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Circulaire oplossing reststoffen oppervlaktewaterzuivering

“Verhip! Het kan ook zonder slib.”

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Joint Research Programme

Bridging Science to Practice

Colophon



Circulaire oplossing reststoffen oppervlaktewaterzuivering

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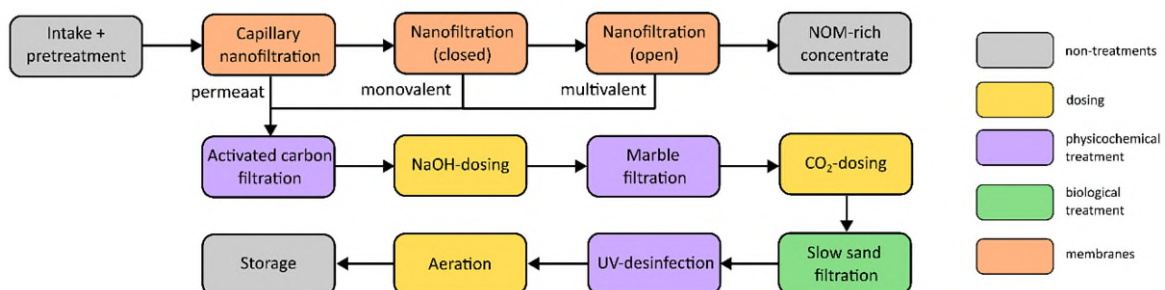
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Managementsamenvatting

Mogelijkheden om zuiveringslocaties effectief te ontwerpen vanuit het oogpunt van circulariteits en hergebruik reststoffen

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Oppervlaktewaterzuiveringstechnologieën zijn voortdurend in ontwikkeling. Circulariteit als uitgangspunt nemen bij de bouw van een zuiveringslocatie, kan operationele en investeringskosten besparen en de milieu-impact verlagen. Bij zuiveringslocatie “De Punt” van Waterbedrijf Groningen produceert een op aluminium gebaseerde coagulatie-flocculatie-bezinking zuiveringsstap een grote hoeveelheid slib. Dit slib bevat veel water, maar kan niet verder worden behandeld. Daarom moet het worden afgevoerd en gestort. Dit is een duur proces. In dit project onderzoeken we dit scenario samen met twee alternatieve, circulaire scenario’s, gebaseerd op membraanfiltratie of ionuitwisseling. Doorrekeningen laten zien dat de kwaliteit van het gezuiverde water over het algemeen dezelfde kwaliteit heeft als in de huidige situatie, en er veel minder of geen slib wordt geproduceerd. De scenario’s produceren wel een reststroom waarin het natuurlijk organisch materiaal geconcentreerd is. Dit product heeft mogelijk een afzetmarkt als bodemverbeteraar, maar er moeten nog verdere zuiveringsstappen worden uitgevoerd voor dit product als zodanig vermarkt kan worden. Aan de hand van de chemische samenstelling van alle stromen in de huidige situatie en de voorgestelde scenario’s zijn de verschillen in milieu-impact en operationele kosten berekend. Met deze informatie kan een zuiveringslocatie effectief ontworpen worden vanuit circulariteitsoogpunt.



Een flowchart van een voorstel voor een alternatieve zuiveringstrein

Belang: Ontwerp optimale circulaire zuiveringslocaties

Bij zuiveringslocatie “De Punt” van Waterbedrijf Groningen produceert een op aluminium gebaseerde coagulatie-flocculatie-bezinking zuiveringsstap een grote hoeveelheid slib. Dit slib bevat veel water, maar kan niet verder worden behandeld. Daarom moet het worden afgevoerd en gestort. Dit is een duur proces. Het bouwen van zuiveringsinstallaties gebaseerd op circulariteit kan milieu-impact en kosten verminderen. Op dit moment worden veel zuiveringslocaties gebouwd met significante reststromen. Locaties ontwerpen en bouwen vanuit een circulariteitsoogpunt kan mogelijkheden bieden

om grote reststromen te hergebruiken in plaats van tegen hoge kosten te lozen.

Aanpak: Circulaire zuiveringsconcepten voorstellen en doorrekenen

Voor zuiveringslocatie De Punt zijn twee zuiveringsconcepten voorgesteld die geënt zijn op circulariteit en doorgerekend: een scenario zoals hierboven afgebeeld, dat berust op opeenvolgende membraanfiltratiestappen; en een scenario dat berust op een ionuitwisselingstap. Beide scenario’s kunnen selectief natuurlijk organisch materiaal uit de watermatrix scheiden voor verder gebruik. De chemische compositie van alle stromen in deze concepten is berekend, en daarmee zijn milieu-

impactstudies en kostenramingen gedaan. Deze doorrekeningen zijn vergeleken met een doorrekening van de huidige situatie.

Resultaten: Circulaire zuiveringsvoorstellen produceren minder reststroom

Doorrekeningen laten zien dat de kwaliteit van het gezuiverde water over het algemeen dezelfde is als in de huidige situatie en dat de voorgestelde concepten geen of veel minder slib produceren en dus een centraal probleem in de huidige situatie oplossen. De voorgestelde concepten produceren wel reststromen met natuurlijk organisch materiaal, die mogelijk verder bewerkt kunnen worden tot bodemverbeteraar. De doorrekeningen van de voorstelconcepten geven wel aan dat de operationele kosten en de milieu-impact mogelijk hoger zijn, maar deze uitkomst neemt niet mee dat in de huidige situatie er ook veel kosten zijn voor het lozen van het ijzerslib. Daardoor zullen de voorgestelde scenario's mogelijk beter uit de bus

komen, omdat deze lozing een grote kostenpost in de huidige situatie is.

Toepassing: Circulariteit kan dure reststromen voorkomen

De voorgestelde circulaire zuiveringsconcepten kunnen alternatieven bieden voor de huidige dure en milieu-impactvolle reststromen, mits de erbij ontstane reststromen verder kunnen worden gezuiverd. Aan de andere kant moet wel meegenomen worden dat deze concepten hand in hand gaan met andere kosten en impact, en dat een goede overweging moet worden gemaakt voordat er gekozen wordt voor één concept. Met de verkregen informatie kan een zuiveringslocatie effectief ontworpen worden vanuit circulariteitsoogpunt.

Rapport

Het onderzoek is samengevat in *Circulaire oplossing reststoffen oppervlaktewaterzuivering* (BTO 2024.066).

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1 Introduction

Surface water treatment is a continuously developing process. In the last few decades, a lot of energy and effort has been spent to develop new treatment pathways and technologies focusing on sustainability, circularity and reducing or reusing waste streams. (Smol, Adam, & Preisner, 2020). One of the methods to achieve a reduction of waste streams or increase circularity is reimagining the sequence of water treatment techniques (or *treatment train*) used in a treatment plant, using waste streams from one treatment technique as feed streams for another. Another method to achieve circularity is to valorize waste streams: finding potential buyers for the waste streams, to make use of the waste streams that are produced, rather than it going to waste.

At treatment plant “De Punt” of Waterbedrijf Groningen (WBG), the treatment train comprises a coagulation-flocculation-sedimentation step using polyaluminium chloride as its coagulant. This step is primarily used to remove the *color*, caused by the presence of humic substances and other organic compounds. However, the coagulation-flocculation-sedimentation produces a waste stream of aluminium hydroxide sludge. This stream cannot easily be put to use or treated in other steps currently employed at “De Punt”, and the sludge is currently taken away to landfill. This is costly, both economically (it costs money to take the sludge to landfill) and environmentally (aluminium hydroxide is not being reused). A point of economic consideration is that the aluminium sludge contains very high levels (98 wt%) of water, which makes the sludge heavy in terms of weight and landfill pricing is by weight.

WBG is interested in changing their treatment train to reduce the amount of this aluminium sludge. In recent years, several new techniques have been researched, developed and used to incorporate circularity into treatment trains, both by KWR (Hofman-Caris, van den Brand, Huiting, Vries, & Wols, 2019) and water treatment companies (Vitens HumVI, PWN Andijk ionenwisselaar). In this report we analyze the current situation, and consider several alternatives to improve economic and environmental options. We design two scenarios that are alternatives to the current situation, each with circularity and valorizability in mind. We analyze each scenario, and calculate the chemical compositions for each of these scenarios in detail using mass balance modelling. Then we perform a life cycle analysis and calculate the economic and environmental impact for the scenarios and the current situation. Finally, we interpret our findings and provide practical advice regarding the different options, the waste streams and their environmental and economic impact.

In this report, we begin in Chapter 2 with describing the different treatment train proposals, including the current train used at “De Punt” by WBG. In Chapter 3, we calculate the chemical compositions of the different treatment trains by a mass balance model. In Chapter 4 we calculate the impacts of these treatment trains: a cost analysis to produce drinking water through each of these trains, and a life cycle analysis to calculate the environmental of the different trains. Finally, we compare the different trains and provide an overview of which train is suitable for which situation.

2 Different scenarios

In this chapter we discuss different scenarios for water treatment at “De Punt”. We start with the current situation, and then consider the two alternative scenarios. In later chapters we will analyze the chemical composition of the output stream and waste streams, we will analyze the economic and environmental impact of each of these scenarios and finally we will discuss what the pros and cons for each of these scenarios are.

2.1 Scenario 1: current scenario

The current scenario is depicted as in Figure 1. It starts with the intake of surface water from the river the Drentsche Aa, and limited storage in water mixing basins. Then, hydrochloric acid is added to the water in preparation for the coagulation-flocculation-sedimentation and further treatment steps. Oxygen dosing, double layer sand / anthracite filtration, activated carbon filtration, UV disinfection and slow sand filtration steps follow the coagulation-flocculation-sedimentation. The resulting water is aerated, sodium hydroxide is added to bring the calcium carbonate concentration up (saturation index to a value of -0,20), and the water is brought to storage.

The main purpose of the aluminum coagulation-flocculation-sedimentation in this treatment train is to remove particulate matter, including organic compounds and humic substances. These compounds give the water a certain color (yellow-brown) and coagulation-flocculation-sedimentation is applied to alleviate this color. Double layer filtration is a rapid sand / anthracite filtration technique, where water is filtered through a filter composed of layers of crushed anthracite and sand. Rapid sand filtration is often used to remove precipitate material from the water (small remaining coagulated material from the previous step) and the removal of iron and other inorganic ions. Activated carbon filtration is a method used to remove a broad range of compounds from the water, such as small organic compounds (e.g. medicinal waste). UV-disinfection is a step to inactivate bacterial material and other pathogens in the water. Slow sand filtration is a technique where water is filtered through a sand filter, like with rapid sand filtration. However, in contrast to rapid sand filtration, the speed with which the water is filtered through the sand is much lower, leading to a biofilm (“schmutzdecke”) to form on top of the sand. This film metabolizes organic compounds and absorbs bacterial cells.

