharge is an important benefit for all alternatives. This is a significant and consistent benefit regardless of which alternative is implemented. There are small differences in the other qualitative benefits between the alternatives, but they should all be accounted for in the overall comparison.

To sum up, no single alternative dominates across the different criteria. Alternative A performs best economically in the base case but has the least potential and is constrained from being economically favourable. Alternatives B and C offer higher water recovery volumes and substantially reduce wastewater discharge. This gives them better economic potential and climate benefits, but at a significantly higher investment cost. The findings from the results are discussed further in chapter 6.

6 Discussion

This chapter discusses the results of the comparison of the strategies evaluated for rinse water recirculation at the Lackarebäck water treatment plant. It looks at economic, climate-related, operational, and risk-related aspects. The following sections will discuss and examine the findings and trade-offs between water recovery, costs, benefits, climate effects, and risk-related aspects for alternatives.

6.1 Interpretation of economic results

The economic results show that none of the three alternatives is financially profitable. Both the economic NPV and the climate-adjusted NPV remain negative for all alternatives, which means that the monetized benefits are not high enough to cover the investment and operational costs over the analysis period of 50 years. For a municipal water utility, investments are rarely economically self-sustaining and should be evaluated against broader objectives such as service reliability and system resilience. Therefore, the result should not be understood as that rinse water recirculation has no value, but the question is whether the benefits that fall outside of the NPV calculations are large enough to justify the investments.

Following the sensitivity analysis, it is clear that the economic results are highly dependent on the value assigned to reducing discharge to the wastewater system. The value was set to 3 SEK/m^3 in the base case and 1 and 5 SEK/m^3 in the sensitivity analysis. This led to a change in NPV with a range of 87-93 MSEK or ±44 MSEK on the current NPV. The level of dependence on this parameter is a weakness in the analysis. The value was derived from a study on infiltration and inflow water, which differs from the residual streams from Lackarebäck in terms of flow patterns, water quality and seasonal variations. Also, there is uncertainty related to how changes in residual streams to the WWTP would affect the need of future investments. The streams from Lackarebäck currently contribute with a stable and predictable flow to the wastewater system. Reducing this load could reduce the need of future capacity investment at Ryaverket. This additional economic benefit is only marginally captured in the base value of 3 SEK/m^3 and one could therefore argue that 3 SEK/m^3 is too low and does not capture the full benefit of reducing the volume of this stream. However, how the reduction of this specific volume would affect the investments at Ryaverket is uncertain. And therefore, to improve the reliability of the economic assessment, a site-specific value for Lackarebäck should be developed.

The threshold analysis shows that alternatives B and C need a wastewater discharge value of 6 to 7 SEK/m^3 to make the NPV zero. This is a significant change compared with the base case, but it is not completely unrealistic given the ongoing changes in water policies, driven by the EU directive on wastewater treatment.

Alternative A is the only option that has a negative annual operating result. Changes to the discount rate, analysis period, or investment cost alone cannot make its NPV zero or positive. The threshold analysis shows that a discharge handling value of 13 SEK/m^3 would be required to make Alternative A breakeven, which is not plausible. Alternative A recirculates the fewest streams and has a much smaller reduction in wastewater discharge which explains the negative annual operating result. Alternative A could therefore be seen as less economically risky on paper, but also as the least attractive as a long-term option.

An interesting finding is that Alternative C performs worse than B despite recirculating approximately 55,000 m^3/year more water. The addition of sedimentation treatment in Alternative C leads to higher energy use and increased chemical costs, making the process more demanding overall. This shows that after a certain point, recirculating more water, which needs more extensive treatment, becomes more costly than beneficial.

The cost per user interpretation shows that the annualized net cost is relatively small when distributed across the connected water users. However, this does not change the overall economic assessment, since the alternatives still produce negative NPVs in the base case.

6.2 Trade-off between water recovery and complexity

Three alternatives were designed to represent different levels of water recovery, pre-treatment, investment and operational complexity. Looking at all the decision criteria together shows trade-offs that are not visible in the economic results alone and gives a different ranking than the base NPV.

Alternative A has an economic advantage given its low investment cost and therefore also its low NPV. As discussed in 6.1 it has no chance of having a positive NPV and compared with alternatives B and C it has no operational strengths. Alternative A has the highest risk profile of the three alternatives despite being the simplest system. This is particularly due to returning first filtrate from carbon filtration without pre-treatment, which introduces a risk of particle accumulation and water quality issues that are not present in B and C. The combination of weak economic potential and the highest risk profile make Alternative A an unattractive alternative despite its low investment cost.

This challenges the assumption that simpler systems are preferred. Increased treatment in alternatives B and C increases both cost and complexity, but they reduce risks. This is supported by previous studies that shows that ultrafiltration and sedimentation can improve the quality of backwash water recirculation (Komorowska-Kaufman & Toczek, 2022; Wolska et al., 2025). In drinking water production, pre-treatment is important and lower investment costs should not be prioritized over water quality and safety.

Alternative C gives marginally higher water recovery than Alternative B. Adding about 2% more water volume requires roughly 17% higher investment, introduces more complexity, results in greater carbon emissions, and provides a somewhat lower annual climate benefit. None of the analysed scenarios produces a result where Alternative C is clearly better than B on multiple criteria. Therefore, Alternative C appears hard to justify unless regulations or other operational factors demand complete processing of all residual streams before they are recirculated.

