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Investigating nutrient filter options for water inlet points in Land van Maas en Waal

BSC THESIS

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Waterschap Rivierenland

Preface

Before you lies the bachelor thesis “Investigating nutrient filter options for water inlet points in Land van Maas en Waal”. It has been written to graduate from the Bachelor Civil Engineering at University Twente. The writing of this thesis took place from April 11th 2023 till June 21st 2023.

The choice for this subject was made after inquiring at Waterschap Rivierenland if any assignments were available for a bachelor student that wanted to perform their bachelor thesis at Waterschap Rivierenland. One of the options was investigating nutrient filters at the inlet points of Land van Maas en Waal. I had very little knowledge about filters and it seemed like a fun challenge to step out of my comfort zone and try something which I knew very little about.

I would like to thank Sjoerd Pietersen who was my supervisor within Waterschap Rivierenland and who helped me get in contact with the right experts within Waterschap Rivierenland and also offered me feedback that helped improve my work. I would also like to thank Dr. ir. Geert Campmans for helping me stay on track during the process of the thesis and for the insightful feedback on my work. I would also like to thank the people at Waterschap Rivierenland that provided me with the necessary data for my thesis. Finally, I would like to thank my friends and family for supporting me during the writing of this thesis.

I hope you enjoy reading my thesis.

Stefan Grandia

Tiel, June 21, 2023

Abstract

In this research, the possibility of filtering nutrients out of the inlet water of Land van Maas en Waal is researched. In times of drought, more water needs to be let into Land van Maas en Waal. This water comes from rivers and canals and has a high nutrient concentration and contains a lot of algae. This low-quality water causes problems in Land van Maas en Waal because a high nutrient concentration and warm temperature are good circumstances for toxic blue-green algae to bloom. Making the water not safe for use. The research question is: *What type of filter is most suited to remove the nutrients from the inlet water at the five inlet points in het Land van Maas en Waal?* The research was performed by reviewing available literature and having interviews with experts of Waterschap Rivierenland. The filters have been compared with the use of a multi-criteria decision analysis. From the research, it became clear that a discontinuous sand filter would be the most suited filter for filtering inlet water, of the filters that have been analysed. While the filter is most suited for filtration and is deemed to be cost-effective more research needs to be done to see if filtering inlet water is a viable measure to improve the water quality and prevent algae blooms.

Table of Contents

List of Figures

List of tables

List of equations

List of abbreviations

AHP	Analytical hierarchy process
FTE	Full time equivalent
GAC	Granulated activated carbon
MCDA	Multi-criteria decision analysis
MTR	Maximum allowable risk
PACAS	Powdered active carbon in active sludge
PE	Population equivalent, the amount of wastewater that needs to be treated for one inhabitant
WFD	European water framework directive
WWTP	Wastewater treatment plant

1. Introduction

In the past years, there have been several dry years, with 2022 even reaching the top five driest years recorded in the Netherlands. These droughts cause problems with the supply of water as well as with the quality of water. During the dry periods more water has to be let into Land van Maas en Waal since there is no rainfall and there is a higher demand for water for irrigation. The water in these rivers contains a lot of nutrients. This is caused by the dumping of effluent from water treatment facilities on the rivers. In the slower-flowing parts of the rivers algae blooms grow. This low-quality water, which contains a lot of nutrients and algae is then used as inlet water for Land van Maas en Waal. The high nutrient concentration causes algae blooms in the water system, these algae combined with the algae that get let in cause high concentrations of toxins which can prevent the water from being safe to use. Besides the toxins, the algae also cause stench and can cause low-oxygen concentration in the water. To prevent the negative effects that are caused by letting this water in Waterschap Rivierenland wants to investigate the possibility of filtering nutrients out of the inlet water. In this thesis, the possibilities of filtering the inlet water at the five inlet points of Land van Maas en Waal will be investigated.

First, the problem will be stated together with the research objective in Chapter 2. After that, the research question and the sub-questions will be stated in Chapter 3. Then in Chapter 4, some context will be given, this context consists of an explanation of the study area, the current water quality in Land van Maas en Waal, and information about blue-green algae. In Chapter 5 the methodology that is used to get to the results will be explained. In Chapter 6 important information about the inlet points is gathered. This will include the discharge at the inlet points and the water quality at the inlet points. In chapter 7 several filter types will be assessed on their ability to remove nutrients. The filters that reach sufficient nutrient removal will be assessed further in Chapter 8. Then, in chapter 9 the filters will be compared using a multi-criteria decision analysis. Finally, in Chapter 10 the cost-effectiveness of the filter will be calculated and compared to other measures to see how it compares to other measures.

2. Problem statement and research objective

During droughts the composition of the water supply for the polder changes, more water originates from the Maas and the Maas-Waal Channel, the water quality in these rivers is worse than in the polder and therefore harms the water quality inside the polder. The most pressing issue is the high amount of nutrients in the water, this causes a nuisance by increasing the growth of algae, and floating water plants, this increase in biomass causes the oxygen content of the water to decrease.

The research objective is to assess possible solutions to the decreased water quality in the form of filter construction at the five water inlet points of Land van Maas en Waal. If a solution is found the possibility of using the solution throughout the management area of Waterschap Rivierenland will also need to be assessed.

3. Research question

In this research question the nutrients refer to all phosphate and nitrates in the water. The five inlet points refer to the inlet point at Weurt, the sluice at Landewijer, the Teersesluis, Blauwe Sluis, and Rijksche Sluis. These points are shown in Figure 2. Since this study will be focused on nutrients in the water, water quality will mostly be focused on nutrients in the water. Finally, effective removal of nutrients refers to how well the filter removes the nutrients from the water. In the next questions, the feasibility of using these filters at the inlet locations is assessed.

- What type of filter is most suited to remove the nutrients from the inlet water at the five inlet points in het Land van Maas en Waal?
    - To what extent is the water quality affected by droughts?
    - Which filter is most effective in removing nutrients from the inlet water?
    - Which filter can realistically be constructed and put into operation at the inlet points?
    - To what extent does the filter construction have an impact on the discharge at the inlet points?

4. Context

The context in which the study will take place is important. In this chapter, the study area and current water quality will be shortly assessed. Additionally, context about the different filter types that can be used will be researched in the literature.

4.1. The study area

The study area is het land van Maas en Waal, this is in an area in the Netherlands which lies in between the Maas and the Waal the study area can be seen in Figure 1. As mentioned earlier the water quality in times of drought needs to be improved. The five inlet points that need to be investigated are the sluice at Weurt, Landewijer, the Teersesluis, Blauwe Sluis, and Rijksche Sluis. These are the inlet point in het Land van Maas en Waal and will be the primary part of the study, they can be seen in Figure 2. Possible ways to use the designed filter construction throughout the management area of Waterschap Rivierenland will also be assessed however, only land van Maas en Waal is part of the study area. The construction of filters at other inlet points in the management area will be discussed in the discussion.

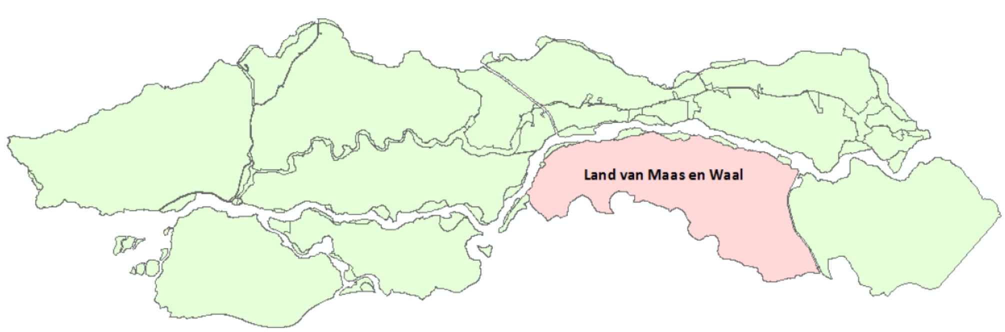

Figure 1: Management area of Waterschap Rivierenland. Land van Maas en Waal has been highlighted (Royal HaskoningDHV, 2019)

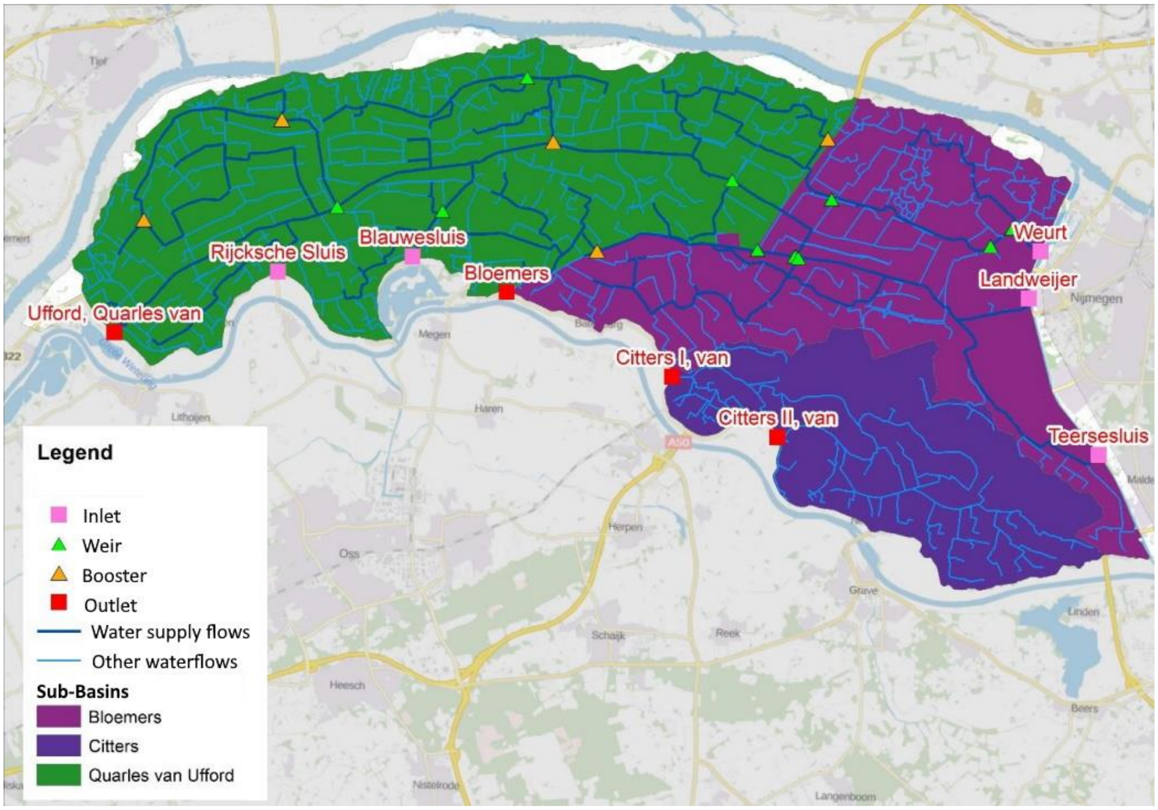

Figure 2: Locations important objects and sub-basins of het Land van Maas en Waal (Royal HaskoningDHV, 2019)

4.2. Water quality

For the water quality, there are three important parts. Firstly, the current state of water quality is important to know. Secondly, it is important to know what the effects of drought on water quality are. Finally, it is vital to know more about blue-green algae. Not only the nuisances that they cause but also the limiting factors for their growth. This is important since the point of the filter is to limit algae growth, knowing the limiting circumstances for their growth is therefore vital.

4.2.1. Water quality in Land van Maas en Waal

To design a filter construction at the water inlet points a clear overview of the quality of the water needs to be known. In Royal HaskoningDHV (2019) measurements for the nutrient load in the water of Land van Maas en Waal have been made. The nitrogen concentration can be seen in Figure 3 and the phosphor concentration can be seen in Figure 4. These figures include all available measurements from 2000-2016 in Land van Maas en Waal. Measurements are performed for projects where water quality is important or in cases where water quality seems to be a problem. The peak measurements are therefore not representative of the water quality in Land van Maas en Waal. Instead, the average gives a better representation of the water quality throughout the study area. The summer average (the lower dotted line in the figure) is 2,8 mg/L for nitrogen and 0,3 mg/L for phosphorous.