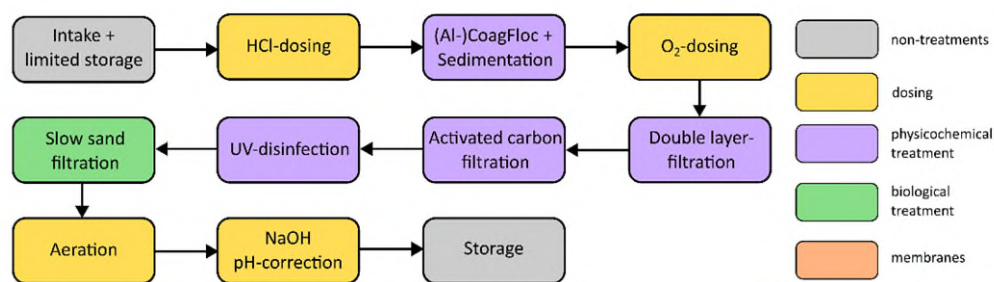


Figure 1: The treatment train at “De Punt”, as currently used by WBG.

According to the experiences by WBG and the chemical measurements of the water at different stages in the treatment train, the train works well with output water quality complying with Dutch legislation. However, the treatment method does generate significant waste, primarily in the form of aluminum flocculation sludge. Contaminants also leave the water by adsorbing to the rapid sand filter, the activated carbon or the slow sand filter. Through backflushing, reactivation and removal of the biofilm, other waste streams are also generated, but these have much lower impact than the aluminum sludge production has. This sludge cannot be used within the drinking water treatment plant and also cannot be sold for use by other organizations. This means it has to be taken away for disposal. The sludge contains a high water percentage, meaning that it has a large weight which is expensive to

get rid of. The challenge in this project is to find scenarios that can achieve similar treatment efficiency for the compounds that are currently treated, while producing less waste material (or *more usable waste material*).

2.2 Scenario 2: membrane-based removal of natural organic material

One option for an alternative treatment train can be found in Figure 2. The purpose of this train is to prevent the need for an aluminum-based coagulation-flocculation-sedimentation step, and not to produce aluminum sludge. Nonetheless, the dissolved organic compounds and natural organic material should still be removed. This is achieved by three consecutive membrane filtration steps to remove the larger organic compounds from the water. The train starts with a capillary nanofiltration step, which rejects (natural) organic compounds and ions, producing a concentrate rich in these compounds. This concentrate is then fed to a closed nanofiltration step: this nanofiltration step (referred to as small-size or closed) is a membrane with a relatively small size cut-off. This primarily rejects the organic compounds and multivalent salts, with monovalent salt continuing on to the permeate. (Frenkel, 2015) Finally, the concentrate of this step is fed to an open nanofiltration step: a membrane with a somewhat larger size cut-off compared to the closed nanofiltration membrane. This membrane rejects mostly the (natural) organic compounds, with multivalent salts go to the permeate. The concentrate from this final nanofiltration step is rich in larger organic material including the natural organic material (NOM).

A concentrated NOM-rich product has been sold by other water companies as a soil improver: NOM-rich products can improve the fertility of the soil and thus increase harvest yields. Soil improvement products are often organic material-rich products, that are used in conjunction with fertilizers. The soil improvement product provides the organic material, while the fertilizer provides the ions like nitrates and phosphates. For instance Vitens, their HumVI product is organic material that has been removed from the water matrix for sale on the market. (Vitens, vitensjaarverslag.nl, 2024) The NOM-rich concentrate produced here might be marketable in a similar fashion, thereby making the removed NOM marketable instead of caught in aluminum sludge.

Several points should be noted here, however. While the exact composition of the HumVI product varies and hard to determine, we know that the project is based on groundwater, whereas “De Punt” is a treatment location based on surface water treatment. Surface water contains a larger concentration of organic micropollutants as compared to groundwater. A significant portion of these compounds will end in the NOM-rich concentrate, reducing the applicability and value of the NOM-rich concentrate as a product for spreading over land to promote plant growth. Furthermore, this concentrate will still contain a significant concentration of salt, primarily multivalent salts. This will be discussed in later chapters, but a relatively high salt concentration also reduces applicability of this NOM-rich product.

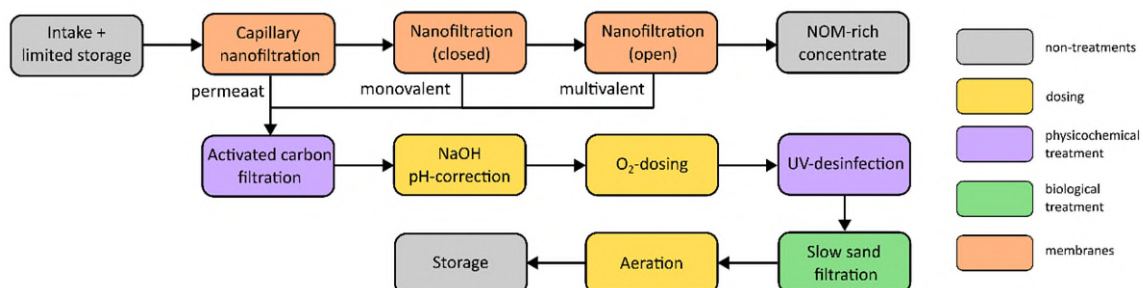


Figure 2: Proposal for alternative treatment scenario. This scenario is based on using membrane filtration steps to remove natural organic material (NOM), which can be used as fertilizer.

The treatment train continues by putting together the permeates from the three nanofiltration steps, and fed to another branch of the treatment train. As these permeates have a low concentration of large organic material, it is not necessary to use a coagulation-flocculation-sedimentation technique after the nanofiltration steps. First an

activated carbon filtration step to remove remaining organic compounds and pollutants (OMP). To make sure the pH of the water is within acceptable limits, NaOH should be added to bring the carbonate saturation index to -0.2, which corresponds to a pH of 7.7 – 8.2.

Thereafter comes an oxygen dosing step to compensate for the loss of oxygen after activated carbon filtration; an alternative to this is an aeration step. However, the risk of aeration compared to oxygen dosing is that at high temperatures (in summer), oxygen solubility is relatively low at atmospheric pressures. In this work we assume oxygen dosing, but aeration could be a cheaper alternative; with the risk that the water needs to be aerated for longer or using a different technique to reach sufficient oxygenation. The water is then treated with UV-disinfection followed by slow sand filtration: first to inactivate biologically active material and to remove organic and bacterial material from the water matrix. Then the water is aerated and sent to storage.

Mass balance modelling as performed and described below or tools such as PHREEQC can give a good indication of the hardness at specific parts of the treatment. Should hardness fall below drinking water standards, one could consider adding a marble filtration step, possibly combined with CO₂ dosing. This step adds bicarbonate and calcium ions to the water matrix, as the marble slowly dissolves into the water. However, it is important to stress here that this will negatively impact the environmental impact and sustainability. It should be noted that pH-control is of high importance in these steps, as the dissolution speed of the marble depends strongly on the pH of the water matrix, and acid reacts with bicarbonate ions to form CO₂-gas.

2.3 Scenario 3: Removal of organics using precipitation and microfiltration

In this scenario, we use ion exchange and microfiltration to remove the natural organic material and color from the water matrix. The treatment train is depicted in **Error! Reference source not found.**

We start with a pretreatment step that includes a microsieve filter, to remove large materials before going into the following steps. Thereafter an anionic ion exchange step is used: a large portion of the negatively charged ions adsorb to the ion exchange resin, which includes organic material such as NOM. After a certain amount of time and when the resin is packed with adsorbed ions, the anions are exchanged by bringing a saturated simple salt (e.g. NaCl) solution into contact with the packed resin: the ions adsorbed to the resin are then exchanged for chloride ions, resulting in a solution with the ions from the influent water matrix in a highly concentrated NaCl-solution.

This anion/NOM-rich solution can then be treated by applying a microfiltration step. This step rejects the NOM and other smaller organic materials into a concentrate stream. Any particles from the sedimentation step will be rejected into a NOM-rich concentrate stream as well. The NOM-poor permeate should be a simple salt (NaCl)-rich waste stream, which could be reused as regeneration product for the ion exchange step, removing the adsorbed ions from the resin.

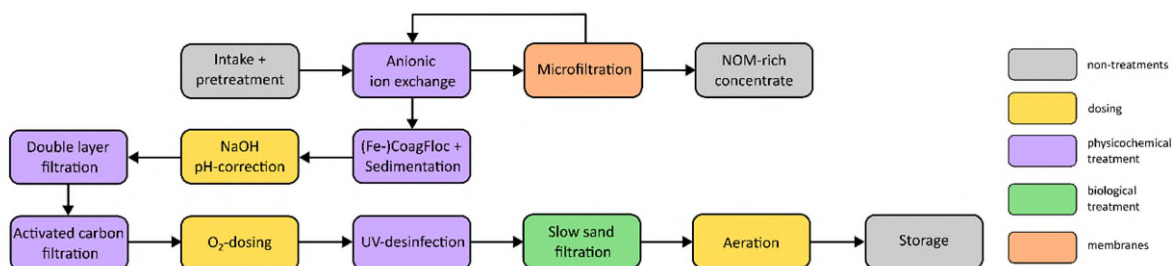


Figure 3: Second proposal for alternative treatment scenario. This scenario is based on using ion exchange to remove negative ions including organics and NOM. Then calcium chloride dosing will remove several small ions from the water matrix and microfiltration will split the remainder up in NOM-poor and NOM-rich components.

This NOM-rich concentrate stream could be of interest in other processes in and outside the water sector. However, several points should be noted here. First of all, the solution is a highly concentrated salt solution, which reduces the possibility of it being used as a soil improver such as the previously mentioned HumVI-product. As mentioned, the exact composition of HumVI is hard to determine, but a saturated salt solution is detrimental for plants. Furthermore, not only natural organic material remains in this NOM-rich concentrate, but other organic material will at least partially end up in this product. This organic material comprises organic micropollutants and small organic acids, reducing the applicability of this stream in terms of circularity and marketability.