Based on this, Alternative B seems like the most well-balanced option when all criteria are considered together. It has much higher water recovery than Alternative A, a less negative NPV compared with C, has the highest annual operating result and the highest annual climate benefit. It should be noted that this conclusion is found at a screening level, and a detailed engineering design could reveal costs or performance differences between the alternatives that are not shown at this stage. However, based on the current information, Alternative B emerges as the most robust choice for further development.

6.3 Climate effects

All three alternatives result in a reduction in greenhouse gas emissions relative to the current situation. However, the size of these benefits and their impact on the overall assessment vary largely between the alternatives and should be looked into.

As previously mentioned, Alternative B achieves a higher net annual climate benefit compared with Alternative C despite recirculating less water. This is a consequence of the more energy and chemical demanding treatment in Alternative C. The climate results therefore show the same pattern as the economic results, suggesting that the additional benefits of Alternative C are too small to justify the added complexity.

An important point is the very low electricity emission factor used in the analysis. The factor of 0.004 kg CO_2 eq/kWh is very low and indicates that the electricity mix used at Kretslopp och Vatten is largely renewable. This limits the benefits of energy savings and removes the costs associated with increased energy consumption. Using a higher emission factor, such as a Nordic or European average, would make the climate differences between the alternatives clearer and have a positive effect on the base NPV. Also, using such a low factor would make the climate results not directly transferable to facilities using a different electricity mix.

The monetized value of climate effects varies from 0.40 MSEK for Alternative A to 13.72 MSEK for alternative B. Including climate effects have a positive impact on the NPV as showed in 5.4. But it does not change the overall ranking between the alternatives or bring any of the alternatives close to being economically beneficial. This is consistent with what (Molinos-Senante et al., 2011) observed. External environmental benefits can change but not reverse a negative economic assessment when using current CO_2 shadow prices. The climate analysis is therefore a supporting argument for the investment case, rather than being decisive on its own.

Also, the construction related emission that are estimated for each alternative should be treated as a coarse screening level estimate, rather than a precise value. The component-based approach used when calculating the emissions does not capture all details in works, installations, or uses exact manufacturing emissions from suppliers. This means that the true emissions from construction could be higher than estimated. A full life cycle analysis would improve the quality and is recommended as a part of future work.

6.4 Risk and water quality

One of the most important risk findings in this study is not captured fully by the risk matrix. This is related to the sampling performed in the pre-study, where some samples of carbon filter backwash water showed PFAS concentrations above the levels in the incoming raw water. If this is confirmed by the additional sampling where the results are not yet available, it could limit the feasibility of alternatives B and C since they both include recirculation of carbon filtration backwash water. Recirculation of water containing elevated concentrations of PFAS could cause gradual accumulation in the treatment process and could cause a worsening in water quality over time. Because PFAS are persistent substances and the rules for drinking water productions are strict, the repeated sampling is important for further planning of alternatives that include recirculation of carbon filtration backwash water.

Regulatory non-compliance is rated as a medium risk for all alternatives. This reflects that the Swedish regulations currently have no specific regulations on backwash water recycling. As discussed in 3.4, Swedish drinking water regulations follow a risk-based approach based on the EU Drinking Water Directive and implemented through LIVSFS 2022:12. This means that the alternatives would need to be supported by a hazard analysis, monitoring routines, and documentation of water quality throughout the treatment process.

Membrane fouling is rated as medium for all alternatives because secondary ultrafiltration is included in each. The ultrafiltration and carbon filter backwash water contains concentrated particles which could make the water more challenging than the raw water. Without previous operational experience from similar systems, fouling frequency and membrane lifetime are uncertain. If fouling is more severe than expected, both operating costs and downtime could increase.

The risk of process failure and downtime is rated as low in Alternative A and B, but medium for Alternative C because it includes more treatment steps and a more complex system. Lackarebäck supplies water to a large population, and even short interruptions could have consequences. This operational risk should be assessed together with economic and climate results when comparing alternatives.

6.5 Qualitative benefits

The assessment of qualitative benefit includes outcomes that have a real significance but are hard to monetize fairly. The most important finding is that all alternatives achieve a high degree of stormwater reduction. This is caused by recirculation of ultrafiltration backwash water and reduces the load on Mölndalsån by approximately 1.4 million cubic meters of water per year. This benefit is also not limited to the water treatment plant only, but it has an effect on the municipal stormwater system. It could lower the risk of overflow during heavy rainfall events, which means it has a high value from an urban water management perspective.

This benefit could potentially have been monetised, for example by using avoided stormwater infrastructure costs, avoided costs in a overflow situation or an environmental value of reduced discharge to Mölndalsån. But because no reliable value was available, combined with the fact that Mölndalsån currently does not have a high risk of overflow it was not monetised. As a result of this the NPV misses the value of this for all alternatives. This should be made clear to decision makers.

The reduction in freshwater pressure and increased supply robustness are rated as limited for Alternative A, and medium for alternatives B and C. These benefits are relevant to Gothenburgs sustainable water use programme, especially during dry summers or high demand periods. Recirculating between 4,400 and to 6,600 m^3/day reduces the raw water abstraction in a meaningful way, even if the effect is not large at a regional scale.