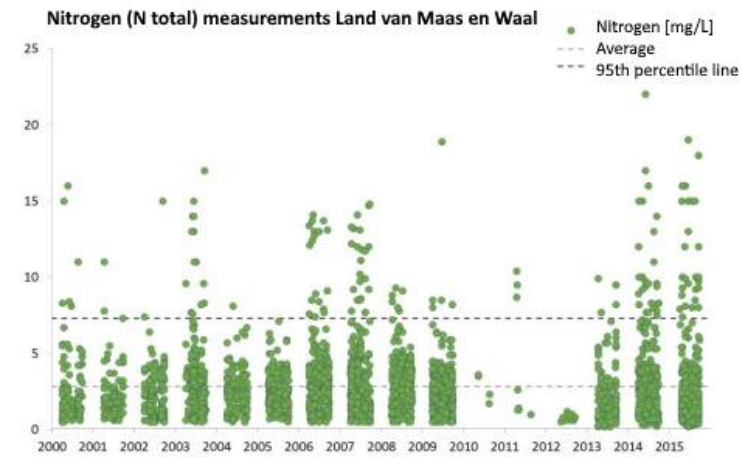

Figure 3: Nitrogen concentration in Land van Maas en Waal (Royal HaskoningDHV, 2019)

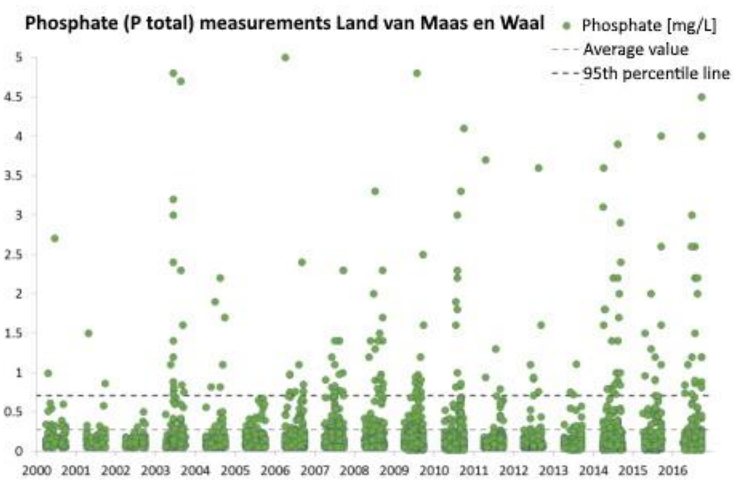

Figure 4: Phosphor concentration in Land van Maas en Waal (Royal HaskoningDHV, 2019)

Table 1: Water norms (van Puijenbroek, Cleij, & Visser, 2010)

Type of waterway	WFD Water type	Nitrogen (mg N/l)	Phosphate (mg P/l)
Ditches	M1, M2, M8	2,4	0,22
Streams	R3-R6, R9-R15, R17-R18	4	0,14
Canals	M3, M4, M6, M7, M10	2,8	0,15
Big rivers	R7, R8, R16	2,5	0,14

In Table 1, the water quality norms for surface water are shown. The different types of waterways have different norms and the data in Figure 3 and Figure 4 does not specify which waterways correspond to which measurement. However, the nitrogen and phosphorous concentration are above the norm for most waterways at the moment. The nitrogen concentration for streams and canals are the only waterway types that currently stay within the norm. To comply to the norm the summer average has to be below the norm. Before the water framework directive was implemented there were only water quality norms for lakes and ponds, in practice these norms were used for all other waterways. The old MTR norm was 2,2 mg N/l and 0,15 mg P/l. The target values were 1,0 mg N/l and 0,05 mg P/l (van Puijenbroek, Cleij, & Visser, 2010). While norms are useful they are not perfect. In paragraph 4.2.2 the limiting circumstances for blue-green algae growth will be discussed.

In Figure 5 part of a map from the WFD plan for 2022-2027 of Waterschap Rivierenland can be seen. The yellow and red areas are the areas with priority for improvement, with Red having the highest priority, followed by yellow and grey. As can be seen almost the entire area of het Land van Maas en Waal is a priority area as the nutrient concentration there is too high. A side note that needs to be made here is that areas get higher priority not only for having high nutrient concentration but also for how much the nutrient load can be altered using measures. From the image, it is also clear that Nitrogen concentration has a higher priority in most of the management areas.

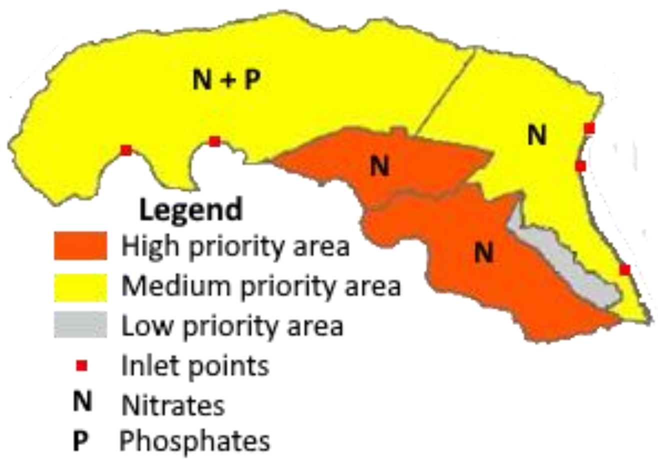

Figure 5: Priority areas nutrient problems in the riverine area (Waterschap Rivierenland, 2020)

4.2.2. Blue-green Algae

The main goal of filtering nutrients out of inlet water is to prevent the nuisance that is caused by blue-green algae. These algae are not actually algae, they are cyanobacteria. The name blue-green algae stems from the period before all lower organisms were split up into eukaryotes and prokaryotes (Lurling M. , 2023) Since blue-green algae do not have any cell organelles, they are eukaryotes and therefore bacteria. They often dominate over other algae because they can float which allows them to float above other algae, limiting their access to light (Loeb & Verdonschot, 2009).

Blue-green algae blooms have several negative effects, one of which is that they release toxins. Not all algae release the same amount or even the same toxins but the toxins they can release can have devastating effects. Four types of toxins can be released by blue-green algae: neurotoxins, cytotoxins, hepatotoxins, and dermatoxins (Lurling & van Dam, 2009). Neurotoxins influence the signalling between nerve cells, this can cause muscle cramps, muscle paralysis, and respiratory arrest. Cytotoxins influence protein synthesis which can cause necrosis in the liver, spleen, and lungs, and can also cause DNA damage. Hepatotoxins cause damage to the liver. Dermatoxins cause irritation on the skin and eyes.

Besides the toxins that they produce the floating layer of algae also cause stench and can cause low-oxygen contents, causing fish to die. In Figure 6 the floating layer of algae at one of the inlet points in the summer of 2022 can be seen. The floating layer builds up in front of the inlet because the water is let in underwater, causing the layer of algae to build up on the surface. Not all algae are on the surface so there is also a lot of algae floating into the polder at the inlet points. Besides the build-up of algae at the inlet points, trouble is also caused by algae being let into the Land van Maas en Waal. Water that contains blue-green algae and their toxins can prevent the water from being used in irrigation, which is often why the water is let in in the first place. In the water inlet protocol of Waterschap Rivierenland, certain levels of cyano-chlorophyll cause limitations or even complete stops of using the inlet water for certain uses such as irrigation of food crops (van den Assem & Ketelaar, 2023). Cyano-chlorophyll is the substance they measure to estimate the amount of algae in the water. This inlet water is especially important during dry periods because the crops need water, however, the growth of blue-green algae is also the biggest during these periods. Which causes big problems.

Figure 6: Floating algae layer at Rijksche Sluis in the summer of 2022 (Hengst)

4.2.3. Previous studies

Water treatment is a widely researched area, the removal of nutrients is also widely researched as wastewater contains a lot of nutrients and those need to be filtered out of the effluent water before it is dumped into the natural water systems. Most of the research in preventing eutrophication seems to be aimed at the prevention of pollution. This can come in the form of improving filtering at wastewater treatment plants or decreasing pollution by agriculture. In Groenendijk et. al (2021) the effectiveness of measures to decrease the nutrient load on the water of agriculture is assessed. Almost all of the measures focus on either source measures or route measures. Source measures in this case are the amount of fertilizer or manure that is used while route measures refer to measures such as buffer strips or wetland strips. However some filter options were also assessed, this was mostly focused on capturing and filtering the water of a farm.

In Lenting et. al (2012) a sand filter to remove phosphates from surface water is constructed and analysed. The problem statement was very similar to the one of this study where in dry periods the nutrient concentration in the inlet water increased and caused algae to bloom. The solution here was a slow vertical sand filter. Phosphates were removed at a high rate but there were some complications with the setup because of the algae growth in the lake where the water originates from, the intake had a high chance to get clogged by the algae. This setup is one example of a filter construction at a water intake point. The de-phosphorization of inlet water has been applied a few times to prevent the eutrophication of peaty lakes. Some lakes/nature areas where this has been applied include the Naardermeer (Boosten, 2007), Veenplas Botshol (Simons, Daalder, Ohm, & Rip, 1991), and the Nieuwkoopse plassen (van der Does & de Jong, 1992). The de-phosphorization of the inlet water was one of many measures that were taken in all of these cases, however in all cases, it did seem to have a positive effect on the water quality.

Most of these studies were at the inlet points of small lakes, which seem less complicated than filtering all the inlet water of an entire water system. This study differs from the previous studies in a few ways. Firstly the previous studies focus on removing only phosphates, while in this study the removal of nitrogen is also included. The magnitude is also quite a bit bigger, the amount of water that needs to be filtered is quite large and the possibility of filtering all this water needs to be researched.

5. Methodology

The methodology of this report consists of five steps. Getting information about the inlet points that is necessary for selecting a suitable filter, finding filters that have sufficient nutrient removal, getting more information about the properties of filters with sufficient nutrient removal, selecting the best filter, and analysing the costs and benefits of constructing such a filter. The methodology of each step will be explained below.

5.1. Information inlet points

The information on the inlet points will be mostly gathered during interviews/talks with the experts at Waterschap Rivierenland. Besides talking to the experts at Waterschap Rivierenland reports from Waterschap Rivierenland about water quality have also been used. For the limiting circumstances of algae growth literature will be used.

5.2. Nutrient removal of filters

To find suitable filters for filtering the inlet water filters with sufficient nutrient removal will need to be found. To find the filters that have sufficient nutrient removal reports about filters that are used at wastewater treatment plants (WWTPs) will be used. In these reports the removal of nutrients is often mentioned. The removal rates in these reports have been used to find filters with sufficient nutrient removal. These filters are then assessed further on other criteria.

5.3. Further gathering of information on suitable filters

The filters with sufficient nutrient removal have been assessed on their capacity, space requirement, costs, energy use, and maintenance requirement. All of this information has been gathered from literature. Most of the reports used are reports about full-scale filters already in use at WWTPs in the Netherlands, reports about pilot setups in the Netherlands have also been used if reports of full-scale filters were not available. Energy use, capacity, space requirement, and maintenance requirement were all readily available in the reports. Costs was sometimes missing or dated. The dated costs have been adjusted for inflation using the inflation data by the Central Bureau of Statistics (CBS). For the missing costs they will be estimated. The costs will be based on the yearly costs of a 100.000 population equivalent (PE) installation. This is chosen since the reports where costs have been calculated also use a 100.000 PE installation as a reference for the calculation. For reference, a 100.000 PE installation processes about

21.000 m^3 per day. The investment costs will be included in the yearly costs in the form of a write-off of a loan. For this the interest rate of 5% is used and for the yearly payment of the borrowed money for the construction of the filter Equation 8 is used. The choice for a yearly write off and the 5% interest rate is made because this is also used in the calculation for the annuity in reports about filter installations.