The permeate of the ion exchange step will also be treated further. Scenario 3 comprises an iron chloride coagulation-flocculation-sedimentation step removing any remaining particulate material, which may not be needed in this train depending on the removal efficiency of particulate matter by the ion exchange step. Hereafter the train comprises a double layer filtration step to remove remaining solid coagulant material, activated carbon filtering to remove remaining organics, oxygen dosing in preparation for UV-disinfection and slow sand filtration, aeration and storage. We note here that iron-based coagulation-flocculation-sedimentation and subsequent NaOH-dosing might not be necessary, as the largest part of the particles and NOM has been removed at that point by the ion exchange step.

An alternative to the above train can be seen in Figure 4. Here, the anion/NOM-rich solution that comes off from the anionic ion exchange steps is further treated by addition of calcium chloride. This calcium precipitates with several ions from the solution, such as phosphates and sulphates, which can then be removed from the solution. This means that less sulphate and phosphates will enter the ion exchange resin as regeneration fluid, and this fluid can be reused for a longer time. It also removes these from the concentrate. It should be noted that this precipitation step will be partial, and ions such as sulfates will partially remain in solution: calcium sulphate is only partially insoluble, and will at least partially remain in solution. A microfiltration step rejects the NOM and other smaller organic materials. Any particles from the sedimentation step will be rejected into a NOM-rich concentrate stream as well. The NOM-poor permeate should be a simple salt (NaCl)-rich waste stream, which could be reused as regeneration product for the ion exchange step, removing the adsorbed ions from the resin.

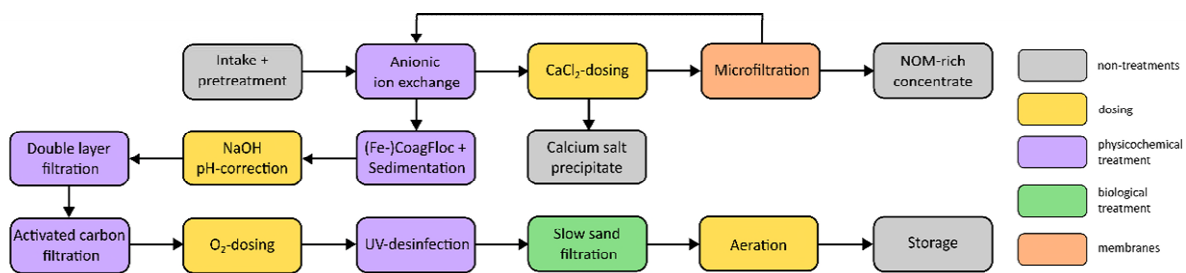


Figure 4: Variation on the second proposal for alternative treatment scenario. This scenario is highly similar to the scenario depicted in Figure 3, but without the calcium chloride precipitation step. The microfiltration step will still split the remainder up in NOM-poor and NOM-rich components.

The effective difference between the two scenarios in this paragraph will be that some precipitable ions will be removed from solution, resulting in a regenerate stream that will still contain less sulphates and phosphates. Furthermore, the NOM-rich concentrate will contain less of these ions, as well. Sulphates and phosphates are beneficial ions for plant growth, so one might consider keeping them in if the NOM-rich concentrate is to be treated further for soil improver. Nonetheless, this is still a stream with near-saturated levels of NaCl, desalination has to be used before it can be repurposed as soil improver. This is done in the HumVI-project as well.

The purpose of this precipitation step is to remove unwanted ions that would otherwise end up in a NOM-rich concentrate or back in the main treated water stream. However, it is questionable whether this would bring the wanted effects: a large part of the salt will remain in solution as calcium cannot remove all unwanted ions.

Furthermore, the precipitate will hold significant water and might break through a microfiltration step due to the fact that precipitate might also be nanoparticle-sized. There are several alternatives for the calcium chloride precipitation steps, as there are other salts that are more efficient at precipitating ions out of solution. One example is barium chloride, which has been discussed during various stages in this project. Barium would also remove sulphates, phosphates and to a lesser extent nitrates. However, barium ions are highly toxic, and we do not recommend the use of barium chloride in a water treatment train, even in a separate branch of the treatment train that does not produce drinking water. This is also the reason why calcium chloride is used in this proposal: calcium is already readily present in drinking water and is not toxic at all. Nonetheless, we expect that this precipitation step will yield unexpected detrimental effects for little benefit.

In the remainder of this document we will consider the scenario as depicted in Figure 3 as Scenario 3a, and the Scenario as depicted in Figure 4 as Scenario 3b.

3 Mass balance modelling

For each of the scenarios described in Chapter 2, we calculate the chemical composition through mass balance modelling. In this chapter we will discuss the results from these models. We discuss each of the three scenarios as described in the previous chapter, including the different subproposals as discussed in section 2.3. This includes a discussion of the chemical compositions of each of the output stream, the waste streams and intermediate positions in the treatment train.

3.1 Method for calculating mass balances

The mass balances were calculated using a calculation tool developed by KWR. In this tool a treatment train can be defined, where a series of treatment techniques are coupled together with defining inflow and outflow streams. The tool then calculates the chemical composition of all effluent streams, given the chemical composition of the influent streams and removal efficiencies per treatment technique. It should be noted that chemical reactions are disregarded in this model, and reactions like carbonate to carbon dioxide gas, or pH reactions are not considered in this work. Therefore, chemical composition should be read as indicative. The tool needs the removal efficiencies for each of the treatment techniques for each of the chemical compounds. This information is defined by the judgement of experienced employees at KWR, and by benchmarking the removal efficiencies with experimental observations from WBG. The tool calculates the chemical composition for outflow water streams, both treated water and waste streams.

3.2 Scenario 1: the current situation

WBG and WLN have provided KWR with a detailed dataset of the chemical compositions of the water at different points in the treatment train. This dataset was used to benchmark the removal efficiencies in our mass balance model: the treatment efficiencies that are achieved by WBG for each of their treatment steps are set in our mass balance model. Some example removal efficiencies can be found in the appendix, but it is beyond the scope of this project to print them all in this document. We did the optimization by comparing the chemical outputs of the calculations to the observations, and iteratively optimizing the removal efficiencies until the output of the tool was satisfactory. In Table 1 we depict the results of the calculation, and the entire dataset can be found in Appendix I. This allows us to use realistic treatment efficiencies for scenarios 2 and 3, and achieve realistic results from our model.

influent into the permeate stream, a significant portion of multivalent ions end up in the concentrate. This means that the concentrate of the three consecutive nanofiltration steps contains a high degree of DOC, but also contains a significant portion of multivalent ions. To a lesser degree, this is the same for monovalent ions. While in an ideal world, we would market this NOM-rich concentrate as a soil improver like with the HumVI-product, these ions will likely prohibit use as soil improver. Soil improvement products typically contain primarily organic matter, increasing the fertility of the soil. Salts such as nitrates and phosphates are readily used by plants but fertilizers are used for the purpose of increasing certain ion concentrations. Repurposing this stream as soil improver will require further desalination steps. (Vitens, WUR-depot, 2013)

One other point that we have mentioned before is the fact that “De Punt” is a surface water treatment plant, and therefore contains more organic micropollutants as compared to ground water treatment. This means that repurposing the concentrate stream as soil improver should consider the organic micropollutants, as this will likely affect the purpose of this stream in soil improvement.

Finally, another significant point is that the produced treated water in scenario 2 contains significantly lower levels of minerals and other compounds as compared to the first scenario. The calculated hardness drops below Dutch drinking water norms: Ca^{2+} and Mg^{2+} -ions should combined be above 1 mmol / L, and in this case it is approximately 0.75 mmol / L. It is therefore recommended that, should scenario 2 be used, experiments are done to check the water hardness before large-scale implementation, and a marble filtration step is introduced should hardness be below minimum levels. On the other hand, scenario 2 would create a good buffer for water quality for a large amount of minerals; fluctuating and worsening influent water quality can be compensated for by choosing this treatment method.

3.4 Scenario 3: removal of organics using ion exchange, precipitation and microfiltration

In this scenario, we discuss proposals for two slightly varying treatment trains (scenarios 3a and 3b). The intention of these trains is to use ion exchange to selectively remove anionic compounds from the water matrix, the product of which is then treated microfiltration and optionally precipitation. The final product is then a stream that primarily contains large-size natural organic material.

Scenario 3a can be seen in Figure 3, and scenario 3b can be seen in Figure 4. In scenario 3a, the ion exchange step separates off the negatively charged DOC, whereafter microfiltration step can then separate dispersed NOM from other dissolved material. The results for this scenario can be found in Table 3, and the full results can be found in Appendix I. For scenario 3b, a precipitation step is used to remove ions from solution, preventing them from re-entering the main stream. The result for this scenario can be seen in Table 4 and results can be found in Appendix I.

A few things stand out from the calculation on scenario 3a, as seen in Table 3. First, the chemical composition of the treated drinking water complies with all drinking water guidelines. The product from this treatment train contains slightly fewer minerals as compared to treatment train 1, but the production volume is somewhat lower. The product contains slightly more minerals as compared to treatment train 2, but well within reasonable parameters.

The ion exchange step is achieved by letting water flow through a bed of ion exchange resin (typically downflow ion exchange geometry), where anionic components adsorb to the resin. After a certain time, a concentrated (often approaching saturation) solution of simple salts is fed over the ion exchange bed, which then drives adsorbed ions to desorb into the regenerate solution. This means that the ion exchange regenerate product has a very high concentration of salt. This is reflected in Table 3, where we assume a regeneration solution of saturated NaCl.

4 Life cycle assessment and cost estimation

In this chapter we will discuss the results from the life cycle assessments and cost estimation. Section 4.1 describes the methodology for both of the assessments. Thereafter, individual scenarios described in the previous chapter will be discussed, allowing a comprehensive analysis of the environmental impacts and cost associated with each of the scenario.

4.1 Methodology

Life Cycle Assessment (LCA)

The performed Life Cycle Assessments (LCA) investigate the environmental impact of the scenarios described in the previous chapters. The methodological approach used to carry out the research followed the ISO-standardized Life Cycle Assessment framework described in ISO 14040/44:2006 (International Standards Organisation, 2006). The unit is m³ per year of influent to the treatment plant. The system boundary for the LCA encompasses the entire treatment process starting from the water intake step and concludes immediately prior to the treated water entering the storage. The LCA was performed using SimaPro 9.2 (Sustainability, 2024) with the Ecoinvent database (Ecoinvent, 2024). The life cycle inventory for this study can be found in Appendix II.