The benefit of a more stable and predictable process inflow is rated a negligible for Alternative A, and limited for alternatives B and C. This reflects that the additional recirculated streams have a small impact on the overall inflow to the treatment plant. And the difference between the alternatives is small and is unlikely to be decisive in the overall assessment.

Overall, the qualitative benefits support the quantitative results, but they do not change the ranking. They do not give a strong argument to prefer Alternative C over Alternative B, since the qualitative benefits for the two alternatives are similar. However, they do support some form of recirculation. Especially the stormwater benefit is important because it would provide an immediate effect from the first day. This benefit is not only important to the water treatment plant, but to the urban water management system as it reduces the load on Mölndalsån.

If the decision-making process focuses on NPV alone, qualitative benefits would be treated as secondary, resulting in an incomplete picture. The identified benefits provide real value to the municipality, even if they are not captured in the NPV calculations. The qualitative assessment should therefore be considered alongside the economic, climate, and risk results. Since several of the qualitative benefits are assessed as moderate to high, the overall assessment could be more favorable than the negative NPV suggests. The decision, therefore, requires the qualitative benefits to be weighed against the NPV. This involves a judgment that cannot be reduced to a number. The role of this study is therefore to make the judgment more informed and transparent.

6.6 Uncertainty and threshold results

The sensitivity, scenario and threshold analysis is one of the more practically useful parts of this study. They translate the slightly abstract NPV results into more practical terms. This is particularly valuable at a screening level, where the aim is to identify key uncertainties and provide decision support rather than produce a definitive decision.

The main challenge in this analysis is that the two parameters with the greatest effect on the NPV, also have relatively low confidence. The discharge handling value and investment cost are both important drivers, but they are both based on either assumptions that may not fit this case fully or preliminary estimates. The NPV results should therefore not be seen as a precise prediction. But instead as a structured way to identify which assumptions are more important and which work should be prioritized in the future.

The scenario analysis shows how the alternatives change when multiple assumptions are changed at the same time. In the pessimistic scenario, alternatives B and C perform worse than in the base case. This highlights the risk when benefits fall below expectations while the costs of the investments increase. Alternative A is less affected due to its smaller system and investment cost.

The optimistic scenario shows an important result. When several parameters change in a positive direction, the NPV of alternatives B and C becomes positive. This shows that economic feasibility is possible under favorable conditions. However, the optimistic scenario assumes that several relatively uncertain parameters change positively at the same time. This includes a lower discount rate, a higher discharge value, a lower investment cost, and a higher climate valuation. While each of these is individually possible, the likelihood of all of them occurring at the same time is low. Alternative A remains negative even in the optimistic scenario, which shows its limited potential.

The threshold analysis for the discharge value is particularly useful. Alternatives B and C require a discharge handling value of above 6 SEK/m^3 to reach a NPV of zero. This is a large increase, but not necessarily impossible, as discussed in section 6.1. The investment cost for alternatives B and C needs to be reduced by about 60-70%, but closing such a large gap is unlikely. This brings attention to the benefits, especially the value of discharge handling and the qualitative benefits. If a larger share of the investment needed at the wastewater treatment plant Ryaverket were included in the discharge handling value, a value of 4-6 SEK/m^3 would not be unreasonable. And if a credible monetary value were assigned to the reduction in stormwater discharge, it could improve the NPV without any other changes. The threshold analysis, therefore, shows both the limitations of the current economic assessment and where it should be strengthened.

The results can also be interpreted in relation to the value of raw water availability. Alternative B has a climate-adjusted NPV of approximately -67 MSEK and recirculates about 6,450 m^3/day, which corresponds to 75 l/s. This means that if the non-monetized value of reduced raw water abstraction and increased supply security exceeds approximately 0.9 MSEK per l/s, Alternative B could be justified socio-economically. This does not mean that Alternative B creates a new water source, but rather that it reduces the need for raw water abstraction and may therefore have value in a future situation with increased pressure on freshwater resources.

6.7 Practical takeaways

The results of this study have several practical takeaways for Kretslopp och vatten and for the future work on rinse water management at Lackarebäck. Most importantly, the results from the additional PFAS verification sampling should be reviewed before further planning. If elevated PFAS levels are found in the carbon filtration backwash water, the alternatives might need to be changed by either excluding this stream or by adding an extra treatment barrier. Detailed planning should proceed after this uncertainty is solved, as this has implications for the drinking water quality.

Alternative B is currently the strongest alternative for further development. The next step would be to perform a more detailed feasibility study. This should include detailed cost and climate estimations, a site-specific discharge handling value, and a framework that meets the requirements of the Swedish drinking water regulations LIVSFS 2022:12. Following these steps can help clarify uncertainties and create a more solid base for making well-informed decisions.

A phased implementation may also be worth considering. Instead of fully committing to one alternative from the start. Some components and technical solutions could be tested first. The most relevant starting point would be the secondary ultrafiltration of the backwash water from ultrafiltration since this is included in all the alternatives and provides a large reduction in stormwater discharge. This would allow practical experience to be gained at a lower financial cost and risk. Later investments could then be built based on the experiences from the first.