Equation 1: Formula for annuity

$$J = \frac{i}{1-(1+i)^{-n}} * T$$

With

- T: Borrowed amount of money
- n: number of periods
- J: Amount to be paid (including the interest rate)
- i: Interest rate

5.4. Choosing the best filter

For the selection of the optimal filter out of the list of filters the analytical hierarchy process (AHP) is used. as described in Saaty (1987). This method is a method of performing a multi-criteria decision analysis (MCDA). The method compares all the criteria to each other using the scale of pairwise comparison. The scale and its meaning can be seen in Figure 7. The weights of each criterion and the consistency of the scoring are then calculated.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2-4-6-8	Intermediate (Average) values	Used to express intermediate values

Source: *Saaty, 1994, pp.19-44.*

Figure 7: Scale of pairwise comparison

The weights are calculated by plugging the scores of the pairwise comparison in a matrix. The matrix is then normalized, this is done by dividing the cells by the sum of the corresponding column. The average of the rows of the normalized matrix are then the weights. In Table 2 a small example of three criteria is given to illustrate how the pairwise comparison is put into the matrix.

Equation 2: Normalizing the matrix

$$n_{ij,n} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$$
$$with$$
$$n_{ij,n}: normalized\ cell\ in\ position\ (i,j)$$
$$r_{ij}: cell\ in\ position\ (i,j) of\ matrix\ r$$

Table 2: Compared criteria and the resulting matrix and weights

Criterion 1	Criterion 2	importance	Matrix r	Weights
A	B	3: A is moderately more important than B	$\begin{pmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{pmatrix}$	$\begin{pmatrix} 0{,}63 \\ 0{,}26 \\ 0{,}11 \end{pmatrix}$
A	C	5: A is strongly more important than B		
B	C	3: B is moderately more important than B		

To check if the weights of the criteria are consistent several steps need to be taken. First, the weighted sum needs to be calculated. To do this the matrix in Table 2 is multiplied by the weights. The sum of the rows of the matrix gives the weighted sum. Then the consistency index needs to be calculated, the equation for the consistency index is shown in Equation 3.

Equation 3: Consistency index

$$CI = \frac{\lambda_{max} - n}{n - 1}$$
$$with$$
$$\lambda_{max} = \frac{\sum_{i=1}^{n} \frac{weighted\ sum}{priority\ vector}}{n}$$
$$n : Number\ of\ criteria$$
$$CI: Consistency\ index$$

After the consistency index is know the consistency ratio needs to be calculated, if the consistency ratio is below 0,10 then the weighting of the criteria has been performed consistent enough. The consistency ratio is calculated with Equation 4. The random index is the average consistency index of 500 random matrices. The random indexes have been calculated in Saaty (1987) and can be seen in Table 3.

Equation 4: Consistency ratio

$$CR = \frac{CI}{RI}$$
$$With$$
$$CR: Consistency\ ratio$$
$$RI: Random\ index$$
$$CI: Consistency\ index$$

Table 3: Random index (Saaty, 1987)

n	1	2	3	4	5	6	7	8	9
RI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,49

After confirming the weights of each criteria they can be applied. To apply the weights and get good scores the criteria need to be split up in cost criteria and benefit criteria. For a cost criteria being low is a positive attribute while for a benefit criteria it needs to be as high as possible. First the properties of all analysed filters will be put into a table. Then the columns will be normalized Equation 5 and Equation 6 are used to normalize the properties of the table. The $_i$ and $_j$ refer to the indices of the columns and rows respectfully. So $r_{2,1}$ would refer to the first row of the second column. After the table is normalized the normalized scores are multiplied by the corresponding weight. The lower the score the better the filter. This can be seen in the equations as a high cost criterion will result in a high normalized cost criterion.

Equation 5: Normalizing cost criterion

$$n_{ij,c} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$$

$$Where$$
$$n_{ij,c}: normalized\ cost\ criterion$$
$$r_{ij}: property\ of\ the\ filter$$
$$m: number\ of\ criteria$$

Equation 6: Normalizing benefit criterion

$$n_{ij,b} = \frac{\frac{1}{r_{ij}}}{\sum_{i=1}^{m} \frac{1}{r_{ij}}}$$

$$Where$$
$$n_{ij,c}: normalized\ benefit\ criterion$$
$$r_{ij}: property\ of\ the\ filter$$
$$m: number\ of\ criteria$$

5.5. Cost-effectiveness

It is always a challenge to analyse the costs and benefits of something without monetary value such as the improvement of water quality. Because improving the water quality is required to reach the WFD norms and prevent nuisance by algae the filter can be compared to other measures to improve the water quality. Since measures need to be taken anyway. To compare the filter to other measures the cost-effectiveness of the measures is used. Cost-effectiveness refers to the amount of money it costs to reduce or filter out 1kg of the contaminant out of the water. In Noij et al. (2008) buffer strips are compared to alternative measures to see which measures are the most cost-effective. To see how efficient of a measure the construction of a filter at the inlet points is the cost-effectiveness of the filter is compared to the other measures. The amount of kg removed contaminant will be calculated with Equation 7. The cost can be calculated using the discharge and the cost per m^3. This gives a good estimate of the costs. The cost can then be divided by the amount of contaminant that is removed to find the cost-effectiveness. Then the filter can be compared to other measures aimed at reducing nutrient concentrations in surface water. If the filter has comparable cost-effectiveness to other measures the application of the filter can be further researched.

Equation 7: Calculating the amount of removed contaminant

$$M_r = Q * (r * c)$$
$$With$$
$$Q: Yearly\ discharge\ in\ liters$$
$$r: Removal\ percentage\ of\ the\ filter$$
$$c: Concentration\ of\ contaminant\ in\ inlet\ water$$

5.6. Overview of methodology

In Figure 8 a schematic overview of the methodology is shown. The required information and methods that are used are shown for each step in the process.

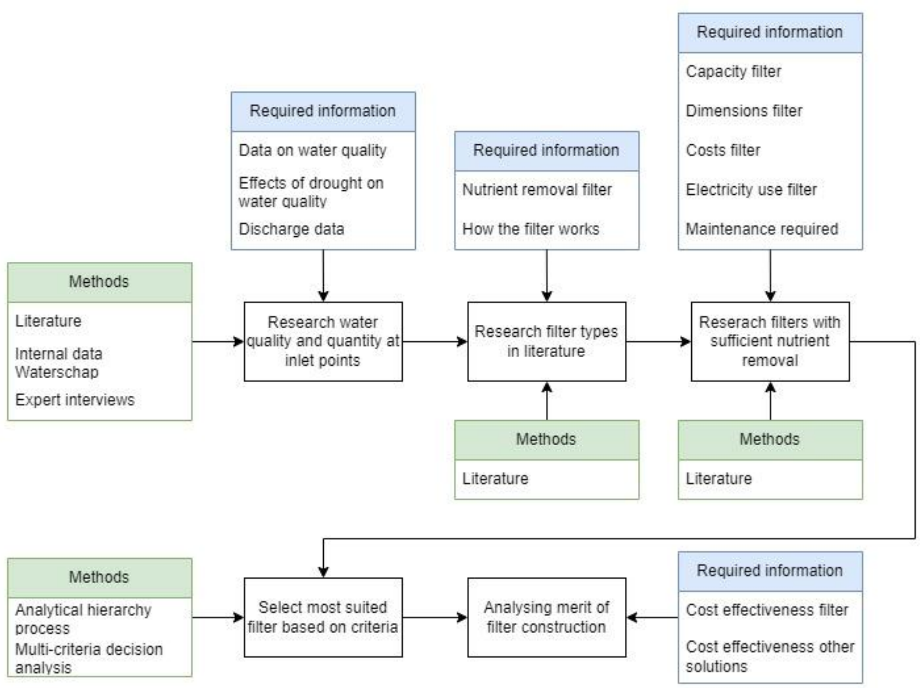

Figure 8: Schematic overview of the methodology

6. Information inlet points

In this chapter, information about the inlet points will be gathered. This information will be important in choosing a filter for the inlet points. This will be the discharge of the inlet points and the water quality at the inlet points. Besides that the impact of drought on the water quality and information on nutrient limitation of blue-green algae.

6.1. Discharge at the inlet points

The five inlet points that need to be researched all work with gravity flow. The water level manager of Land van Maas en Waal gave the discharge that was let in in the summer of 2022 as a reference for a typical discharge in times of drought (Simon den Hengst, (25-4-2023), personal contact). The water needs for each inlet point in 2018 were also calculated (Waterschap Rivierenland, 2018) and can be seen in Table 4 together with the discharge in the summer of 2022. While the water need is higher than the discharge the discharge will be used as a reference when choosing and designing a filter construction. This discharge is chosen since the filter should be able to filter almost all water during the summer, but it does not need to be designed for peak discharges. The filter will have a bypass for any extra water that will be let in in those cases.

Table 4: Discharge and water need of inlet points

Inlet point	Discharge summer 2022 (m^3/s)	Water need 2018 (m^3/s)
Weurt	0,83	1,10
Landeweijer	0,13	0,38
Teerse sluis	0,25	0,55
Blauwe sluis	0,83	1,67
Rijksche sluis	0,33	0,84

6.2. Water quality

6.2.1. Data on water quality at the inlet points

An analysis of the water quality in Land van Maas en Waal was performed in 2021 (Ketelaar, 2021). In this analysis measurements at several locations in Land van Maas en Waal were combined with the measurements at the inlet points and in the river to get a better image of the water quality within Land van Maas en Waal en see how the water quality within Land van Maas en Waal is influenced by the worse water quality of the river water. Using the water routes the share of nitrogen that the inlet water contributes is presented. For sub-basin Quarles van Ufford, 14% of the nitrogen originates from the inlet water. For sub-basin Bloemers, this is 24% (Locations of sub-basins can be seen in Figure 2). Of that nitrogen from inlet water 69% originates from Bloemers with Blauwe Sluis and Rijksche Sluis contributing around 15% each. This shows that the inlet points in sub-basin Bloemers contribute more nitrogen. Assuming the transport of phosphorous is similar, the inlet points in sub-basin Bloemers become more important in reducing nutrient concentrations in Land van Maas en Waal.

The measured water quality at the inlet points can be seen in Table 5, all measurements are from 2014 except for the measurement at Teerse Sluis, which is from 2008. As can be seen the concentrations at the inlet points are comparable to the concentration in the Maas, the concentrations get lower as the water flows through Land van Maas en Waal as it gets mixed with seepage water. Since the concentrations at the inlet points and the Maas are comparable for nitrogen it is assumed that the phosphorous concentration at the inlet points is also similar to the phosphorous concentrations in the Maas.

Table 5: Nutrient summer averages at the inlet points and the Maas (Ketelaar, 2021)

Location	Nitrogen (mg/L)	Phosphorous (mg/L)
Weurt	3,3	-
Blauwe Sluis	2,6	-
Rijksche Sluis	3,5	-
Landeweijer	3,5	-
Teerse sluis (2008)	4,4	-
Maas Keizersveer	3,5	0,11
Maas Belfeld	3,4	0,13

6.2.2. Effects of drought on water quality

In Royal HaskonigDHV (2019) the effects of drought/warm temperatures on the nutrient concentration have been summarized.

- At a higher water temperature, the biological activity of algae and plants increases, and the organisms take up more nutrients, this causes a decrease in nutrient concentration. However, this increase in algae and plants is what needs to be prevented.
- Because of the increase in biomass, there is also more breakdown of organic material in the water and the soil, which causes an increase in nutrients.
- A low-oxygen environment can cause a delayed delivery of phosphates because phosphates that are bound to iron in the soil will become free phosphate in the water.
- More nitrification and de-nitrification take place at a higher temperature. This causes a decrease in nitrates because the dissolved nitrogen is turned into nitrogen gas which dissolves into the atmosphere.

Those were the effects of the biological processes. Besides these processes, there are two other effects of drought on water quality in terms of nutrients.

- Because of the decreased drainage flux, the wash-off of nutrients decreases, which causes the nutrient concentration to decrease.
- Because of increased evaporation, the nutrient concentration in the waterways increases. This is mostly a problem in shallow waterways.

All these effects occur both in the Maas, the Waal, the Maas-Waal channel, and in Land van Maas en Waal. Another negative effect of the drought is that because of lower flow speeds, the temperature of the water increases, with more evaporation as a consequence. This causes a larger share of the water supply of the Maas to consist of effluent from wastewater treatment plants (van den Assem & Ketelaar, 2023), which contains a lot of nutrients. In the slower-flowing parts of the Maas, algae blooms occur. These algae eventually flow towards the inlet points, causing problems.