One of the methods used in the LCA is an Environmental Footprint (EF) assessment, which is an impact assessment for the different scenarios. The EF is a subset of an LCA and has been widely used by the European Commission. It is used to let industries chart the impact of their product manufacturing process based on reliable, verifiable, and comparable information (Commission, Environmental footprint methods, 2024). The method defines a set of categories through which a process or product can impact the environment or ecology, and gives a score on how impactful the process is. The list of impact categories considered in this study is presented in Table .

Table 5. Different impact categories used in this study.

Impact Category
Climate change
Ozone depletion
Ionising radiation
Photochemical ozone formation
Particulate matter
Human toxicity, non-cancer and cancer
Acidification
Eutrophication, freshwater
Eutrophication, marine
Eutrophication, terrestrial
Ecotoxicity, freshwater
Land use
Water use
Resource use, fossils
Resource use, minerals and metals

Each of the different impact categories generates a different amount of impact points depending on the severity of the impact categories. The categories were analysed by normalising the different impact categories into a single unit, which allows one-to-one comparison of the magnitude of the impacts. The final step involves assigning subjective weights to different impact categories based on their perceived importance, in units of EcoPoints (per m³

of influent water). This results in a simple and comparable value for understanding the environmental impact. (Commission, Normalisation method and data for Environmental Footprints, 2014)

It should however be noted that a comprehensive LCA requires a lot of data. If not all information about a process or product is present, a generic process has to be assumed which might cause a lot of uncertainty in the calculations. For the LCA study, the processes are aggregated per output stream, meaning that all process units will be combined into a single output stream whenever feasible. Where data were not available, we assumed a generic water treatment process, which might cause some uncertainty in the LCA results. The share of these electricity technologies are valid for the year 2018 which have been calculated by the data provider. The energy composition have been calculated based on statistics from 2018: IEA World Energy Statistics and Balances and serve as a baseline.

4.1.1 Cost Analysis

Apart from the environmental impact, we also calculate the operational cost for each of the treatment trains. We do this by using the cost calculator developed by Royal Haskoning DHV (RHDHV) (DHV, Kostenstandaard, 2024) in cooperation with Dutch water companies. This is a broadly used tool that companies and research entities are using as an initial estimation tool for large investment plans, future expansion models and benchmarking studies. The developer states that the uncertainty in the result can be around 30% (DHV, Handleiding kostencalculator, 2015), and the units are €cents per cubic meter of influent water.

Scenario 1: the current situation

Figure 6 shows the environmental impact of the different water treatment techniques for Scenario 1, or the as-is situation at WBG. The impact units are Ecopoints per cubic meter of treated water. The bar chart shows the relative magnitude of the Ecopoints in that category, and below the chart we give the absolute values for each category and treatment technique.

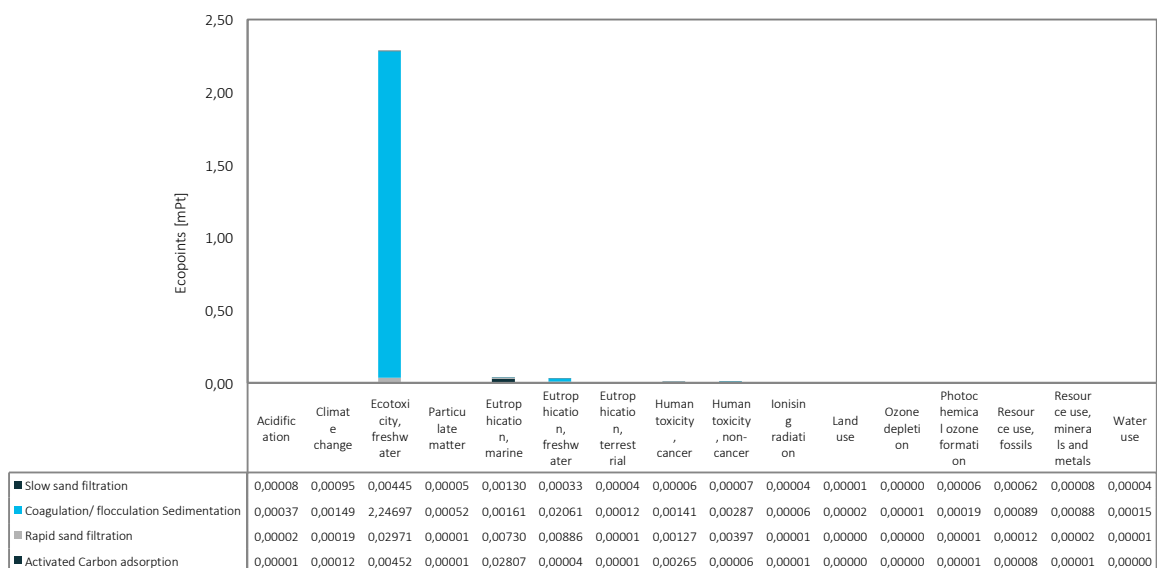


Figure 5: Life cycle analysis results for scenario 1, the currently employed scenario at “De Punt” by WBG. Below the bar chart, the exact ecopoint values are given per treatment technique and per category.

It is immediately clear that only one treatment technique and its residual stream have significant environmental impact and only in one impact category: the aluminum coagulation-flocculation-sedimentation technique causes a lot of environmental impact in the ecotoxicity category. The root cause of this is the production of aluminum sludge

from the polyaluminium chloride, which is a material that is toxic to aquatic organisms. All other categories have a relatively low environmental impact.

In Figure 7, the operational cost of the different water treatment methods per cubic meter are shown for Scenario 1. The order in the figure is the same as the order of the treatment train. We see that slow sand filtration is the most expensive treatment method, costing 24.67 cents per cubic meter of to be treated water. The operational cost of slow sand filtration is relatively high due to its high depreciation cost. These costs were calculated using the RHDHV cost calculator (DHV, Kostenstandaard, 2024). Other expensive techniques are activated carbon filtration (cost of purchase or reactivation of carbon filters, while the specific number of reactivation cycles are not documented, it is estimated that about 3 cents per cubic meter is contributed by the depreciation of carbon material and 0.17 cents per cubic meter for the leaching of carbon material for reuse) and rapid sand filtration (also depreciation and backwashing). Coagulation-flocculation-sedimentation does not show up here as a significant operational cost. This is due to the fact that the cost is associated with the disposal of the waste stream, and in this calculation we only consider operational costs of the technique itself. Important to note here is that operational

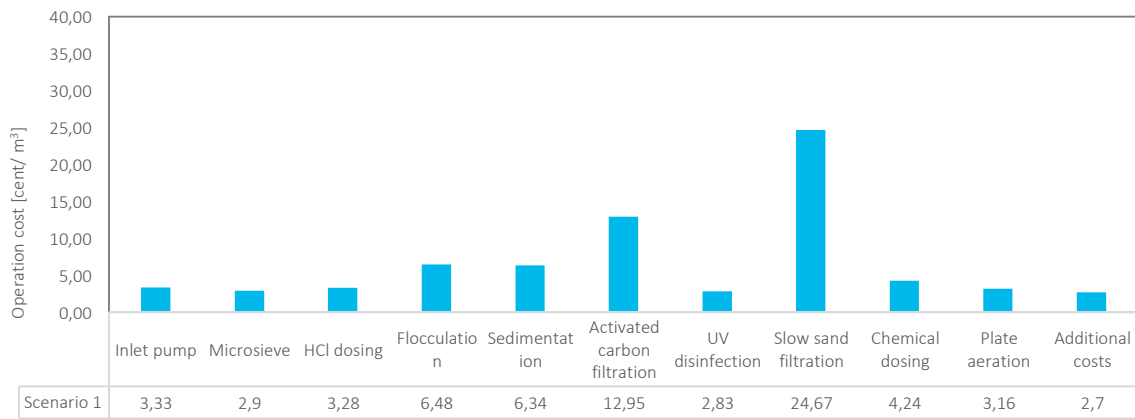


Figure 7: Operational cost analysis results for scenario 1, the currently employed scenario at “De Punt” by WBG. On the bottom, the operational costs in ct/m³.

cost also includes necessary regular purchases such as chemicals needed for operation.

4.2 Scenario 2: membrane-based removal of natural organic material

In Figure 8 we show the environmental impact of the different water treatment methods per cubic meter for Scenario 2. We compare three situations: using the energy mix from average Dutch providers, using a fully renewable mix from wind energy, or using an energy mix from a solar power plant. We can see that the major contribution to environmental impact comes from energy consumption, as impact is very high for non-renewable energy but drops when renewable energy is used. The series of capillary nanofiltration processes have the highest environmental impact across all categories, as these membrane-based processes use have a high energy demand to create the pressure necessary to push the water through the membrane. Energy consumption is one of the main drivers of climate change since most energy still comes from fossil fuels such as coal, oil and gas. However, we want to note here that Dutch water companies use a good amount of green energy, and we expect the environmental impact of energy use by Dutch water companies to be lower. In appendix III, we show an LCA picture for scenario 2 like in Figure 6, using the average energy mix. Note however that WBG uses a renewable energy mix. As illustrated in Figure 10, a comparison of the ecopoints for the energy mix per kWh per m³ between the energy mix, full wind energy and solar energy is shown. 5

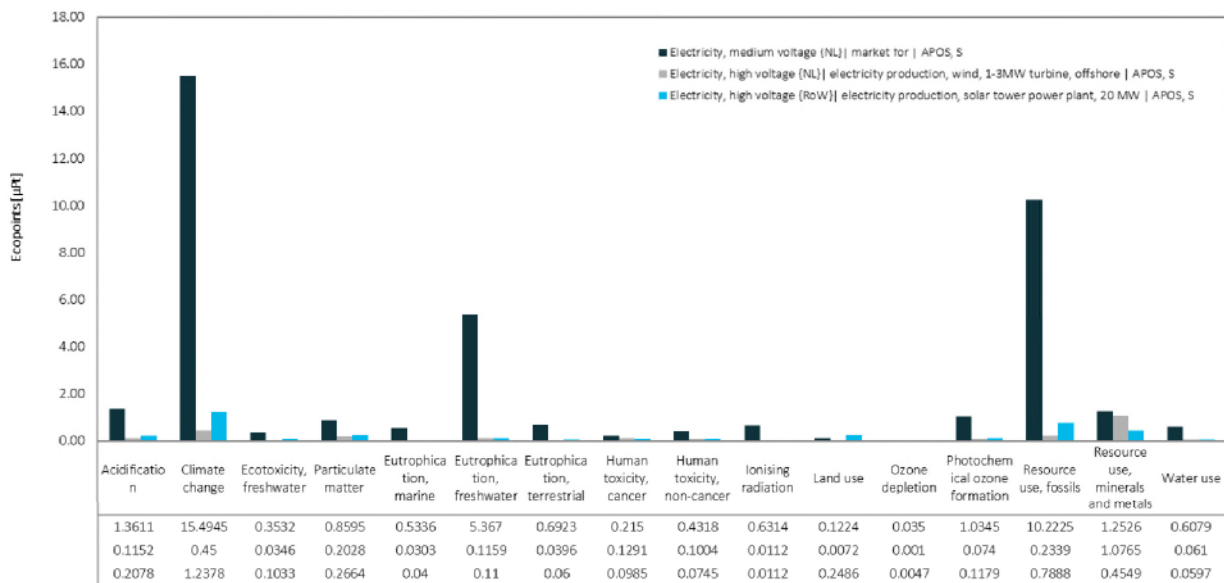


Figure 8: Comparison of the ecopoints for the energy mix per kWh per m³ between the energy mix, full wind energy and solar energy