The results also suggest that some elements from the alternatives are more relevant than others. From Alternative A, the lower complexity and focus on ultrafiltration backwash recirculation prove valuable. From Alternative B, recirculation of carbon filter backwash water provides a large increase in wastewater reduction and climate benefit which has proved to be the most valuable part of the study. From Alternative C, the sedimentation step may be relevant if future water quality requirements make additional pre-treatment barriers necessary, but the full Alternative C is currently difficult to justify.

Finally, the reduction in stormwater discharge and the potential increase in supply robustness should be used as an extra argument when having dialogue with the municipality. Redirecting 1.4 million m^3/year from the stormwater system supports urban water management, while a reduction of raw water abstraction can improve robustness in periods with high demand or limited raw water availability. These effects are not fully a part of the calculated NPV and should be included when considering future planning.

6.8 Methodological limitations

This study's results are impacted by several methodological limitations that affect the accuracy and ability to generalize the findings. The main limitation is that all alternatives are conceptual, with none of them having been developed in detail. The investment costs, for example, are therefore a preliminary assessment. This is seen as acceptable at this screening level comparison, but it means that the NPV values are highly uncertain.

This is especially significant for alternatives B and C, as the investment cost is the second most influential factor and has a strong impact on the calculated NPV. The sensitivity analysis with a ±20% range gives a better understanding of this uncertainty, but it may not capture the full range of cost variations. If the actual investment cost becomes higher than estimated, the economic assessment would be weaker.

Using approximate values for key parameters introduces uncertainty to the assessment. The most obvious example is the discharge handling value of 3 SEK/m^3, but also the wastewater emission factor and other values are uncertain. The sensitivity and scenario analysis help show how these assumptions affect the results, but they cannot replace a more reliable specific value.

The qualitative risk assessment has some limitations. The scale for assessing likelihood and consequence has three levels, which makes it easier to compare and understand different scenarios. However, the actual probabilities are unknown. To improve this assessment, failure mode and effect analysis or fault tree analysis could be used to provide a stronger understanding of the risk related to the alternatives.

The climate assessment also involves uncertainties. The emissions were calculated using a component-based approach, which does not specifically include all works and installations. Chemical emissions were also estimated only using an average emission factor and an average chemical use increase which not fully captures the exact values of each chemical that is used. These are simplifications that are deemed acceptable for a screening level analysis but should be refined at a later stage.

A bigger methodological question is whether CBA was the best framework to use for this assessment. As discussed in section 2.7, CBA was chosen because it provides a transparent and reproducible basis for decision-making. However, the results of this study also show a weakness in this approach. Benefits that cannot be reliably monetized are excluded from the main ranking even though they are equally important. The clearest example is the stormwater reduction.

A multi-criteria framework could have included qualitative benefits more directly into the overall comparison between the alternatives, but this also requires weighting the criteria, which introduces subjectivity. The choice of CBA is therefore seen as acceptable, but it favours costs and benefits that are more easily monetized.

6.9 Final recommendations

Based on the results and discussion in this study, the following recommendations are offered to support decision-making at Lackarebäck water treatment plant.

Alternative B is recommended as the basis for further development. This alternative provides the best balance across the evaluation criteria, with a positive annual operating result, the highest annual climate benefit, a manageable risk profile, and the potential to become economically feasible under future favourable conditions. Alternative C only provides limited additional benefits compared with Alternative B, while it is at the same time more complex and more costly. Although Alternative A has the least negative NPV, it is less attractive from an overall decision-making perspective. This is because it recirculates the smallest volume of water, provides the lowest climate benefit, has a negative annual operating result, and its NPV remains negative even under optimistic assumptions. Its lower investment cost explains the less negative NPV, but it does not indicate stronger long-term potential compared with Alternative B. Alternative A is therefore considered less attractive when overall performance and future potential are considered.

The next phase should focus on reducing the uncertainties that are identified in this study. This includes performing verification sampling of water quality to investigate the PFAS concentration in the carbon filter backwash water, perform detailed engineering cost estimations and develop site specific estimations of the wastewater discharge handling value. The stormwater reduction benefit should also be explored more thoroughly as this is a clear and immediate benefit with a high value. These steps could improve the reliability of the economic assessment and provide a better understanding for decision-making.

It is also important to note that the alternatives in this study are presented as fixed alternatives. In reality a different approach should be possible. The results show that reduced wastewater discharge is the main economic benefit, while reduced raw water abstraction has a smaller effect on the result. This suggests that it is more to win by prioritizing streams that reduce wastewater discharge, especially carbon filter backwash water, rather than implementing one full alternative as it is defined in this study. An approach that focuses on the most valuable parts from Alternative B could potentially achieve similar benefits with a lower investment cost. This type of approach has not been assessed in detail in this study, but the results suggest that it should be considered going forward.

Finally, the economic assessment should not be seen as final. The threshold analysis shows that the feasibility of alternatives B and C depends on the future regulations and pricing conditions. If wastewater costs, climate values or water policy changes, the result will also change. The assessment should therefore be updated over time as new information becomes available.

7 Conclusions

This thesis evaluated three predefined rinse water recirculation alternatives at Lackarebäck water treatment plant using a cost-benefit analysis framework combined with climate impact assessment, qualitative risk assessment, and qualitative benefit assessment. Based on the results and discussion, the main conclusions are listed below.