6.2.3. Limiting circumstances blue-green algae

To prevent algae blooms nutrient limitation is the best option. While both phosphorous and nitrogen can be limiting factors for algae growth (Loeb & Verdonschot, 2009) this is not the same for all species of blue-green algae, they can consume nitrogen gas from the atmosphere. This means that blue-green algae can dominate when just nitrogen is limited because the blue-green algae can use nitrogen from the atmosphere while other species in the water cannot. However, under N-limited conditions, the addition of phosphorous gives a lower growth response of cyanobacteria than the addition of nitrogen meaning that cyanobacteria are still somewhat limited by nitrogen limitation (Andersen, Williamson, Gonzalez, & Vanni, 2020). Nitrogen limitation should not be the goal though since this causes dominance of the cyanobacteria. This is not wanted since they release toxins. However, in the same study, they also showed an increase in N-limitation during the summer. The researchers, therefore, recommend a dual limitation strategy to prevent algae blooms in lakes. So, while the most important factor in preventing algae growth is removing phosphorous. Removing nitrogen is less important since limiting just nitrogen does not work. Nonetheless, it can still help limit cyanobacteria growth. In choosing a suitable filter technique, P-removal needs to be prioritized over N-removal.

Knowing this the question of what concentration should be aimed for still remains. The criteria for P-total concentrations in shallow Canadian lakes is set between 0,06 and 0,08 mg P/L (Heiskary & Bruce Wilson, 2008). This concentration allows for macrophytes to settle and prevent nuisance by algal blooms. For deep recreational lakes, a concentration of 0,04 mg P/L was recommended. The situation of shallow lakes is likely comparable to the situation in Land van Maas en Waal and it corresponds to the old MTR target value of 0,05 mg P/L. So, while the water in the Maas is currently complying with the WFD norms, it is still high enough to cause problems, in filtration the target of 0,05 mg P/L should be used.

7. Types of filters

In this chapter, the tertiary filter options will be assessed on nutrient removal. Tertiary treatment is the last step in wastewater treatment. This step is meant for the extensive removal of nutrients and the removal of medicine residue. In wastewater treatment, there are three steps after the preliminary filtration that filters out rough objects (Idrica, 2022). The primary step consists of removing suspended solids. The secondary step is designed to remove organic matter from the water. The tertiary treatment of the water is used to remove medicine residue and sometimes also to achieve enhanced nutrient removal. This tertiary treatment of the water is most comparable to the treatment that needs to be achieved in the case that is being researched as enhanced nutrient removal is the goal of this research. In the Netherlands, the most commonly used methods for tertiary water treatment in the Netherlands are the granulated active carbon filter, the ozone filter, and the powdered active coal in activated sludge (Wessels & Driessen, 2021). While tertiary treatment of wastewater has a focus on removing medicine residue sometimes the enhanced removal of nutrients is also a goal (van Nieuwenhuijzen, Bloks, Essed, & de Jong, 2017). In this chapter, the tertiary wastewater treatment techniques will be assessed for their effectiveness in removing nutrients. Besides the tertiary techniques, helophyte filters will also be assessed as this is a commonly used natural filter option for nutrient removal in the Netherlands. Finally, sand filtration will also be assessed as this is one of the most common filter techniques and there are filter options available that facilitate extensive nutrient removal. The filters that offer extensive nutrient removal will be assessed and compared in the next chapters.

Table 6: Filter types that will be assessed for nutrient removal

Filter	Filter type
GAC filter	Granular activated carbon filter

Continuous B-GAC	Biologically active granular activated carbon filter
1-STEP filter	Biologically active granular activated carbon filter
Ozone filter	Ozonisation followed by Biologically active granular activated carbon or sand filter
PACAS filter	Active sludge system
Horizontal flow filter	Helophyte filter
Vertical flow filter	Helophyte filter
Aerated filter	Helophyte filter
Waterharmonica	Helophyte filter
Continuous sand filtration	Sand filter
Discontinuous sand filtration	Sand filter

7.1. General description Nitrogen and phosphorous removal

Since most filters use the same types of processes with slight adjustments to remove nitrogen and phosphorous the removal techniques will be discussed here to prevent repetitiveness in the explanation of the working of the filters. For the removal of phosphates, the main methods that are used are coagulations and flocculation. With coagulation, the phosphates bind to an insoluble substance that can then be filtered out. Some substances that are frequently used are Fe(III)Cl3 and PAC (poly-aluminium chloride) (Emis, 2010) With flocculation the phosphates bind together and create insoluble flakes, these flakes can then also be filtered out.

For the removal of nitrogen nitrification and denitrification are used. Nitrification is the oxidation of ammonia to nitrite and nitrate. This is an important step as ammonia can be toxic to fish (Ergas & Aponte-Morales, 2014). The nitrates and nitrites are then removed with a process called denitrification; denitrification utilizes autotrophic heterotrophic microorganisms. The heterotrophic microorganisms usually harvest energy from the transfer of electrons in organic bonds of oxygen. Oxygen functions as an electron acceptor, in a low-oxygen environment these microorganisms can use nitrates as their electron acceptor. The autotrophic microorganisms can harvest energy from the sun and will in a low-oxygen environment use nitrates as their electron acceptor. For this process, the oxygen concentration must remain low, as the process is slowed down at an oxygen concentration of 0,5 mg/l (STOWA, 2009).

7.2. Granulated active carbon filters

The granulated active carbon (GAC) filter works using adsorption to the granulated active carbon. The carbon is activated in a chamber without oxygen. In Figure 9 the adsorption of gases and chemicals to the activated carbon is schematized. The activation of the carbon is done by heating it, which increases the surface area (U.S. Department of Health, 2022). The filter is quite unsustainable and expensive as the effectiveness of the filter declines after 3 months (STOWA, 2019) after which it needs to be replaced. However, new methods which re-activate the carbon are being developed and these methods make the filter more sustainable and cheaper to use. GAC is a widely used and accepted method of removing micro-contaminants.

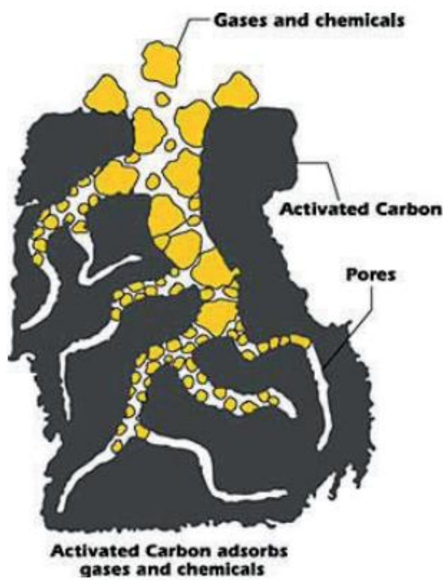

Figure 9: Pore-structure granular activated carbon (van Nieuwenhuijzen, Bloks, Essed, & de Jong, 2017)

7.2.1. Nutrient removal

In STOWA (2010) the use of activated carbon filters after passing the settling tank has been analysed. While nitrate was removed with varying rates of success at the different WWTPs, ranging from 11% to 55% removal. This was probably caused by microorganisms in the filter and not caused by the filter itself. Phosphates had even lower removal rates, ranging from 0 to 15%. For the organic phosphate part of that the removal is much higher, however, the filter quickly gets saturated. Because of the low nitrogen removal and the low P-total removal, combined with the quick saturation of the filter with organic phosphates the use of granulated activated carbon for removing nutrients was discouraged (STOWA, 2010).

7.3. Biologically activated carbon filters

A variation on the GAC filter is a biological activated carbon filter. In this type of filter, several types of bacteria and microorganisms live on the carbon, and they can break down medicine residue and organic substances. This also increases the lifetime of the filter because the adsorption capacity is increased and because more substances are broken down instead of being adsorped. The 1-Step filter is a BAC filter that is focused on nutrient removal. The filter works by adding coagulant and methanol, the coagulant binds the phosphates so they can be filtered and the methanol is added as a carbon source so the nitrogen can be removed by microorganisms in the coal filter (van Nieuwenhuijzen, Bloks, Essed, & de Jong, 2017). The 1-Step filter has performed well in removing N and P, as well as more WFD (Water Framework Directive of the EU) relevant substances in the pilot application of the filter (STOWA, 2009). The filter removes phosphate with coagulation and flocculation. The 1-Step filter that was used in the pilot had a maximum capacity of 15 m^3/h (STOWA, 2009).

7.3.1. Nutrient removal

Before choosing a filter, the effectiveness at which the filter removes nutrients and the drawbacks of the removal needs to be known. The feasibility study for the pilot did not focus on nutrient removal, however, when testing for P-removal, by adding coagulant for two weeks the P concentration went from 0,7-0,9 mg/L to <0,2 mg/L (STOWA, 2022), showing that the installation is suitable nutrient removal as well. Simultaneous removal of both phosphates and nitrates is possible, thanks to the biological aspect of the filter. All ammonium is transformed into nitrate in the filter (de Vogel, van der Maas, Kloosterman-Greftenhuis, & Dost, 2020). The 1-STEP filter does better in the removal of nutrients since it was designed with nutrient removal in mind. The nitrogen removal was 67% at a concentration of 5,6 mg N/L influent. For phosphates, the filter had a removal of 71% at a concentration of 0,52 mg P/L.

7.4. Ozone filters

The ozone filter as described in de Jong & Bechger (2020) works by applying a dose of Ozone which cause ozone oxidation to occur. In this process, biological effluents are oxidized making them mineralized and biodegradable. After the ozone oxidization, another filter is used to filter out any other effluents. In Jong & Bechger (2020) the 1-STEP filter is used, this filter is a GAC filter, but this setup is not at the required technology readiness level. In other versions of the ozone filter the filter after the ozone oxidization is a sand filter. In Figure 10 a block diagram of the O3-Step filter is shown. The O3-step filter design from the study has a design capacity of 1100 m^3/h which translates to 0,30 m^3/s. One negative side of the ozone dosage was believed to be that the system creates bromate, which can cause cancer. However, the formed bromate concentration seems to be lower in the GAC-filter (Witteveen en Bos, 2022).

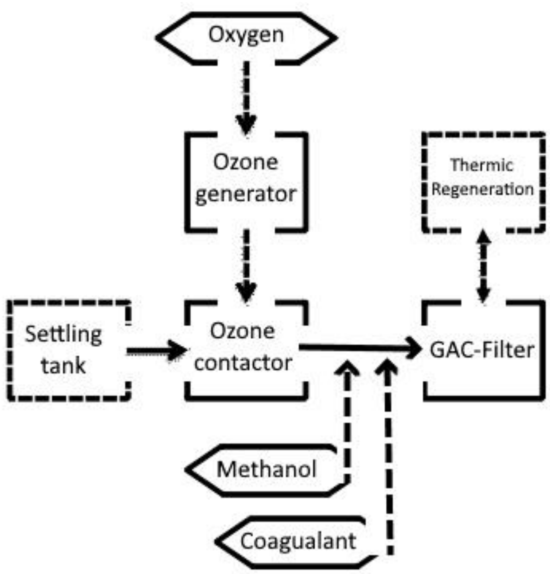

Figure 10: Block diagram of the 03 Step filter (de Jong & Bechger, 2020)

7.4.1. Nutrient removal

While the ozone filter can have efficient nutrient removal, this is mostly because of the filter after the ozonisation. Since the nutrients do not need to be oxidized the ozone filter is an unnecessary step. The O3-Step filter has the same nutrient removal as the 1-STEP filter.

7.5. Powdered active carbon filters

Powdered active coal can also be dosed in a process to remove contaminants. An example of this is the powdered active carbon in active sludge (PACAS) The powdered activated coal works similarly to the GAC where it adsorbs contaminants and can then be filtered out. The PACAS filter is the cheapest method of removing contaminants and it also works quite well (STOWA, 2018).

7.5.1. Nutrient removal

The nutrient removal of the powdered active carbon filter is not very high. For nitrogen, there is no significant added removal when dosing powdered active carbon into the sludge filter (STOWA, 2018) while phosphates were decreased. The reference street had a concentration of 0,43mg/L while the PACAS street had a concentration of 0,16mg/L (STOWA, 2018). This makes the removal rate 63% for Phosphorous.