Scenario 2 is able to produce drinking water with low mineral concentrations, and provides an opportunity to recover natural organic material from the influent water as described in sections 2.2 and 3.2. Such high recovery values might have a beneficial effect on environmental impact as less water is lost during treatment. We note that water loss is not studied in this report as the LCA model does not account for this. There is also a trade-off of the higher energy costs and its associated environmental impact as compared to the fact that there is no longer an aluminum sludge waste stream (relative to scenario 1), also the chemicals added for the coagulation, flocculation and sedimentation processes.

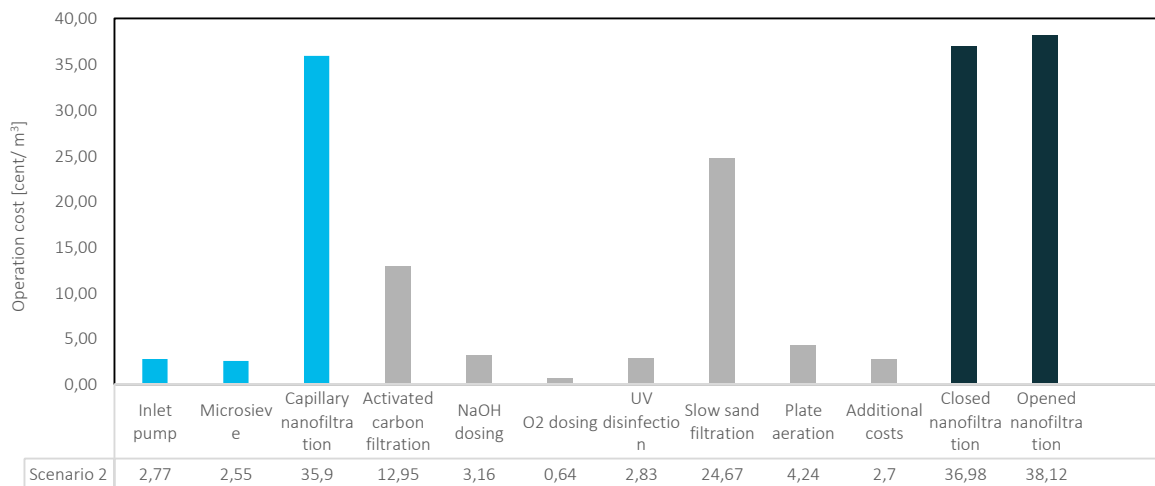


Figure 9: Operational cost assessment for scenario 2, which is based on three consecutive nanofiltration steps as described in Section 2.2. The blue bars as techniques before the split-up in two different branches, where the grey bars are the “main” train section; and the dark navy bars are the nanofiltration branch that ends in NOM-rich concentrate

In Figure 11, we show the operational costs for scenario 2. In this figure, we show the blue bars as techniques before the split-up in two different branches (Figure 2); the grey bars are the “main” train section; and the dark navy bars are the nanofiltration branch that ends in NOM-rich concentrate. About 60% of the operational costs of the system stems from the sequential nanofiltration processes. As said, this comes from the energy needed to set up the pressure over the nanofiltration membranes. Other costs come from sources like depreciation as described in the previous section, or from chemicals needed for dosing.

4.3 Scenario 3: removal of organics using precipitation and microfiltration

In Figure 12, we show the environmental impact for Scenario 3a. This scenario was based on the removal of NOM by ion exchange and microfiltration. We see that the coagulation-flocculation-sedimentation process (denotes as sedimentation) has the highest environmental impact, most prominently in the ecotoxicity impact category. This is due to the addition of the iron chloride as the precipitating agent as described above. Chloride can contribute to freshwater ecotoxicity by disrupting osmoregulation in aquatic organisms, leading to increased stress and potential mortality in sensitive species. Iron ions can contribute to freshwater ecotoxicity by precipitating with carbonates, potentially reducing water hardness and affecting the availability of essential ions needed by aquatic. It is important to note here that this waste stream can be reused to regenerate the ion exchange resin: it still contains primarily sodium chloride, and will be able to regenerate ion exchange resin relatively well. Due to limitations by the model, also the boundary of the study, the energy and consumptions for the regeneration path is not considered in this study, instead this study assumes a steady state of 90% regenerated resin, and 10% of fresh sodium chloride for each gram of sodium chloride required for the process.

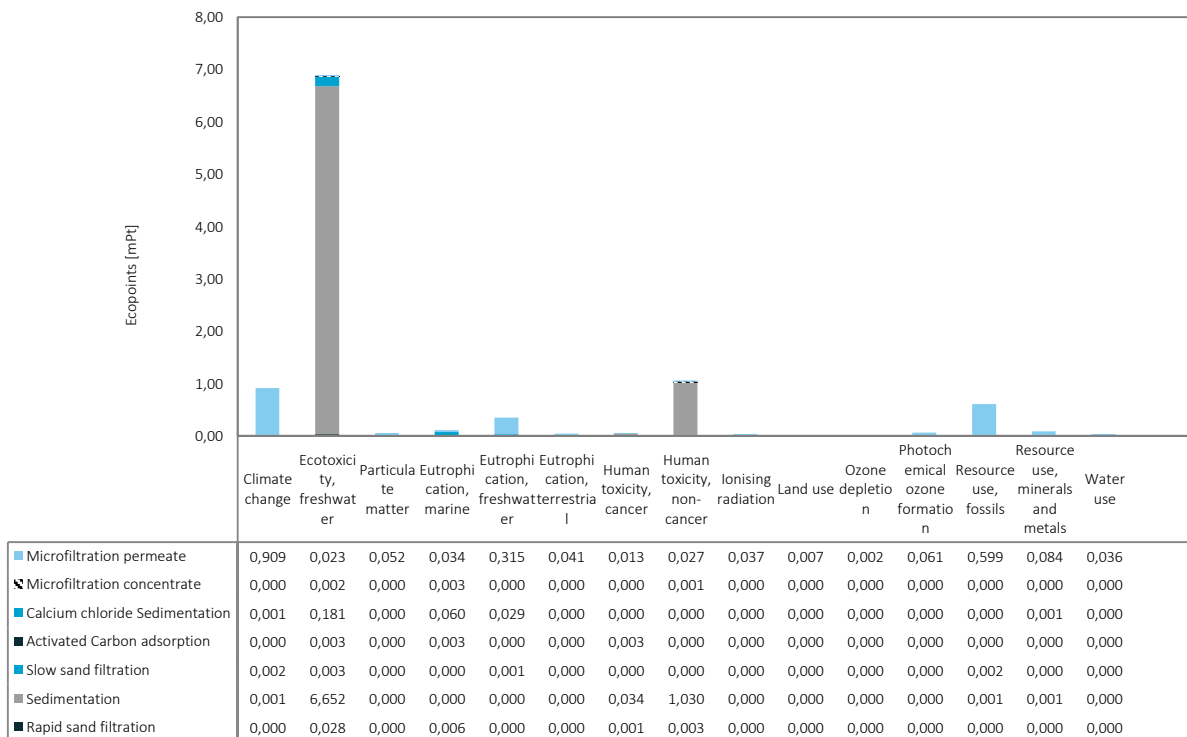


Figure 12. Life cycle analysis results for scenario 3a, which is based on an ion exchange step, a calcium chloride precipitation step and a microfiltration step, as described in Section 2.3. **Error! Reference source not found.**11 we

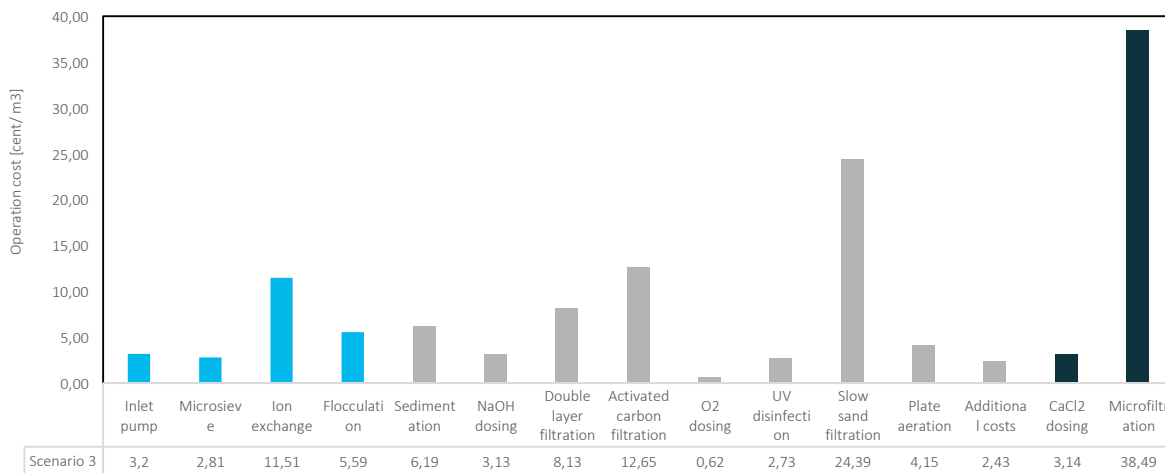


Figure 13: Operational cost assessment for scenario 3a, which is based on an ion exchange step, a calcium chloride precipitation step and a microfiltration step, as described in Section 2.3.

show the operational cost calculation for Scenario 3b. The colors are again split up, with the blue all techniques before the ion exchange, the grey are the “main” train techniques, and the navy bars are the NOM-rich production techniques. We see that the overall expenses are lower than in Scenario 2, but higher than scenario 1. The cost mainly comes from the relatively expensive microfiltration, slow sand filtration and activated carbon filtration, which have high costs per cubic meter of treated water. Other processes show a much lower cost per cubic meter of water. These processes consume less chemicals, energy and labor, and have longer lifespans and lower maintenance requirements. As for scenario 3a, the LCA’s and cost analyses are relatively similar, and therefore we

do not show them as figures in this report. For more information, we show the chemical compositions of all the streams in Appendix I.