- All three alternatives result in a negative NPV, which means that the monetized benefits do not cover the costs over the analysis period under the current assumptions.
- Alternative A has the least negative NPV due to its lower investment cost, but it also has limited water recovery, a negative annual operating result, and limited potential to become economically feasible.
- Alternative B provides the best balance between water recovery, economic potential, climate benefits, and operational risks. It is therefore the recommended alternative for further development. This recommendation depends on the results of the ongoing PFAS sampling in the carbon filter backwash water, which is also recirculated in Alternative C and must therefore be verified before either alternative is developed further.
- Alternative C provides only a small additional increase in water recovery compared with Alternative B but requires higher investment costs. It introduces greater operational complexity, but also the most extensive treatment.
- The economic results are most sensitive to the value assigned to reduced wastewater discharge and to the investment cost. These parameters should therefore be carefully assessed and refined before any decision is made.
- The reduction in stormwater discharge and the potential improvement in supply robustness are important benefits that are not captured in the NPV calculations.

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Appendix A: Input parameters

Parameter	Value	Unit	Used for	Comment
Analysis period	50	years	NPV	Analysis period used for NPV calculations.
Discount rate	3.5%	%	NPV	Consistent with Naturvårdsverket guidelines for environmental infrastructure.
Raw water cost (pumping only)	0.140	SEK/m^3	Benefits	0.200 kWh/m^3 * 0.70 SEK/kWh. See Appendix B.
Discharge handling value	3.00	SEK/m^3	Benefits	Avoided marginal wastewater cost. Based on PM by Saletti (2025).
Electricity price	0.70	SEK/kWh	Benefits & costs	Average cost, provided by Kretslopp och Vatten.
Raw water pumping energy	0.200	kWh/m^3	Benefits	Representative value recommended by supervisor at Kretslopp och Vatten. Based on hydraulic energy equation.
Emission factor: raw water	0.001	kg CO_2e/m^3	Climate	0.200 kWh/m^3 * 0.004 kg CO_2e/kWh.
Emission factor: wastewater treatment	0.170	kg CO_2e/m^3	Climate	Marginal factor, Saletti (2025). Average plant factor (Ryaverket) =0.31 not used as base.
Emission factor: electricity	0.004	kg CO_2e/kWh	Climate	Specific to Kretslopp och Vatten electricity mix. Very low due to renewable share.
Emission factor: chemicals	0.459	kg CO_2e/kg	Climate	Average factor. Source: Svenskt Vatten climate calculation tool.
CO_2 shadow price	5.9	SEK/kg CO_2e	Climate	Midpoint of 4.4-7.4 SEK/kg, Göteborgs Stad, Anthesis Enveco AB.

Appendix B: Calculation of Pumping Energy

Raw water pumping energy input

Raw water pumping energy is calculated using the hydraulic energy equation:

$$E = \frac{\rho * g * H}{\eta * 3.6 * 10^6} \text{ in [kWh/m}^3\text{]}$$

Parameter	Symbol	Value	Unit	Comment
Water density	ρ	1 000	kg/m^3	
Gravitational acceleration	g	9.81	m/s^2	
Pump head	H	65	m	Height difference
Pump efficiency	η	0.75	-	Assumed 75%.
Turbine recovery Lackarebäck	-	-0.010	kWh/m^3	Energy recovered by turbine
Net raw water pumping energy	**-**	**0.200**	**kWh/m^3**	Value used in CBA calculations after recommendations from supervisor.

Internal recirculation pumping energy

Pump efficiency η = 0.70 for all recirculation lines. Used when calculating additional pumping cost.

Pumping line	**Head (m)**	**Vol (m^3/d)**	**E (kWh/d)**	**A**	**B**	**C**	**Total kWh/year**
UF rinse water to secondary UF	5	3 900	75.91	X	X	X	55 457
First filtrate to carbon filter	10	500	19.46	X	X	X	14 201
GAC rinse water to secondary UF	10	1 900	73.96	-	X	X	53 987
Clear phase to process	5	100 and 300	1.95 and 5.84	-	X	X	1422/4261
Total extra energy (kWh/year)				**34812**	**61809**	**63940**	

Appendix C: Detailed Economic Results per Alternative

Alternative A

Item	Value	Unit	Comment
INVESTMENT COSTS			
Secondary UF system	25 000 000 SEK	SEK	Secondary UF reject assumed negligible.
Buffer tanks / equalisation volumes	5 000 000 SEK	SEK	Existing tanks for UF. 5 MSEK for first filtrate.
Piping and installation	550 000 SEK	SEK	150k UF + 300k + 100k first filtrate.
Pumps, controls, engineering	0 SEK	SEK	Included in above estimates.
Total INVESTMENT COST	**30 550 000 SEK**	SEK	Year 0.
ANNUAL BENEFITS			
Value of reduced wastewater discharge	547 500 SEK/year	SEK/year	182 500 m^3/year * 3.00 SEK/m^3
Value of reduced raw water pumping energy	224 840 SEK/year	SEK/year	1 606 000 m^3/year * 0.200 kWh/m^3 * 0.70 SEK/kWh
Total annual benefits	**772 340 SEK/year**	SEK/year	
ANNUAL COSTS			
Cost of extra pumping energy	24 368 SEK/year	SEK/year	34 812 kWh/year * 0.70 SEK/kWh
Maintenance and membrane replacement	100 000 SEK/year	SEK/year	700 000 SEK every 7th year, annualised.
Operating cost (labour + chemicals)	1 200 000 SEK/year	SEK/year	Chemicals ca. 200 000 SEK/year.
Total annual costs	**1 324 368 SEK/year**	SEK/year	
Net annual operating result	**-552 028 SEK/year**	SEK/year	Negative: operating costs exceed benefits.
NPV SUMMARY			
Base NPV (50 year, 3.5%)	-43 498 165 SEK	SEK	PV of net annual result minus INVESTMENT COST.
NPV of monetised climate effects	399 434 SEK	SEK	See Appendix D.3.
Climate-adjusted NPV	**-43 098 731 SEK**	SEK	Base NPV + NPV climate effects.