7.6. Helophyte filters

All options that have been discussed so far are mechanical filters. A more natural solution that is frequently used is a helophyte filter. A helophyte filter uses plants, usually reeds and bacteria in the soil to remove contaminants, including nutrients. Besides the biological breakdown of substances and nutrients, there are also physical processes that filter out substances. Phosphates, for example, are mostly removed by precipitation, sorption, and plant intake. Nitrogen on the other hand is removed by nitrification and denitrification by bacteria. For nitrification oxygen is required while for denitrification a low-oxygen environment and a carbon source are required. Helophyte filters offer a cheaper and more sustainable way of filtering water. However, they also have disadvantages. They take up a lot of space, have a low capacity, they stop fully functioning in winter and autumn because it is a biological process.
Within helophyte filters, three distinct groups can be made. The first type is open water systems, such as the 'Waterharmonica' which is used in the Netherlands to make the effluent of WWTPs more natural and to remove nutrients and other substances (van den Boomen & Kampf, 2013). These open-water systems let the water flow horizontally over the soil in which the helophytes are planted, removing nutrients in the process. The second subgroup is horizontal flow helophyte filters, in these filters, the water flows through the soil in which reeds are planted. The water gets filtered by biological and physical processes.

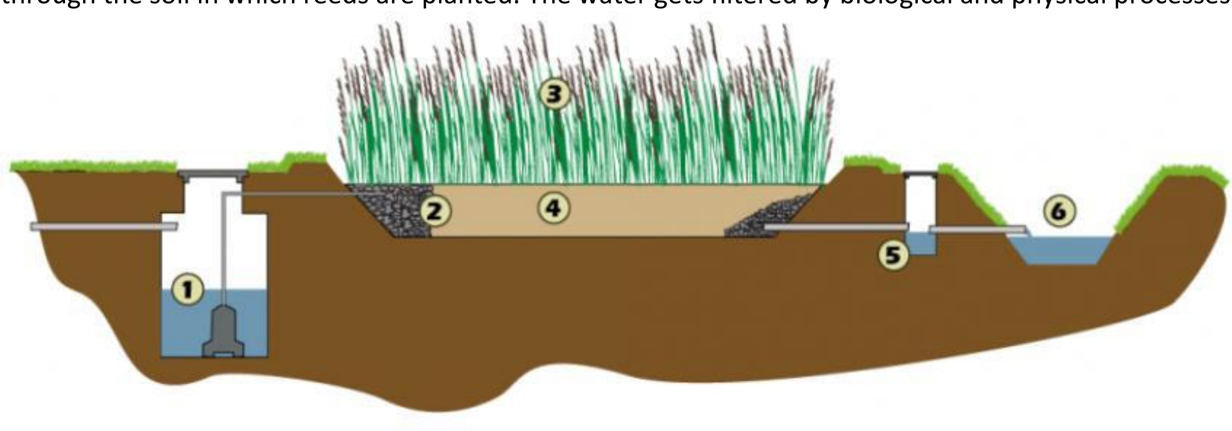

Figure 11: Horizontal flow helophyte filter (Wetlantec, 2023)

1:pump, 2: gravel , 3: Reeds, 4: filter substrate, 5: sampling well, 6: Into surface water

The third sub-group is a vertical flow helophyte filter. In this filter type, the water flows vertically through the soil in which the reeds are planted, as the name suggests. An advantage of the vertical filter is that it includes aerobic as well as anaerobic zones, which is good for the removal of nitrogen.

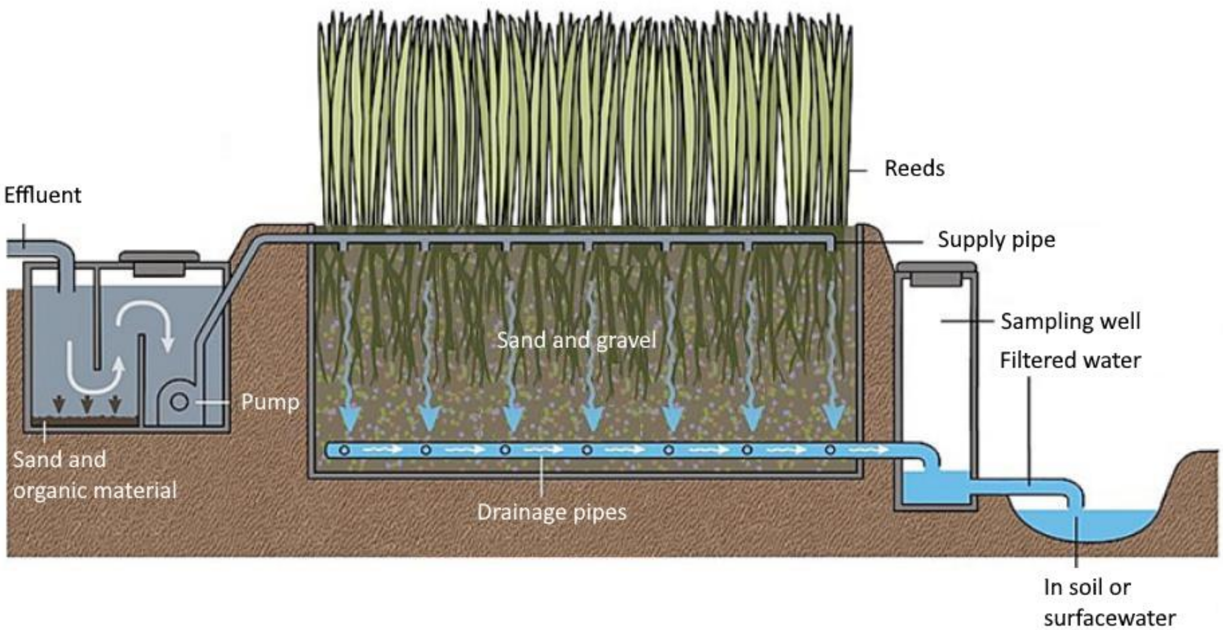

Figure 12: Vertical flow helophyte filter (RioNed, 2023)

Hybrid filters also exist, these filters combine the horizontal and vertical flow filters by linking the two types of flow. The hybrid filter was found to be more successful in removing nitrogen and phosphates at the same time (Vymazal, 2005). Another variation on the helophyte filter is the aerated filter, this filter type is either a vertical or horizontal flow helophyte filter with added aeration. A benefit of this aeration is that it allows more control in the removal of contaminants. Less space is also required because of the aeration. In Figure 13 a schematic overview of an aerated filter can be seen.

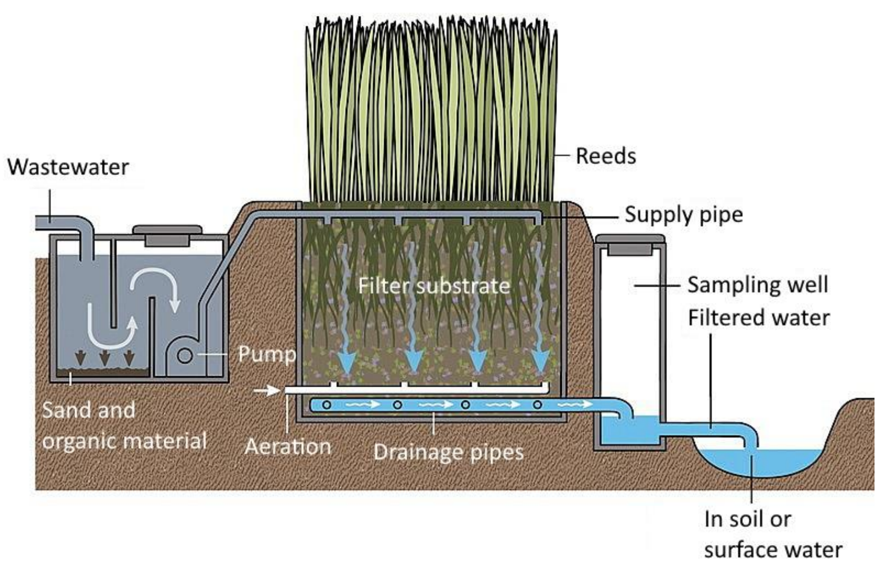

Figure 13: Vertical flow aerated helophyte filter (RIONED, 2023)

7.6.1. Nutrient removal

Nutrient removal depends on several factors one of which is time one filter setup, which uses narrow and broadleaf cattails, had a 40-60% nitrogen removal rate at 6h retention time and 60-80% nitrogen removal at longer durations. In a study that assessed several natural options/helophyte filters, several filter types were considered as alternatives to more mechanical methods for tertiary water treatment. They were considered to be a viable alternative to GAC, Ozone + sand, and PACAS for the removal of medicine residue and nutrients (Bestman, et al., 2022). Most filter forms had effective removal of both nitrogen and phosphates. Besides that 7 of the 11 guide substances were also removed to some extent by all helophyte filter options. An advantage of these natural systems is that they are cheaper in operation, have a lower carbon footprint, and they also store water which can be used in dry periods. Helophyte filters do require more space than the more conventional filters but most of this space is wetlands as opposed to the large constructions that the conventional filters require.

In van den Bulk et. al (2022) data for nutrient and medicine residue removal from literature was assessed to see if natural water treatment technologies could be a useful alternative to the mechanical technologies that are currently in use. The removal efficiencies for the different filter types can be seen in Table 7. The removal efficiencies are averages of systems that fall into that category, so some setups may achieve a higher or lower removal rate. As can be seen, the aerated filter has the highest removal efficiency. Some advantages of the aerated filter are that they take up less space and that the filter can be guided to better removal by adding more or less oxygen. While the Waterharmonica is also able to achieve extensive nutrient removal, such as the Klaterwater filter for the Efteling. This filter removes 66% of nitrogen and 99% of phosphorous (van den Boomen & Kampf, 2013). However, at Klaterwater the effluent first gets treated by a sand filter, so it is unsure whether the nutrient removal is completely done by the Waterharmonica. Besides that, a very long retention time is also needed, which will require a lot of space to support the discharge at the inlet points. Since the goal of most Waterharmonica's is to make the water more natural most Waterharmonica's do not have such a long retention time and therefore the removal rate is quite low. Another noteworthy point is that the Waterharmonica can also cause negative P-total removal, which means that the concentration increases.

Table 7: Average removal efficiency of different helophyte filter types (van den Bulk, et al., 2022)

	Horizontal flow filter	Vertical flow filter	Aerated filter	Waterharmonica
Average N-total removal	42%	45%	62%	10-50%
Average P-total removal	41%	60%	65%	-40 – 90%

7.7. Sand filtration

For sand filtration, there are several options to choose from, but there are essentially two types of sand filtration, continuous sand filtration and discontinuous sand filtration. Since a relatively large amount of influent needs to be processed continuous sand filtration is the most suited option. Besides that, there is also more experience with continuous sand filtration in the Netherlands. The continuous sand filtration setups in the Netherlands are also preferred for nitrogen removal while for phosphorous removal both filter function equally (Janssen, et al., 2006). This is because the bed filter is a bit rougher, which allows for a shorter retention time. A continuous sand filter as the final treatment step uses the same removal techniques as the other filters, the phosphates are filtered with the help of a coagulant and the nitrogen is removed with a biological process. In Figure 14 a side profile of the continuous sand filter can be seen. The filter works by feeding the water into the bottom of the filter letting it pass through the sand before being transported away. The microorganisms on the sand filter out organic components, this includes nitrogen. Iron or aluminium salts are usually added as a coagulant for the removal of phosphates. A small amount of the sand gets transported to the top where it can be rinsed with filtered water. This water can then be fed back to be filtered again.