5 Scenario comparison

In this chapter we compare the different scenarios with each other. We will draw conclusions which scenarios would be best suited for which situations, and discuss what scenario is best at which category.

Chemical composition of main treated water streams

First we discuss the chemical composition of the treated water streams. The full results can be seen in Tables 1-4 and Appendix I, and we highlight some interesting chemical species in Table 5.

Table 5: Selected chemical concentrations in the main treated water streams.

Chemical species	Untreated water	Scenario 1	Scenario 2	Scenario 3a	Scenario 3b
Calcium [mg/L]	42.6	42.6	23.2	42.6	42.6
Chloride [mg/L]	27.9	41.2	26.8	48.2	48.2
DOC [mg/L]	9.80	4.10	1.08	0.84	0.84
Nitrate [mg/L]	4.10	3.71	3.56	0.38	0.38
Treatment efficiency [vol. influent / treated water]	N/A	88.9% (real: 93%)	92.9%	87.1%	87.1%

A couple of things stand out. We see that most calcium concentrations are at reasonable concentrations and treatment trains do not significantly affect this concentration. Only the capillary nanofiltration steps affect the calcium strongly, which is why scenario 2 has a lower calcium concentration than others. This is of significance, as the water hardness in scenario 2 is below the Dutch drinking water norms, so this should be considered and raised if scenario 2 is implemented. It is therefore recommended to consider adding a marble filtration step to this scenario, as discussed in chapter 3.

The chloride concentration varies more strongly between scenarios. Due to the addition of polyaluminum chloride in the aluminium-based coagulation-flocculation, the salt concentration in scenario 1 is somewhat higher than the untreated water. Scenario 2 does not have any such addition, so this has a lower chloride concentration than scenario 1. Scenario 3 has iron chloride flocculation, so chloride is again somewhat higher here. However, since the DOC concentration is lower at this stage due to the ion exchange steps, less iron chloride may be needed, so the chloride concentration is lower.

DOC is significantly lower in the scenarios 2 and 3. This is due to the focus of these scenarios, which is to selectively remove these into one waste stream. In scenario 2, this is done by consecutive nanofiltration steps; in scenario 3, this is done by ion exchange and precipitation. This means that most DOC ends up in a waste stream, and the only technique that efficiently removes DOC in scenario 1 is the aluminium coagulation-flocculation-sedimentation step. It is however good to consider to what extent DOC removal is necessary: stronger removal might be too much effort for too little gain. Nitrates are also not necessarily a problem, as they are at relatively low levels. They are not being removed significantly in scenarios 1 and 2. However, in scenario 3 they are removed due to the ion exchange step. This then ends up in the NOM/DOC-rich concentrate or the precipitates in these scenarios.

Finally, we calculate that the treatment efficiency, that is the ratio of amount of treated water over the amount of influent water, is best at scenario 2, with scenario 1 coming second, and scenarios 3 coming last. However, efficiencies are for all scenarios quite good. Scenario 2 loses less water due to the absence of a coagulation/flocculation step. Scenario 3 loses water through consecutive water treatment steps. It should be noted that the current efficiency (scenario 1) is in reality about 93%, so somewhat higher than calculated values. Furthermore, the backwashing loss is sent to the mixing basin and then sent through the treatment train, and taking this into account would raise efficiency to 99%.

Chemical composition of DOC-containing residual streams

Here we consider the residual streams that are meant to contain the DOC. In the case of scenario 1, this is the coagulation-flocculation stream; in scenario 2, this is the concentrate from the consecutive nanofiltration membrane steps, and in scenarios 3, this is the ion exchange-precipitation-microfiltration concentrate. They are shown in Table 6.

Table 6: Selected chemical concentrations in residual water streams that are intended to hold the most DOC/NOM.

Chemical species	Untreated water	Scenario 1 aluminum sludge	Scenario 2 nanofiltration concentrate	Scenario 3a ion exchange- microfiltration	Scenario 3b ion exchange- microfiltration
Calcium [mg/L]	42.6	42.6	1260	7.01	42.6
Chloride [mg/L]	27.9	28.9	97.1	$2.2 \cdot 10^5$	$2.2 \cdot 10^5$
DOC [mg/L]	9.80	196	531	3920	3920
Nitrate [mg/L]	4.10	4.10	14.2	7.86	184
Stream volume [% of initial water]	N/A	2%	1.6%	0.08%	0.08%

Here, a few things arise that are interesting. First, we see in scenario 1 that aluminium coagulation-flocculation-sedimentation can capture a significant part of the DOC from the untreated water; however, it is then unfeasible to remove it again after it being adsorbed to the aluminium flocs. Scenarios 2 and 3 do a better job at removing DOC in a much more usable form: a liquid form with primarily ions and DOCs, primarily NOMs. The concentration of DOC is in these scenarios also much higher, especially in scenario 3 where the NOM. Depending on the purpose of this waste stream and the demands of the market, either product might be more beneficial to produce. However, as we noted earlier, the stream in scenario 2 will contain OMP and salt, which will need consideration before using it as a soil improvement product.

The ion concentration is important to consider, as this product has its applications in soil improvement, but high concentrations of salt can impede this. Scenario 1 does not put focus on ion removal, as the influent water is already of concentrations that are within drinking water norms. Scenarios 2 and 3 focus more on ions in the different streams. In scenario 2, we find a very high concentration of calcium in the concentrate, due to the consecutive nanofiltration steps that only partially separate multivalent ions and macromolecular material. In scenario 3a and 3b, the product is essentially a saturated solution of chlorides, due to it being used as regenerate. This regeneration fluid should be recycled and used more than once. Other ions, such as sulphates are present in high concentrations in the NOM-rich streams in scenarios 2 and 3a; 3b reduces this by precipitation. If it is of interest to repurpose this product as HumVI given the considerations described above, the higher concentrations of

sulphates are likely much less of a problem than the high concentrations of chloride. In summary, one should carefully consider the market purpose before choosing either of the scenarios.

Life cycle impact assessment

If we compare the environmental impact of each of the scenarios, some points stand out. First, we compare the three scenarios (scenarios 1, 2 and 3b) among each other in Figure 14. Note that, as mentioned before, this figure still assumes a grey energy mix – in reality WBG uses a renewable energy mix. The summed ecopoint scores per scenario are 2.37 mpt (milli-Ecopoints) per cubic meter of influent water for scenario 1, 3.8 mpt per cubic meter of influent water for scenario 2 and 10.38 mpt per cubic meter of influent water for scenario 3b. (note that these numbers assume a renewable energy mix). We can see that scenario 3 has a higher environmental impact than the other two, assuming that solar energy is used for scenario 2, otherwise scenario 2 jumps to 38 mpt per cubic meter. The primary point of impact for scenario 3b is the iron sludge creation. In summary, we see that scenario 2 can be very low in impact if the right energy is used. Scenario 3b mostly has impact through its coagulation-flocculation-sedimentation step, but this might not be necessary as ion exchange can also be efficient in removing particulate matter. The current scenario is the least impactful, but scenario 3b is also very low in environmental impact.

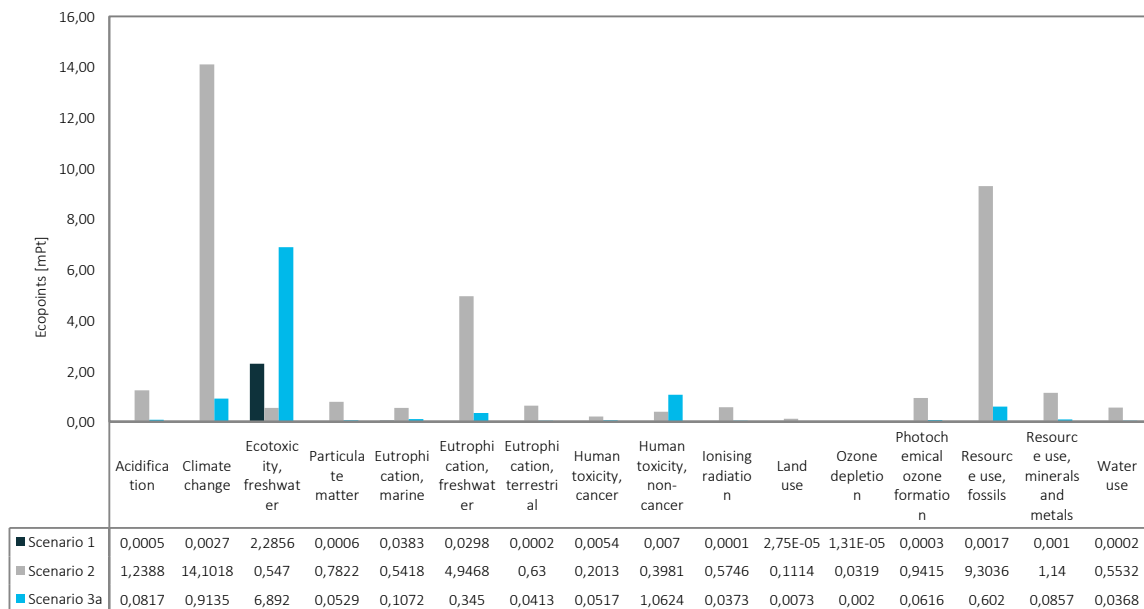


Figure 14: Comparison between the environmental impact between the three different scenarios.

A comparison specifically between scenarios 3a and 3b is shown in Figure 15. It is clear that there is a very minor difference between the two in terms of environmental impact: the change is the precipitation of salts with calcium chloride, which primarily impact the salt concentration in a residual stream.

Operational cost analysis

In Figure 16 we show the cost comparison between the three scenarios in cent / m³. It is apparent that scenario 2 has the highest operation cost compared to the other two scenarios. The total operational cost for scenarios 1, 2 and 3a is 72.88 cent / m³, 167.51 cent / m³ and 129.16 cent / m³ respectively. Scenario 2 and 3a have a percentage difference in operation cost of 129.84% and 77.22% relative to Scenario 1 respectively. For both cases, the highest proportion of their operation cost lies within the pressure driven membrane processes. As mentioned before, these costs are *operational* costs only, and costs like getting rid of aluminium sludge and capital investment are not taken into account.