Alternative B

Item	Value	Unit	Comment
INVESTMENT COSTS			
Secondary UF system	50 000 000 SEK	SEK	Double capacity compared with Alt A.
Buffer tanks / equalisation volumes	65 000 000 SEK	SEK	40 MSEK UF+GAC buffers; 20 MSEK sedimentation; 5 MSEK FF.
Piping and installation	850 000 SEK	SEK	Alt A + 300 000 SEK.
Pumps, controls, engineering	0 SEK	SEK	Included in above estimates.
Total INVESTMENT COST	**115 850 000 SEK**	SEK	Year 0.
ANNUAL BENEFITS			
Value of reduced wastewater discharge	2 792 250 SEK/year	SEK/year	930 750 m^3/year * 3.00 SEK/m^3
Value of reduced raw water pumping energy	329 595 SEK/year	SEK/year	2 354 250 m^3/year * 0.200 kWh/m^3 * 0.70 SEK/kWh
Total annual benefits	**3 121 845 SEK/year**	SEK/year	
ANNUAL COSTS			
Cost of extra pumping energy	43 266 SEK/year	SEK/year	61 809 kWh/year * 0.70 SEK/kWh
Maintenance and membrane replacement	200 000 SEK/year	SEK/year	Double membranes compared with Alt A.
Operating cost (labour + chemicals)	1 400 000 SEK/year	SEK/year	
Total annual costs	**1 643 266 SEK/year**	SEK/year	
Net annual operating result	**1 478 579 SEK/year**	SEK/year	Positive: benefits exceed operating costs.
NPV SUMMARY			
Base NPV (50 year, 3.5%)	-81 169 020 SEK	SEK	PV of net annual result minus INVESTMENT COST.
NPV of monetised climate effects	13 717 275 SEK	SEK	See Appendix D.3.
Climate-adjusted NPV	**-67 451 745 SEK**	SEK	Base NPV + NPV climate effects.

Alternative C

Item	Value	Unit	Comment
INVESTMENT COSTS			
Secondary UF system	60 000 000 SEK	SEK	Increased capacity vs Alt B.
Sedimentation (lamella)	10 000 000 SEK	SEK	New lamella sedimentation step for clarified supernatant.
Buffer tanks / equalisation volumes	65 000 000 SEK	SEK	Same as Alt B.
Piping and installation	950 000 SEK	SEK	Alt B + 100 000 SEK.
Pumps, controls, engineering	0 SEK	SEK	Included in above estimates.
Total INVESTMENT COST	**135 950 000 SEK**	SEK	Year 0.
ANNUAL BENEFITS			
Value of reduced wastewater discharge	2 956 500 SEK/year	SEK/year	985 500 m^3/year * 3.00 SEK/m^3
Value of reduced raw water pumping energy	337 260 SEK/year	SEK/year	2 409 000 m^3/year * 0.200 kWh/m^3 * 0.70 SEK/kWh
Total annual benefits	**3 293 760 SEK/year**	SEK/year	
ANNUAL COSTS			
Cost of extra pumping energy	44 758 SEK/year	SEK/year	63 940 kWh/year * 0.70 SEK/kWh
Maintenance and membrane replacement	250 000 SEK/year	SEK/year	More membranes than Alt B.
Operating cost (labour + chemicals)	1 800 000 SEK/year	SEK/year	Higher due to sedimentation step.
Total annual costs	**2 094 758 SEK/year**	SEK/year	
Net annual operating result	**1 199 002 SEK/year**	SEK/year	Positive: benefits exceed operating costs.
NPV SUMMARY			
Base NPV (50 year, 3.5%)	-107 826 670 SEK	SEK	PV of net annual result minus INVESTMENT COST.
NPV of monetised climate effects	10 694 829 SEK	SEK	See Appendix D.3.
Climate-adjusted NPV	**-97 131 841 SEK**	SEK	Base NPV + NPV climate effects.

Appendix D: Climate Impact Calculations

Construction emissions:

Screening level estimates only. Does not represent a full life cycle assessment.