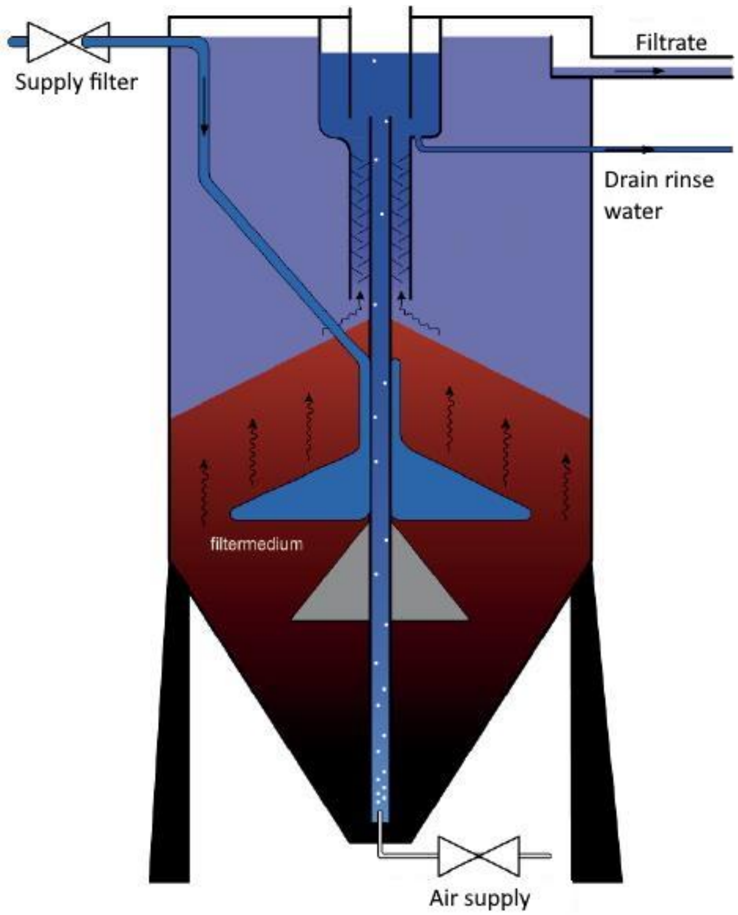

Figure 14: Side profile continuous sand filter (Baltussen, 2011)

Discontinuous sand filtration has a very simple working principle. The influent is added at the top of the filter and flows through the filter bed. By adding metal salts, the removal of phosphorous is made possible. For the removal of Nitrogen microorganisms in the filter bed use nitrification and de-nitrification to remove nitrogen. Adding enough carbon into the filter is important to stimulate this removal. The filter is fed discontinuous, as said in the name. It is fed at an interval after which the water slowly flows through the filter bed. When the filter bed resistance gets too high the filter is rinsed with water and air. The side profile of the filter can be seen in Figure 15.

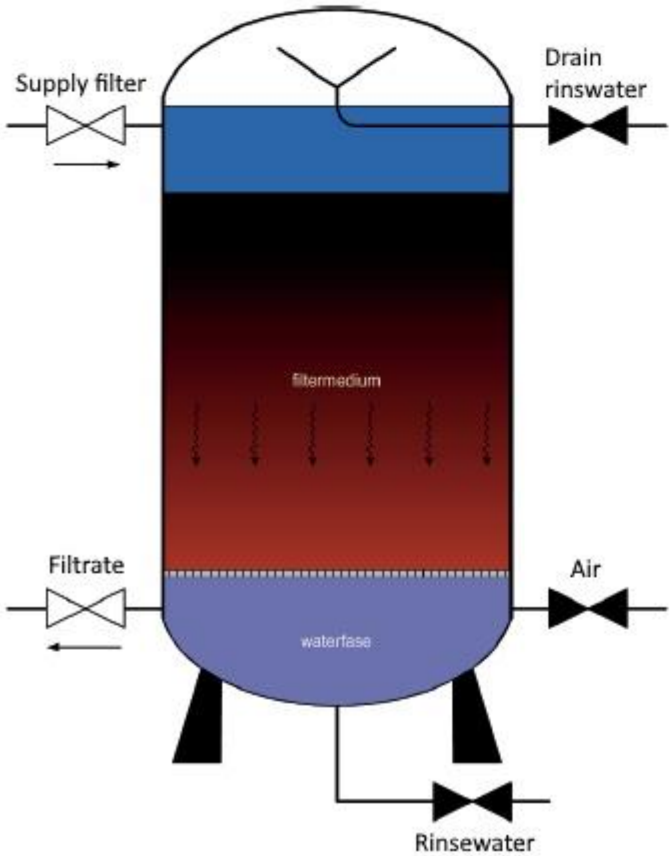

Figure 15: Discontinuous sand filtration (Baltussen, 2011)

7.7.1. Nutrient removal

The nutrient removal in continuous sand filtration depends on the coagulant dosage and the concentration of the influent. When the concentration P-total is more consistent in the influent the filter can be calibrated better which means that the phosphate removal is higher. A continuous sand filter can then get high P-total removal of 90% at a hydraulic load of 9,4 m/h (m^3 per m^2 filter bed area per hour) and a P-total concentration of 0,77 mg/l in the influent (Janssen, et al., 2006). For nitrogen, an N-total removal of 40% was realized at a WWTP where the influent had an N-total concentration of 4,3 mg/l, so the effluent reached the norm of <2,2 mg/l N-total. Higher rates of removal were achieved at other WWTPs (up to 90%), however, the influent had much higher concentrations so N-total concentrations in the effluent were below the norm. The hydraulic load for this filter was 15 m/h.

Discontinuous sand filtration had an N-total removal rate of 87% at an N-total concentration of the influent being 15,7 mg N/L (Janssen, et al., 2006). A P-total removal rate of up to 89% was also realized (Janssen, et al., 2006). With a concentration of 0,45 mg P/L of the influent. The hydraulic load for this filter was 20 m/h.

Table 8: Nutrient removal rates of sand filters

	Continuous sand filter	Discontinuous sand filter
N-total removal	40-81%	87%
P-total removal	90%	89%

7.8. Suitable filters

Not all the filters that have been discussed are suitable for the required task. Only the filters with sufficient nutrient removal will be further analysed in Chapter 8. In Table 9 an overview of the filters that have been examined in Chapter 7 is shown. 60% removal of both nitrogen and phosphorous is chosen as the cut-off point. Ideally, the removal would be higher but most of the filters analysed do not reach such removal. With 60% removal, the target of 0,05 mg P/L would be reached if the concentrations in Table 5 are used. The target of 1,0 mg N/L would almost be reached.

The filters that are then suited to be further analysed are the 1-STEP filter, the ozone filter, the Aerated helophyte filter, the continuous sand filter, and the discontinuous sand filter. These are all suited because they have more than 60% removal for both Nitrogen and Phosphorous. Even thought the ozone filter has sufficient removal it is omitted since the ozonisation does not add to the nutrient removal; therefore, the nutrient removal is the same as the 1-STEP filter. Adding the step of ozonisation is unnecessary for the application that is being researched. Adding the ozone filter to the comparison would essentially compare two of the same filters but one of them just has an extra unnecessary step. Because of this, the ozone filter is omitted from the comparison.

Table 9: Overview of filters

Filter	Filter function	N-removal	P-removal	Suitable
GAC filter	Adsorption of contaminants to the GAC	11-55%	0-15%	No
Continuous B-GAC	Coagulation or flocculation of phosphates after which it is adsorped to the GAC. Nitrification and de-nitrification by bacteria	- ~	78%	No
1-STEP filter	Coagulation or flocculation of phosphates after which it is adsorped to the GAC. Nitrification and de-nitrification by bacteria	67%	71%	Yes
Ozone filter	Ozoninization followed by 1-STEP or sand filtration	67%*	71%*	Yes*
PACAS filter	Coagulation and flocculation of phosphates. Nitrification and de-nitrification by bacteria	0%	63%	No
Horizontal flow filter	Nutrient uptake of plants, binding of phosphates to the substrate used, nitrification and de-nitrification by bacteria.	42%	41%	No
Vertical flow filter	Nutrient uptake of plants, binding of phosphates to the substrate used,	45%	60%	No

	nitrification and de-nitrification by bacteria.			
Aerated filter	Nutrient uptake of plants, binding of phosphates to the substrate used, nitrification and de-nitrification by bacteria.	62%	65%	Yes
Waterharmonica	Nutrient uptake of plants, binding of phosphates to the substrate used, nitrification and de-nitrification by bacteria.	10-50%	-40 – 90%	No
Continuous Sand filtration	Binding of phosphates to the filter substrate. Nitrification and de-nitrification by bacteria in the filter	40-90%	90%	Yes
Discontinuous sand filtration	Binding of phosphates to the filter substrate. Nitrification and de-nitrification by bacteria in the filter	87%	89%	Yes

*The same nutrient removal as the 1-STEP filter is taken here since the ozone filter that was assessed was followed by a 1-STEP filter. ~ No information on nitrogen removal was found.

8. Information on suitable filters

In this chapter, the filters that are suitable for nutrient removal will be further elaborated on. Their capacity, dimensioning, and costs will be researched. The filter types that will be investigated in more detail are the 1-STEP filter, the Aerated helophyte filter, the waterharmonica, and continuous sand filtration. The costs will be calculated for a 100.000 population equivalent (PE), this is a unit often used in wastewater treatment and means that the installation is made to process the wastewater of 100.000 people. The amount of water such an installation processes in a day is 21.000 m^3. The costs will be calculated using this unit because all filters that already have costs mentioned in the literature are also calculated for a 100.000 PE installation. The final unit for the costs will be €/m^3. This will be calculated by estimating the yearly costs of a 100.000 PE installation and dividing the costs by the yearly amount of filtered water. For the capacity of the filter, the hydraulic load will be used. This is in the unit of m^3 water/m^2 filter bed/h, which is simplified to m/h.

8.1. 1-STEP filter

8.1.1. Dimensions and capacity

The 1-STEP filter constructed in RWZI Horstermeer can process 1550 m^3/h (STOWA, 2013). This filter consists of five filter beds. Each filter bed has an area of 28 m^2. In Table 10 the required filter bed areas for the 1-STEP filter are given based on the discharge in Table 4 and the filter setup that was mentioned before.

Table 10: Required filter bed area per inlet point for the 1-STEP filter

	1-STEP filter (m^2)	Discharge (m^3/h)
Weurt	280	3000
Landeweijer	56	480
Teerse Sluis	84	900
Blauwe Sluis	280	3000
Rijksche Sluis	112	1200

100.000 PE	84	875

8.1.2. Costs

In the STOWA research pieces that were used for the details of nutrient removal and filter capacity the costs of the filters have also been calculated. These costs include the initial building costs and are given in a cost per m^3 treated water. The Costs are based on an installation of 100.000 PE Since the cost for the 1-STEP filter have been calculated in 2009, they will be adjusted for inflation to prevent a bias towards the 1-STEP filter. The exploitation cost includes a write-off of the initial construction cost on a yearly basis. The final exploitation costs are in EUR/m^3, if this is given it can be used since the costs will simply scale up with the added water that is being filtered. The cost for the 1-STEP filter was calculated to be 545.000€ for 100.000 PE (STOWA, 2009). Adjusting this for inflation the costs are 740.984€ per year. Using the amount of water per 100.000 PE the cost of the 1-STEP filter comes out to 0,14€/m^3.

8.1.3. Electricity use and maintenance

The electricity use of the 1-STEP filter depends on the regeneration rate of the active carbon in the filter. If the filter bed is regenerated once a year the electricity use is 0,17 kWh/m^3. If the filter bed is regenerated once every four years the electricity use is 0,12 kWh/m^3 (STOWA, 2009). Since in the cost calculation of the paper once every four years is used this will also be used for electricity use. The filter will require weekly maintenance, consisting of inspection and regular cleaning.

8.2. Aerated helophyte filter

8.2.1. Dimensions and capacity

The aerated helophyte filter requires 0,75 m^2/PE (Phytoair, n.d.). 100.000 PE has a discharge of 21.000 m^3/day (STOWA, 2009). The hydraulic load is then equal to 2,8 m/day. Using the discharge of the summer 2022 from Table 4 the required size for the aerated filter can be calculated for each inlet point. The result can be seen in Table 11.

Table 11: required space helophyte filters at the different inlet points

	Aerated filter	Discharge (m^3/h)
Weurt (ha)	2,6	3000
Landeweijer (ha)	0,4	480
Teerse sluis (ha)	0,8	900
Blauwe sluis (ha)	2,6	3000
Rijksche sluis (ha)	1,0	1200
100.000 PE	0,75	875

8.2.2. Costs

For the vertical flow aerated filter the costs of two systems in van den Bulk, et. al (2022) have been combined. The construction costs of the aeration system are taken from the LECA filter, which is another type of aerated filter. The costs for the basic system and the pump have been taken from a regular vertical flow filter. To come from construction costs to investment costs. Contractor costs need to be added and building costs need to be scaled up. The percentage of 25% and 80% of building costs for these has also been taken from van den Bulk, et. al (2022). Lastly, land purchase needs to be added. Adding this all up gives the investment cost of 3.690.00€ per ha. The operating costs of the filter are low, it consists of a yearly writ-off of the investment costs, the electricity costs, and the management costs. The write-off is calculated in the appendix and management costs are taken from the LECA filter. The electricity use consists of the aeration and the pumping of the water. This use is 150,23 kWh/year based on 100.000 PE The final cost per m^3 for the aerated filter then comes to 0,06 €/m^3.