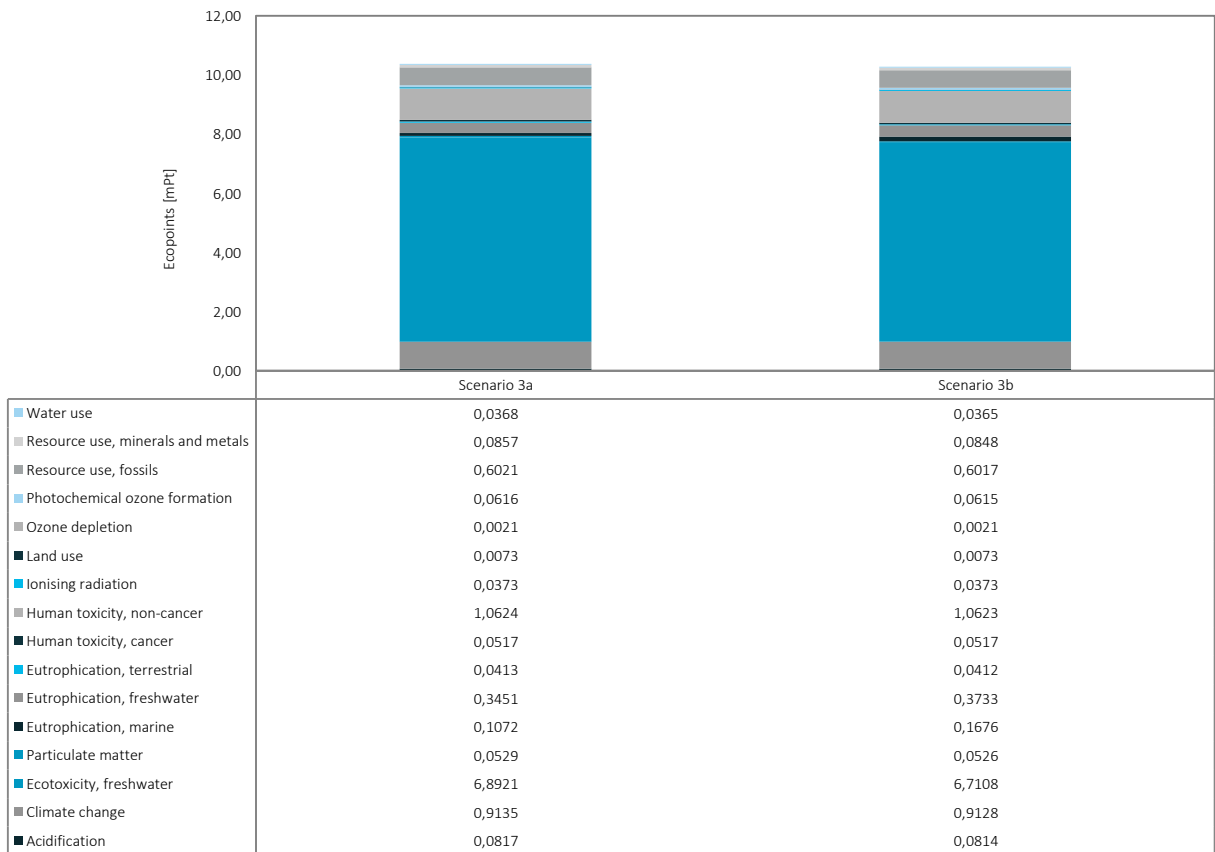


Figure 15: Comparison between the environmental between scenarios 3a and 3b.

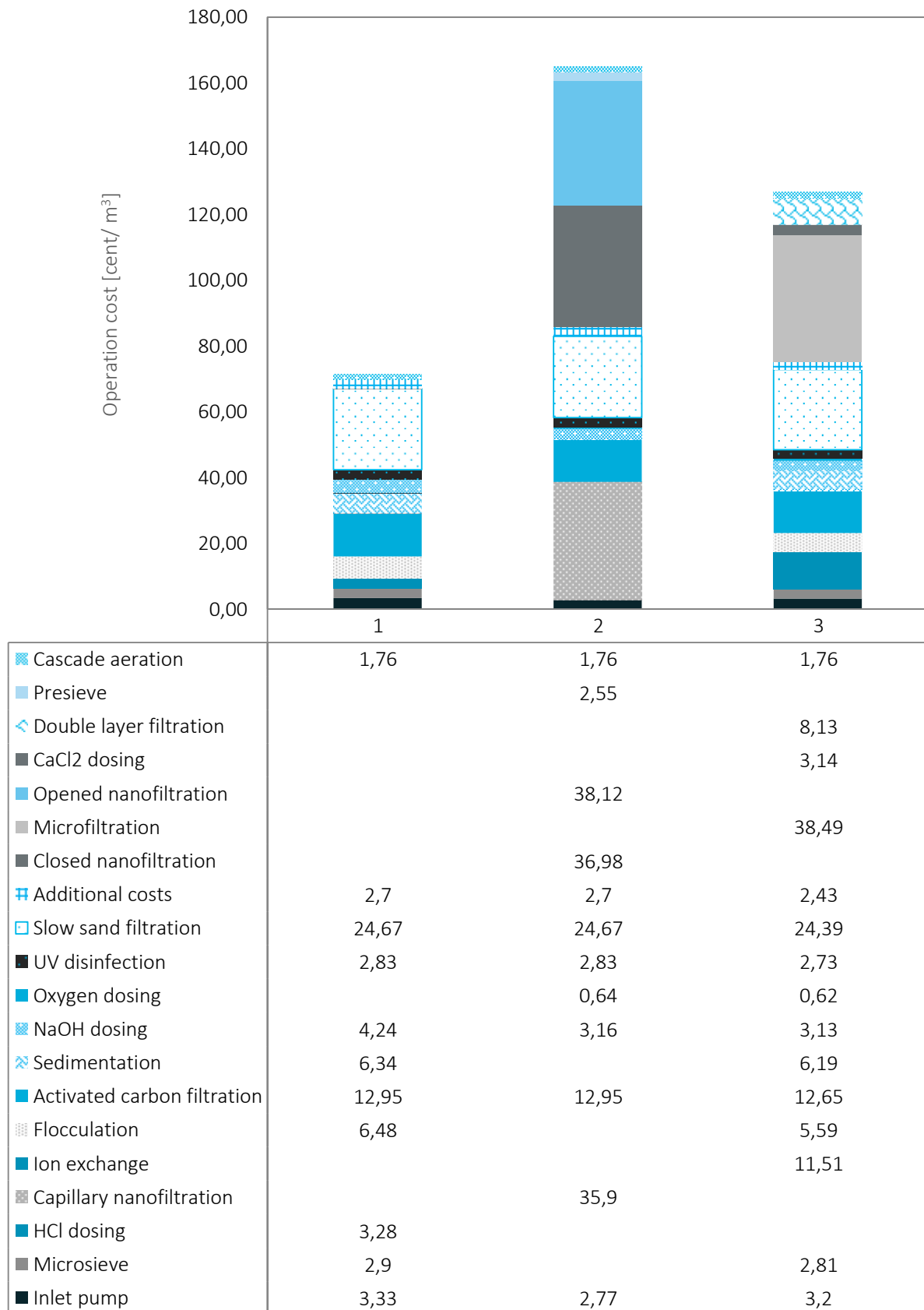


Figure 16. Comparison between the operation cost between the three different scenarios

6 Conclusions

In this report we discuss the current implementation of a water treatment train in “De Punt” by Waterbedrijf Groningen. The current situation uses polyaluminium chloride-based coagulation-flocculation-sedimentation that produces an aluminium hydroxide sludge, which is environmentally impactful and costly to dispose of. We propose several alternative scenarios, each intended to alleviate the need for this coagulation-flocculation-sedimentation step. One scenario is based on three consecutive nanofiltration steps, intended to concentrate the natural organic matter in a single residual stream. Another scenario uses anionic ion exchange steps, the concentrate of which is treated with precipitation steps and microfiltration. These scenarios can effectively remove NOM from the main water stream. The residual streams containing NOM could be interesting for repurposing as soil improvement product; however, the streams should be treated further before this is viable. We calculate the chemical composition of all the streams in each scenario including the current situation using mass balance modelling. Then we calculate the environmental impact and the operational expenditure of each scenario, and finally we compare the different scenarios among each other.

We find that the current scenario and scenario 3 comply with the drinking water standards. Scenario 2 meets almost all standards, but leads to a low water hardness below national norms. Should this scenario be used, it is recommended that a step like marble filtration is added to alleviate these problems. We also find that the proposed scenarios are capable of effectively removing the NOMs. The proposed scenarios produce a stream of different quality, and depending on the demands of the market, each scenario can have its own benefits. We find that a scenario based on ion exchange (scenario 3) has the most environmental impact, primarily due to a flocculation step that might not be necessary due to the preceding ion exchange step. If non-renewable energy is used, a scenario based on consecutive filtration steps (scenario 2) becomes environmentally impactful, but WBG already uses a renewable energy mix.

One specific point of interest in this project is repurposing the DOC / NOM. Concentrated DOC / NOM has been marketed by other Dutch water companies as soil improvement product. In the case of scenarios 2 and 3, DOC is removed into a residual stream of liquid form, and similar approaches might be useful here. However, we find that this will require significant effort beyond what has been researched in this project. Scenarios 2 and 3 produce NOM-rich streams, but these contain a large portion of the OMPs. This also contains a concentrated or nearly-saturated solution of sodium chloride. Other companies, like Vitens, use ground water as their source of NOM-rich material, which means there is less OMP present, and they post-process their NOM-rich stream with desalination. Applying the same technique on location “De Punt” requires a lot more effort; and there is no simple solution for the OMP removal. We therefore recommend caution before trying to repurpose a NOM-rich stream as soil improvement product, and first consider removing the OMPs and the sodium chloride.

We also calculate the operational expenditure for each scenario. While both proposed scenarios have a higher operating costs at a percentage increase of 133% and 79% relative to the current situation, both scenarios also provide an opportunity towards a regenerative business model by attempting to recover the residual streams. Furthermore, operational costs do not take the disposal costs of aluminum sludge into account, which are significant costs (approximately €0.05 per cubic meter, which is equivalent to €350.000,- per year); however, according to our calculations, scenarios 2 and 3 are significantly more expensive than €0.05 per cubic meter of produced water. We therefore expect scenarios 2 and 3 to be more costly than the current situation.