UF membranes

Alternative	Elements	Factor (kg CO_2e/element)	Direct emission (kg CO_2e)	Incl. rack/install (+100%)
Alt A	30	444	13 320	26 640
Alt B	60	444	26 640	53 280
Alt C	60	444	26 640	53 280

Assuming model is X-Flow Xiga

Buffer tanks

Tank	Volume (m^3)	Concrete (m^3)	Factor (kg CO_2e/m^3)	Emission (kg CO_2e)	Used in
First filtrate buffer (*2 sides)	70	12.6	350	4 410 * 2 = 8 820	A, B, C
GAC rinse water buffer (*2 sides)	250	45	350	15 750 * 2 = 31 500	B, C
Sedimentation basin	500	90	350	31 500	B, C

Concrete usage estimated at 0.18 m^3 per m^3 tank volume. Emission factor 350 kg CO_2e/m^3.

Pipes

Pipe section	Dim.	Length A	Length B	Length C	kg/m	Factor	Emission A / B / C (kg CO_2e)
UF rinse to secondary UF (x2)	DN200	120 m	120 m	120 m	40	2 kg/kg	9 600/9 600/9 600
GAC tp buffer to secondary UF (x2)	DN150	-	180 m	180 m	20	2 kg/kg	- /7 200/7 200
First filtrate to buffer (x2)	DN80	80 m	80 m	80 m	15	2 kg/kg	2 400/2 400/2 400
Clear phase to sedimentation	DN150	-	40 m	40 m	20	2 kg/kg	- /1 600/1 600
Sedimentation to UF	DN150	-	-	50 m	20	2 kg/kg	-/-/2 000
Total pipe emission							**12 000/20 800/22 800**

Lamella sedimentation (Alt C only)

Material	**Low**	**Mid**	**High**	**Unit**	**Factor**	**Emission mid (kg CO_2e)**
Concrete	100 m^3	200 m^3	350 m^3	m^3	350 kg CO_2e/m^3	70 000
Reinforcement/steel	10 000 kg	25 000 kg	50 000 kg	kg	2.5 kg CO_2e/kg	62 500
Lamella plates/modules	5 000 kg	10 000 kg	20 000 kg	kg	3.0 kg CO_2e/kg	30 000
Pumps, piping, controls	+ 20%	+ 20%	+ 20%		-	incl.
Installation/transport	+ 20%	+ 20%	+ 20%		-	incl.
Total	**90 000**	**195 000**	**369 000**	kg CO_2e		**90 000 used (low/conservative)**

Low/conservative scenario used.

Summary of total construction emissions

Component	**Alt A (kg CO_2e)**	**Alt B (kg CO_2e)**	**Alt C (kg CO_2e)**
UF membranes (incl. racks)	26 640	53 280	53 280
First filtrate buffer tanks	8 820	8 820	8 820
GAC rinse water buffer tanks	-	31 500	31 500
Sedimentation basin	-	31 500	31 500
Pipes	12 000	20 800	22 800
Lamella sedimentation (Alt C only)	-	-	90 000
Total construction emissions	**47 460 kg CO_2e**	**145 900 kg CO_2e**	**237 900 kg CO_2e**

Chemical emissions calculation

Chemical emissions are estimated from the Lackarebäck 2026 chemical budget, scaled to the additional water volume treated in each alternative. The chemical budget covers the main chemicals used in the treatment process

Chemical budget 2026

Chemical	Annual use (ton/year)	Use (ton/day)	Price (SEK/kg)	Annual cost (kSEK)	Comment / use in process
Aluminum sulphate	1 000	2.740	3	3 000	Coagulation (before flocculation)
Burnt lime	500	1.370	3	1 500	pH adjustment (before flocculation and after UF)
Lut (NaOH)	1 300	3.562	4	5 200	After UF and membrane cleaning (counted as sulphuric acid equivalent)
Sodium hypochlorite (NaOCl)	139	0.381	40	400	After UF and membrane cleaning
Sulphuric acid (H_2SO_4)	20	0.055	3	60	Membrane cleaning
Total	**2 959**			**10 160**	

Extra chemical cost and emissions per alternative

Extra chemical costs are estimated using a simplified method. It is based on the additional volume recirculated. This gives a conservative estimate of the additional need of chemicals. The unit cost is found from the total chemical budget divided by the total volume treated (3.36 SEK/kg average). Emissions are calculated at 0.459 kg CO_2e/kg (weighted average from Svenskt Vatten climate tool, based on the chemical mix above).

Item	Alt A	Alt B	Alt C
Extra chemical cost (SEK/year)	200 000 SEK/year	400 000 SEK/year	600 000 SEK/year
Extra chemical use (kg/year) [divided by 3.36 SEK/kg]	59 418	118 835	178 253
Extra chemical emissions (kg CO_2e/year) [*0.459]	**27 261 kg CO_2e/year**	**54 522 kg CO_2e/year**	**81 782 kg CO_2e/year**

Annual operational climate effects

Positive value = net emission reduction relative to the reference scenario (no recirculation).