Table 12: Costs of aerated helophyte filter

Aerated helophyte	Costs		
Raw construction costs	eur/ha		
Construction aeration	€	1.000.000	(van den Bulk, et al., 2022)
Construction basic systems	€	650.000	(van den Bulk, et al., 2022)
Construction pump	€	150.000	(van den Bulk, et al., 2022)
Raw construction cost total:	€	1.800.000	
Additional contractor costs	€	450.000	25%
Building costs to investment cost	€	1.440.000	80%
Investment costs	€	3.690.000	
Land purchase	€	76.000	
Total investment per ha	€	3.766.000	
Investment 100.000 PE	€	2.824.500	0,75ha
Calculating costs per m3			
Write-off	€	183.738	5% interest
Electricity	€	79.624	0,53 €/kWh
Management and maintenance	€	34.000	(van den Bulk, et al., 2022)
Total yearly costs	€	297.362	
Costs per m3	€	0,06	

8.2.3. Electricity use and maintenance

As mentioned before the aerated helophyte filter uses 150,23 kWh/year. The electricity use per m^3 of filtered water is 0,028 kWh/m^3. The system needs to be mowed once a year and the technical parts of the filter will require periodical maintenance (van den Bulk, et al., 2022). For the periodical maintenance, 4 times a year will be assumed.

8.3. Continuous sand filter

8.3.1. Capacity and dimensions

Design principles derived from experience in the Netherlands and abroad give a bed height of 1,5-2,0m. With a filtration speed of between 15-25 $m^3/m^2/h$. However, for extensive phosphate removal, a lower hydraulic load of 9,4 m/h is required. Using the reference discharge in Table 4 the required filter bed area is calculated, the result can be seen in Table 13.

Table 13: Required filter bed area for continuous sand filtration

	Required filter bed area (m^2)	Discharge (m^3/h)
Weurt	318	3000
Landeweijer	50	480
Teerse Sluis	96	900
Blauwe Sluis	318	3000
Rijksche Sluis	126	1200
100.000 PE	93	875

8.3.2. Costs

An estimate for the investment costs for a continuous sand filter is 20.000€ per m^2 filter bed area (Baltussen, 2011). Adjusting this for inflation the costs are 26525€ per m^2 filter bed area. The calculation will be performed for 100.000 PE since all other costs calculations are also performed for 100.000 PE for 100.000 PE the filter bed would have to be 93 m^2. Making the investment costs 2.469.066 €. The yearly write-off is calculated in the appendix. The energy use of this installation is 0,1 kWh/m^3 (Baltussen, 2011). The installation will produce sludge, which costs money to be processed. It is assumed that the same amount of sludge is produced as in the 1-STEP filter since the same processes for removing the nutrients are used. The cost for processing this sludge is 107.377 € when adjusted for inflation (STOWA, 2009). Finally, the personnel costs that come with the filer, 1 full-time equivalent (FTE) is taken, which in STOWA reports costs €50.000. All together the costs per m^3 for continuous sand filtration come to 0,13€/m^3. All the costs can be seen in Table 14.

Table 14: Costs of continuous sand filtration

Continuous sand filtration	
Investment costs	€ 2.469.066
Yearly write-off investment	€ 160.616
Personnel costs	€ 50.000
Maintenance costs	€ 81.479
Sludge removal	€ 107.377
Rinse water	€ 10.182
Electricity	€ 284.372
Total yearly costs	€ 694.025,93
Costs per m3	€ 0,13

8.3.3. Electricity use and maintenance

The average electricity use of continuous sand filtration is 0,1 kWh/m^3 (Baltussen, 2011). The filter will have to be maintained weekly. Maintenance of the filter is about half a day of work for one person and consists of cleaning the measurement instruments and inspecting the entire filter (Janssen, et al., 2006).

8.4. Discontinuous sand filtration

8.4.1. Capacity and dimension

The discontinuous sand filters that had sufficient nutrient removal had a hydraulic load of 20 m/h. Using the discharges in Table 4 the required filter bed area can be calculated. In Table 15 the required filter bed area is shown for all the inlet points, as well as for a 100.000 PE installation.

Table 15: Required filter bed area discontinuous sand filtration

	Required filter bed area (m^2)	Discharge (m^3/h)
Weurt	149	3000
Landeweijer	23	480
Teerse Sluis	45	900
Blauwe Sluis	149	3000
Rijksche Sluis	59	1200
100.000 PE	44	875

8.4.2. Costs

The investment costs for the discontinuous sand filter are the same as that of the continuous sand filter (Baltussen, 2011). Adjusted for inflation the investment costs are 26525€ per m^2. Electricity use is 0,04 kWh/m^3 (Baltussen, 2011), this comes to 214620 kWh/year. The maintenance costs consist of 3% of the investment costs. Then 10% extra is taken for unexpected maintenance that might be required. For sludge removal and rinse water needed it is assumed that the costs are the same as the 1-STEP filter. They have been adjusted for inflation and can be seen in the table (STOWA, 2009). The yearly write-off is calculated with a 5% interest rate and the calculations can be seen in the Appendix. Finally, the personnel costs that come with the filer, 1 full-time equivalent (FTE) is taken, which in STOWA reports costs €50.000. The costs per m^3 for a 100.000 PE installation are then 0,07 €/m^3.

Table 16: Costs for discontinuous sand filtration

Discontinuous sand filtration		
Investment costs	€	1.160.461
Yearly write-off investment	€	75.490
Personnel costs	€	50.000
Maintenance costs	€	38.295
Sludge removal	€	107.377
Rinse water	€	10.182
Electricity	€	113.749
Total yearly costs	€	395.092,45
Costs per m3	€	0,07

8.4.3. Electricity use and maintenance

The average electricity use of continuous sand filtration is 0,04 kWh/m^3 (Baltussen, 2011). This comes to 214620 kWh/year. Just as with continuous sand filtration the filter will have to be maintained weekly.

Maintenance of the filter is about half a day of work for one person and consists of cleaning the measurement instruments and inspecting the entire filter (Janssen, et al., 2006).

8.5. Overview filters

In Table 17 an overview of the properties of each filter type can be seen. In the next chapter, the filters will be compared using a multi-criteria decision analysis with these properties being the criteria.

Table 17: Overview of each filter's properties

	N-removal (% removed)	P-removal (% removed)	Cost (€/m^3)	Maintenance (times/year)	Space (m^2)	Electricity use (kWh/m^3)
1-STEP	0,67	0,71	0,14	52	84	0,12
Aerated helophyte	0,62	0,65	0,06	5	8000	0,028
Discontinuous sand	0,9	0,9	0,07	52	44	0,04
Continuous sand	0,87	0,89	0,15	52	93	0,1

9. Choosing a filter type

Now that the different filter types have been assessed and the current water quality and the desired water quality are known a filter type can be chosen. The filters will be chosen with a multi-criteria decision analysis (MCDA). Since the results of the MCDA can differ between inlet points a separate MCDA per inlet point will be performed so the optimal filter for each inlet point is chosen. Four filters will be compared. The 1-STEP filter, the continuous sand filter, the waterharmonica, and the aerated helophyte filter. For the MCDA the analytical hierarchy process (Saaty, 1987) will be used. This method works as follows. The objective, goal and alternatives are defined. Then, using a pairwise comparison between two criteria, the priorities among criteria are set. From these criteria, weights are derived. A consistency check is then performed to see if the weights are consistent all over. Then, using the weight and the properties of each filter type, the alternatives can be ranked for each location.

9.1. Setting criteria

A list of criteria needs to be made, these criteria should reflect the wishes of Waterschap Rivierenland and take practical considerations into account. There are four main criteria for the filter. Improving water quality, being possible to realise, and low resource demand.

Improving water quality has two sub-criteria. Phosphate removal and nitrogen removal. Phosphate removal and nitrogen removal have been split up since phosphate removal is more important and because filters have varying results in removing both at the same time. Splitting them up allows for filters that have better phosphate removal to be prioritized. If the filter can filter out algae as well as nutrients there is a bigger increase in water quality which is desired. Hilde Ketelaar, an advisor on water quality and ecology within Waterschap Rivierenland, mentioned that filtering out algae is an important factor in improving the water quality (Ketelaar (24-05-2023), personal contact). However, not much information was found on the removal of algae by each filter type. Since the scope of the study is also to filter nutrients out of the water and little information was available, algae removal has not been included as a criterion.

The possibility of realising the filter depends mostly on the cost and the space that is required for the filter. If a filter is too expensive it will be harder to fit it into the budget. It is also important that money is being spent on the right things since public money is used. The required space may also impact the realisation of the project since some of the inlet points are in the built environment and do not have a lot of space available for the construction of a filter. Therefore, more compact filters should be preferred.

Low resource demand is important as having a filter which requires a lot of attention and energy will make it less attractive to use as a solution. The sub-criteria are maintenance and electricity use. Maintenance and operation of the filter is also an important criterion. When visiting the inlet points with the administrator that manages the inlet points the main concern of the administrator seemed to be the maintenance of such a filter as this would be another responsibility for the people working in the field that have limited resources and time. The electricity use is important since Waterschap Rivierenland strives to be sustainable and a filter that uses a lot of energy does not fit this goal. All the criteria and sub-criteria can be seen in Figure 16.

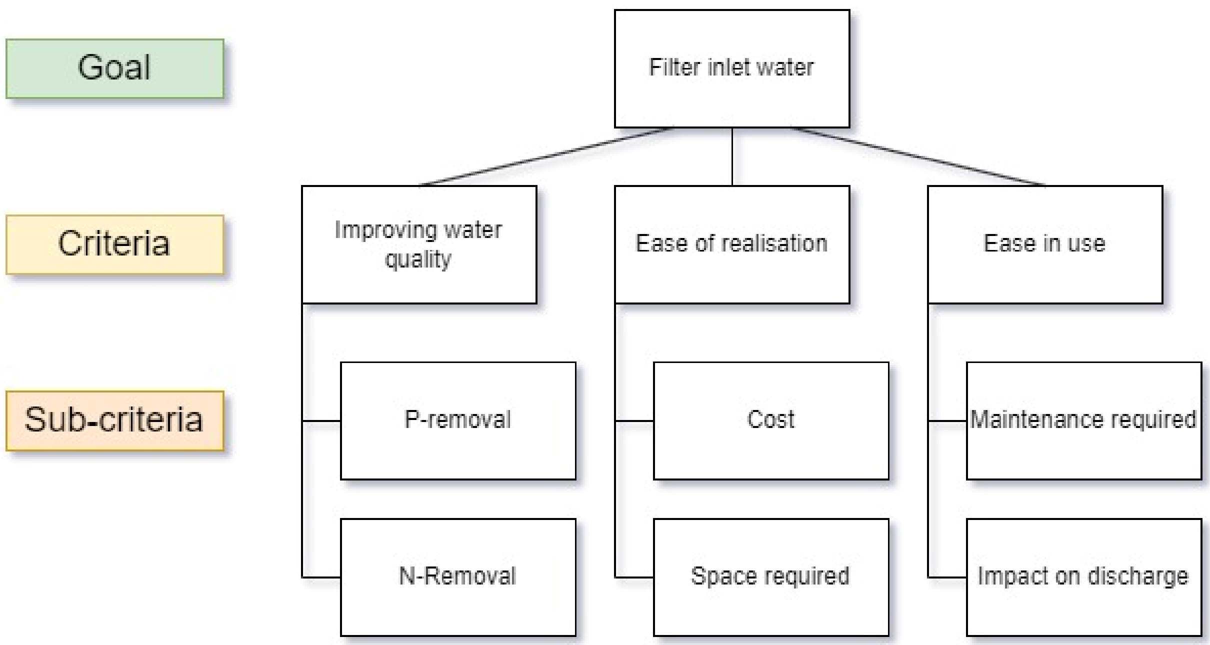

Figure 16: Hierarchy tree

9.2. Weighting criteria

For the MCDA the weights of the criteria are one of the most important factors in deciding which filter type to use. To make sure the weights of the criteria are consistent the analytical hierarchy method (Saaty, 1987) will be used. This method uses the pairwise comparison of the criteria to create a weighted vector with the importance of each criterion. These weights are then checked to see if they are consistent using a mathematical algorithm. The pairwise comparison is performed using the scale of pairwise comparison, shown in Figure 7. Before using the scale the importance of each criterion needs to be assessed.