In brief, we propose several scenarios that can prevent the need for aluminium-based coagulation-flocculation-sedimentation and lead to a residual stream that could be used in other processes. Each scenario has its benefits and its drawbacks, but each scenario can be used to effectively treat surface water from “de Drentsche Aa”.

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Long name	Unit	Calcium precipitate		Micro-filtration permeate	Micro-filtration concentrate	Iron sludge	Retended material Double layer Filtration	Retended material Activated Carbon	Retended material Slow Sand Filtration	Treated water	
		mg/L	µg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
Ammonium	mg/L	0,00	0,10	0,10	0,10	0,10	5,00	0,00	0,00	0,00	
Aluminium	µg/L	0,00	0,12	0,12	0,12	4,30	0,56	3,76	0,01	0,01	
Arsenic	µg/L	0,00	6,50	6,50	6,50	10,61	16,24	0,00	0,00	0,00	
Barium	µg/L	0,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	
Cadmium	µg/L	0,00	0,00	0,00	0,00	0,06	0,06	0,03	0,00	0,00	
Calcium	mg/L	1,54E+03	7,01	7,01	7,01	42,60	42,60	42,60	42,60	42,60	
Chloride	mg/L	1,77E+03	2,20E+05	2,20E+05	2,20E+05	48,20	48,20	48,20	48,20	48,20	
Chromium	µg/L	0,00	1,53	1,53	1,53	15,30	12,49	40,78	0,67	0,67	
DOC	mg/L	0,00	245,00	3,92E+03	4,19E-07	0,04	0,02	0,00	0,00	0,00	
Phosphate ortho	mg/L	4,95	4,19E-07	1,00	1,00	35,00	15,31	0,00	0,00	0,00	
Iron (III)	mg/L	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Mercury	mg/L	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Magnesium	mg/L	0,00	5,30	5,30	5,30	26,50	4,87	4,87	4,87	4,87	
Manganese (II)	mg/L	0,00	0,10	0,10	0,10	1,00	4,04	0,03	0,00	0,00	
Sodium	mg/L	0,00	1,41E+05	1,41E+05	1,41E+05	17,40	18,44	18,44	18,44	19,59	
Nitrate	mg/L	176,64	7,86	7,86	7,86	0,42	0,42	8,37	0,38	0,38	
Silica	mg/L	0,00	10,60	10,60	10,60	10,60	10,60	0,00	106,53	10,17	
Nitrogen (N ₂)	mg/L	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Sulphate	mg/L	389,98	0,02	0,02	0,02	11,94	11,94	11,94	11,94	11,94	
TOC	mg/L	0,00	357,50	5,72E+03	5,72E+03	58,37	4,47	69,28	27,00	1,22	
Zinc	µg/L	0,00	4,34	4,34	4,34	86,70	79,62	43,33	28,44	0,21	
Oxygen (O ₂)	mg/L	0,00	10,63	10,63	10,63	10,63	10,63	10,63	11,72	9,10	
Water	L	0,00	19,20	0,80	0,80	19,60	18,82	4,60	4,38	870,88	
		Initial water									
		Intra-train stream									
		Residual stream									
		Treated water									

Appendix II: LCA Inventorisation

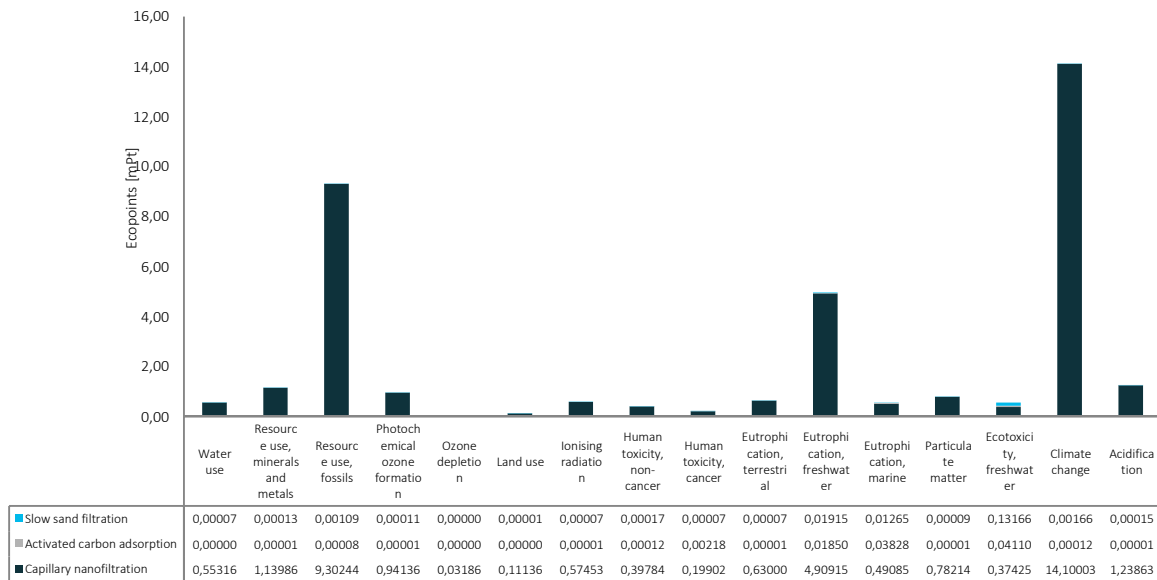
Scenario	Technology	Processes	Database	value	unit
1	Activated Carbon Adsorption	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	8	Wh
1	Rapid Sand Filtration	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	12	Wh
1	Coagulation, Flocculation Sedimentation	HCl dosing	Hydrochloric acid, without water, in 30% solution state {RER} market for APOS, S	5	g
		Dosing Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	3	Wh
		Flocculation	Electricity, medium voltage {NL} market for APOS, S	20	Wh
		PAC dosing	Polyaluminium chloride {GLO} market for polyaluminium chloride APOS, S	20	g
		Sedimentation energy	Electricity, medium voltage {NL} market for APOS, S	5	Wh
1	Slow Sand Filtration	UV dosing	Electricity, medium voltage {NL} market for APOS, S	54	Wh
		Slow sand Filtration	Electricity, medium voltage {NL} market for APOS, S	4	Wh

		NaOH dosage	Electricity, medium voltage {NL} market for APOS, S	3	Wh
		Aeration	Electricity, medium voltage {NL} market for APOS, S	40	Wh
2	Activated Carbon Adsorption	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	8	Wh
2	Nanofiltration	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	1.09E9	J
		Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	1.09E9	J
		Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	1.09E9	J
2	Slow Sand Filtration	UV dosing	Electricity, medium voltage {NL} market for APOS, S	54	Wh
		Slow sand Filtration	Electricity, medium voltage {NL} market for APOS, S	4	Wh
		NaOH dosing	Electricity, medium voltage {NL} market for APOS, S	3	Wh
		O2 dosing	Electricity, medium voltage {NL} market for APOS, S	6	Wh
		Aeration	Electricity, medium voltage {NL} market for APOS, S	40	Wh

3	Activated Carbon Adsorption	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	8	Wh
3	Double layer filtration	Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	20	Wh
		HCl dosing	Hydrochloric acid, without water, in 30% solution state {RER} market for APOS, S	5	g
		PAC dosing	Electricity, medium voltage {NL} market for APOS, S	3	Wh
		Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	10	Wh
		Iron Chloride Dosing	Iron (III) chloride, without water, in 40% solution state {GLO} market for APOS, S	20	g
		Energy Consumption	Electricity, medium voltage {NL} market for APOS, S	5	Wh
3	Slow Sand Filtration	UV dosing	Electricity, medium voltage {NL} market for APOS, S	54	Wh
		Slow sand Filtration	Electricity, medium voltage {NL} market for APOS, S	4	Wh
		NaOH dosing	Electricity, medium voltage {NL} market for APOS, S	3	Wh
		O2 dosing energy consumption	Electricity, medium voltage {NL} market for APOS, S	50	Wh

		O2 dosing	Oxygen, liquid {RER} market for APOS, S	1	g
		Aeration	Electricity, medium voltage {NL} market for APOS, S	40	Wh

Appendix III: LCA Scenario 2, detailed breakdown



Life cycle analysis results for scenario 2, which is based on three consecutive nanofiltration steps as described in Section 2.2. This LCA is based on the non-renewable energy mix that is average on the Dutch energy nets.

Appendix IV: Brief summary of precipitation model

The mass balance calculation described in this report is based on administrated removal percentages per technique and per chemical entity. One of the few exceptions to this method is the precipitation steps described in scenarios 3. Below, we will briefly discuss the method with which this calculation was done.

We first take the example of calcium precipitation. First, the solubility for the calcium salts was looked up, given the negatively charged ions that are most prevalent in the water matrix and a reasonable water temperature. Then, a table was made with the concentrations of the calcium and with each of the prevalent counterions. For each of the salts, it was checked whether a combination of calcium ions and counterions exceeded the solubility, and these combinations were noted. It was assumed that each of these combinations precipitated and a small amount (5%, relative to the amount of counterion still present) was removed from the table. These last two steps were repeated until all calcium-counterion combinations were below the threshold of solubility. The output of this technique is the removed material (precipitate) and the final chemical composition. Other precipitation steps were done by looking up other solubilities for other coion-counterion combinations.

Appendix V: example removal efficiencies (polyaluminium chloride-based coagulation- flocculation-sedimentation)

In the below tables, the recoveries and retentions are given. Recovery is defined as the amount of water that an effluent stream contains: in this case, 90% of the water leaves the flocculation technique as treated water, and 2% is retained in the sludge. Retentions are defined as follows:

$$R = \frac{c_s}{c_{in}} \cdot 100\%$$

R is here the retention, c_s is the concentration of the stream of concern and c_{in} is the concentration of the feed water. It should be noted that, if retention is 100%, the compound does not interact with the treatment and the concentration in the treated water (and in the sludge) is the same as the concentration in the feed water.

Recovery water main stream	Recovery water sludge stream
98%	2%

	Retention (to treated water)
Aluminium	69%
Ammonium	100%
Calcium	100%
Carbonate	100%
Chloride	100%
DOC	39%
Iron (III)	69%
Magnesium	8%
Manganese	18%
Methane	100%
Nitrate	100%
Oxygen	100%

Phosphate (total)	69%
Potassium	100%
Sodium	100%
Sulphate	100%
Suspended material	69%