Effect	Formula	Alt A	Alt B	Alt C
AVOIDED EMISSIONS				
Reduced raw water abstraction	Volume * 0.0008 kg CO_2e/m^3	1 285 kg CO_2e/year	1 883 kg CO_2e/year	1 927 kg CO_2e/year
Reduced wastewater discharge	Volume * 0.17 kg CO_2e/m^3	31 025 kg CO_2e/year	158 228 kg CO_2e/year	167 535 kg CO_2e/year
INCREASED EMISSIONS				
Additional electricity use	Extra kWh * 0.004 kg CO_2e/kWh	139 kg CO_2e/year	247 kg CO_2e/year	256 kg CO_2e/year
Additional chemical use	Extra kg * 0.459 kg CO_2e/kg (see D.2)	27 261 kg CO_2e/year	54 522 kg CO_2e/year	81 782 kg CO_2e/year
Net annual climate effect	**Avoided - Increased**	**4 910 kg CO_2e/year**	**105 342 kg CO_2e/year**	**87 424 kg CO_2e/year**

Monetised climate effects and climate-adjusted NPV

Item	Alt A	Alt B	Alt C
Net annual operational climate effect (kg CO_2e/year)	4 910 kg CO_2e/year	105 342 kg CO_2e/year	87 424 kg CO_2e/year
Annual monetary value (SEK/year) [* 5.9 SEK/kg]	28 967 SEK/year	621 518 SEK/year	515 801 SEK/year
Construction emissions (kg CO_2e, year 0)	47 460 kg CO_2e	145 900 kg CO_2e	237 900 kg CO_2e
Monetary construction cost (SEK) [* 5.9]	280 014 SEK	860 810 SEK	1 403 610 SEK
NPV of climate effects (SEK)	**399 434 SEK**	**13 717 275 SEK**	**10 694 829 SEK**
Base NPV (SEK)	-43 498 165 SEK	-81 169 020 SEK	-107 826 670 SEK
Climate-adjusted NPV (SEK)	**-43 098 731 SEK**	**-67 451 745 SEK**	**-97 131 841 SEK**

Appendix E: Cost per Person

Annuity factor

$$\text{Annuity factor} = \frac{1-(1+r)^{-n}}{r}$$

Parameter	Value
Discount rate (r)	3.5%
Analysis period (n)	50 years
Annuity factor	**23.4556**

Net annualised cost per alternative

Item	Alt A	Alt B	Alt C
Total investment cost	30 550 000 SEK	115 850 000 SEK	135 950 000 SEK
Annuity factor	23.4556	23.4556	23.4556
Annualised investment	1 302 461 SEK/year	4 939 119 SEK/year	5 369 720 SEK/year
Net annual operating result	-552 028 SEK/year	1 478 579 SEK/year	1 199 002 SEK/year
Net annualised cost	**1 854 488 SEK/year**	**3 460 536 SEK/year**	**4 597 051 SEK/year**

Theoretical cost per person per year

	Number of people	Alt A (SEK/person/year)	Alt B (SEK/person/year)	Alt C (SEK/person/year)
Full network	600 000	3.09	5.77	7.66
Lackarebäck only	300 000	6.18	11.54	15.32

Appendix F: Sensitivity, Scenario and Threshold analysis

Sensitivity analysis parameter ranges

Parameter	Low	Base	High	NPV range A (MSEK)	NPV range B (MSEK)	NPV range C (MSEK)
Discharge handling value (SEK/m^3)	1	3	5	17.1	87.3	92.5
Investment cost (±%)	-20%	base	+20%	12.2	46.3	54.4
Operational cost (±%)	-20%	base	+20%	12.4	15.4	19.7
Reduced discharge to sewer (±%)	-20%	base	+20%	6.9	35.0	37.0
Wastewater emission factor (kg CO_2e/m^3)	0.10	0.17	0.31	5.3	27.0	28.7
Discount rate (%)	2.0	3.5	5.0	6.9	27.7	22.6
Analysis period (years)	30	50	70	4.0	16.0	13.0
CO_2 shadow price (SEK/kg)	4.4	5.9	7.4	0.2	7.0	5.4
Electricity price (SEK/kWh)	0.50	0.70	1.00	3.4	4.8	4.9
Reduced raw water abstraction (±%)	-20%	base	+20%	2.2	3.2	3.3
Construction emissions (±%)	-20%	base	+20%	0.1	0.3	0.6

Scenario analysis

Scenario	Alt A (MSEK)	Alt B (MSEK)	Alt C (MSEK)	Changed parameters
Base case (with climate-adjustment)	-43.1	-67.5	-97.1	All at base value.
Pessimistic	-56.4	-149.1	-182.5	r=5%, n=30, CO_2=4.4 SEK/kg, dis.val=1 SEK/m^3, elec=0.5, EF WW=0.10, Inv.cost +20%, Op.cost+20%
Optimistic	-13.4	+79.0	+57.4	r=2%, CO_2=7.4, dis.val=5, elec=0.9, EF ww=0.31, Inv.cost -20%, Op.cost -20%
Climate focus	-38.6	-41.3	-70.5	CO_2=7.4 SEK/kg, EF wastewater=0.31 kg CO_2e/m^3

Threshold analysis

Threshold parameter	Alt A	Alt B	Alt C	Base value
Required discharge value for NPV = 0 (SEK/m^3)	13.07	6.09	7.21	3.00 SEK/m^3
Required INVESTMENT COST reduction for NPV = 0	Not possible	-58% (67.5 MSEK)	-72% (97.1 MSEK)	A: 30.6 / B: 115.9 / C: 136.0 MSEK
Required CO_2 shadow price for NPV = 0 (SEK/kg)	645	34.95	59.50	5.9 SEK/kg
Required extra raw water reduction (Mm^3/year)	12.8	19.9	28.6	
Required extra wastewater reduction (Mm^3/year)	0.46	0.72	1.03	

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