Since the goal is to filter water the improving water quality criteria are some of the most important. P-removal is seen as more important since nutrient limitation caused by low phosphorous concentration is easier to accomplish and more common, as explained in paragraph 4.2.2. N-removal, cost and space have the same level of importance. Removing nitrogen is one of the main goals of the project, while cost and space requirement are important factors in the realisation of the project since it would be impossible to realise the project if it costs too much or takes up too much space. Therefore, they get the same weight. Next is maintenance, a filter which will have to be frequently maintained would be impractical since maintenance requires specific knowledge of filtration systems, however, the filters will not be at a WWTP but will be at inlet points so someone would have to constantly travel to the inlet points for the maintenance. However, this will probably not be a deciding factor in deciding if the project would be viable. Lastly, electricity use is the least important factor since the filters do not use that much energy and because the cost of energy use is incorporated in the costs.

The weighting of the criteria has been discussed with one of the water quality experts within Waterschap Rivierenland, Hilde Ketelaar. She agreed that the weights were representative of the needs of Waterschap Rivierenland (Hilde Ketelaar (7-6-2023), personal contact).

Now the scale of pairwise comparison is used to compare all criteria. All criteria are compared to each other in Table 18. When the criteria are compared the other way around the inverse is used. All scores are filled in in Table 19. To make it more clear: when looking at a row the criteria that is in that row is criteria A.

Table 18: Application of scale of pairwise comparison

Criteria A	Criteria B	
P-removal	N-removal	2: A is slightly more important than B
P-removal	Cost	2: A is slightly more important than B
P-removal	Maintenance	4: A is between moderately and strongly more important than B
P-removal	Space	2: A is slightly more important than B
P-removal	Electricity use	5: A is strongly more important than B
N-removal	Cost	1: A is equally important as B
N-removal	Maintenance	2: A is slightly more important than B
N-removal	Space	1: A is equally important as B
N-removal	Electricity use	3: A is moderately more important than B
Cost	Maintenance	2: A is slightly more important than B
Cost	Space	1: A is equally important as B
Cost	Electricity use	3: A is moderately more important than B
Maintenance	Space	2: A is slightly more important than B
Maintenance	Electricity use	2: A is slightly more important than B
Space	Electricity use	3: A is moderately more important than B

Table 19: Compared criteria

	N-removal	P-removal	Cost	Maintenance	Space	Electricity use
N-removal	1,00	0,50	1,00	2,00	1,00	3,00
P-removal	2,00	1,00	2,00	4,00	2,00	5,00
Cost	1,00	0,50	1,00	2,00	1,00	3,00
Maintenance	0,50	0,25	0,50	1,00	1,00	2,00

Space	1,00	0,50	1,00	1,00	1,00	3,00
Electricity use	0,33	0,20	0,33	0,50	0,33	1,00
SUM	**5,83**	**2,95**	**5,83**	**10,50**	**6,33**	**17,00**

The weights of each criterion are found by normalizing the table, this is done by taking the sum of each column, dividing each cell in the table by this sum and then taking the average of the rows (Equation 2). In the appendix, the normalized table can be found. The weights that the criteria get can be seen in Table 20.

Table 20: Weights criteria

Criterion	Weight
N-removal	0,17
P-removal	0,34
Cost	0,17
Maintenance	0,10
Space	0,16
Electricity use	0,06

To check the consistency of the weights the consistency index is used, the formula can be seen in Equation 3. λ_{max} is the 6,06 and the calculation can be seen in Appendix 14.2. Filling in the formula with n = 6 and λ_{max} =6,06 the CI is 0,067. After finding the consistency index the consistency ratio can be calculated. RI is the average random consistency index this RI is calculated in Saaty (1987). Because there are 6 criteria the RI is 1,24, as can be seen in Table 3. Filling in Equation 4 gives CR =0,01. If the consistency ratio is higher than 0,1 the weighting is too inconsistent. 0,01 ≤ 0,1 so the weights of the criteria are consistent. Now the weights can be used to determine the ranking of the filters.

To determine the ranking the data that has been gathered for each filter in chapter 8 is filled in in the decision matrix. This can be seen in Table 21. The table is then normalized using Equation 5 and Equation 6. In this case, N-removal and P-removal are the only benefit criteria while the rest are cost criteria. When the decision matrix is normalized it can be multiplied with the weight, the sum of this multiplication gives the score for the filter type, the lower the score, the better. The result can be seen in Table 22.

Table 21: Decision matrix

	N-removal (% removed)	P-removal (% removed)	Cost (€/m^3)	Maintenance (times/year)	Space (m^2)	Electricity use (kWh/m^3)
1-STEP	0,67	0,71	0,14	52	84	0,12
Aerated helophyte	0,62	0,65	0,06	5	8000	0,028
Discontinuous sand	0,9	0,9	0,07	52	44	0,04
Continuous sand	0,87	0,89	0,15	52	93	0,1

Table 22: Normalized decision matrix with scores

	N-removal	P-removal	Cost	Maintenance	Space	Electricity use	**Scores**	**Ranking**
1-STEP	0,28	0,27	0,30	0,47	0,01	0,47	**0,268**	**3**
Aerated helophyte	0,30	0,30	0,13	0,05	0,97	0,11	**0,337**	**4**
Discontinuous sand	0,21	0,21	0,26	0,02	0,01	0,03	**0,156**	**1**
Continuous sand	0,21	0,22	0,32	0,47	0,01	0,39	**0,238**	**2**

From the scores, it becomes clear that discontinuous sand filtration is the clear winner. The filter is most suited for the removal of nutrients at the inlet points with the criteria and weights that have been used.

10. Costs effectiveness

To see if the filter is an effective measure the cost-effectiveness of the filter will be compared to the cost-effectiveness of other measures against nutrients in the surface water. The cost-effectiveness of a measure is how much it costs to remove 1 kg of a substance. Using this unit allows for easy comparison of measures. In Table 23 the average yearly discharge of the period 2016-2020 is given for each inlet point. Using this discharge, and the cost per m^3 of the filter the yearly costs can be calculated. The amount of N and P that is removed is calculated using Equation 7 with the concentrations that are found in Table 5. For the P-total concentration at the inlet point, the concentration of Maas Belfeld is chosen since this measurement point lies upstream of the inlets while Keizersveer lies downstream of the inlet points. The results can be seen in Table 23.

Table 23: Cost and amount of nutrients removed for the average discharge of 2016-2020

Inlet point	Yearly discharge (average 2016-2020)	Yearly costs for discharge	kg N Removed	kg P removed
Weurt	21691 m^3	€ 554.203	22730	916
Landeweijer	5576 m^3	€ 142.459	6197	235
Teerse Sluis	6976 m^3	€ 178.233	9747	295
Blauwe Sluis	20720 m^3	€ 529.403	17107	875
Rijksche Sluis	4371 m^3	€ 111.668	4858	185

Using the amount of N and P removed and the costs the cost-effectiveness is calculated. The result can be seen in Table 24. Some notes need to be made. Firstly, the cost-effectiveness has been calculated for both substances with the total costs since splitting up which costs correspond to N and which to P would be complicated. Secondly, the cost-effectiveness of P is the same for each inlet point since the same concentration is used. Finally, the cost-effectiveness at Teerse Sluis is way better than at the other inlet points, this is caused by the higher concentration in Table 5, which is a bit outdated. In reality, the cost-effectiveness is probably similar to the other inlet points.

Table 24: Cost-effectiveness filter

Inlet point	Cost-effectiveness N [€/kg]	Cost-effectiveness P [€/kg]

Weurt	24,38	605,01
Landeweijer	22,99	605,01
Teerse Sluis	18,29	605,01
Blauwe Sluis	30,95	605,01
Rijksche Sluis	22,99	605,01

In Noij et al. (2008) the cost-effectiveness of other nutrient-limiting measures is compared to buffer strips. Using the cost-effectiveness that was calculated in this report the cost-effectiveness of the filter can be compared. In the report, the measures are split up into different ground types. The ground type at the inlet point is mostly sandy (Assinck) so the cost-effectiveness in sand will be used. The cost-effectiveness of some route measures and end-of-pipe measures is shown in Table 25. The cost-effectiveness has not been adjusted for inflation. As can be seen, the filter does quite well in de cost-effectiveness for N removal but performs worse when looking at the P removal. This is also reflected when looking at the ranks that are used in Noij et al (2008) measures are put in a rank based on their cost-effectiveness and ranks 1-3 are comparable to taking extra measures at WWTPs. In Table 26 these ranks are shown. The filter comes in at rank 2 for N-removal (if adjusted for inflation) and rank 3 for P-removal (if adjusted for inflation). This shows that the filter is cost-effective. However, for the prevention of algae blooms the removal of phosphates is the most important, as explained in Paragraph 6.2.3, since the filter is not very cost-effective in the removal of phosphates other measures might be more suitable. Still, further research into the practical implication of the filter could be useful.

Table 25: Cost-effectiveness of alternative measures, adapted from Noij et al. (2008)

Measures	Cost-effectiveness N [€/kg]	Cost-effectiveness P [€/kg]
Buffer strip, minimum maintenance	24-98	269-717
Buffer strip, mowing in September	-	156-313
Buffer strip, renew every 6 years	-	133-302
Stopping drainage	0	70-130
Deep drainage	80-200	600-1560
Blocking run-off	34	330

Table 26: Ranks of cost-effectiveness (Noij, et al., 2008)

Rank	N [€/kg]	P [€/kg]
1	<10	<100
2	10-20	100-200
3	20-50	200-500
4	50-200	500-2000
5	>200	>2000

11. Conclusion

To conclude, this research set out to find the most suited filter for the removal of nutrients from the inlet water at the five inlet points in het Land van Maas en Waal. To answer this question some sub-questions have been used.

First, *What is the effect of droughts on the water quality?* Several processes influence the water quality during the drought but most of them lead to an increase in nutrients in the water, this is the case in the larger rivers as well as the smaller stream in Land van Maas en Waal. This increase in nutrients together with higher temperatures leads to algae blooms which have negative effects such as the release of toxins and causing a low-oxygen concentration in the water, killing water plants and fish.

The next question that needs to be answered is: *which filter is most effective in removing nutrients from the inlet water?* The discontinuous sand filter has the highest removal rates at 90% removal of both phosphorous and nitrogen.

The next sub-question is: *Which filter can realistically be constructed and put into operation at the inlet points?* The filters that have been analysed in Chapter 8 could all be constructed at the inlet points. The aerated helophyte filter might not be realistic at all the inlet points since it requires quite a lot of space.

The next sub-question is: *To what extent does the filter construction have an impact on the discharge at the inlet points?* All filters can filter the reference discharge of the summer of 2022 shown in Table 4. If more water is desired a bypass will allow more water to be let in. The aerated helophyte filter and the discontinuous sand filter are filled in batches after which they slowly empty. This will impact the discharge. The rest of the filters have continuous flow so the impact on the discharge is minimal. However, at times the filter may need to be rinsed because the filter media is clogged. If this is the case water cannot be let in until the filter is rinsed.

Now, to answer the main research question. Which filter is most suited for the filtration of the inlet water? According to the analysis that has been performed the best filter, from the filters that have been analysed, is the discontinuous sand filter. The filter is relatively compact and has a high nutrient removal rate while being one of the cheapest options.

12. Discussion

The first point of discussion is the use of removal percentages. The nutrient concentrations in the inlet water are quite low when compared to the influent that is treated at WWTPs. The removal of nutrients might not be as efficient at lower concentrations. This was not considered for all the filters since the quality of the influent was not always given. For the filter for which the quality of the influent was known, it is still unclear how much nutrients would be removed if the concentrations in the influent are low, as is the case with the inlet water. This also means that the cost-effectiveness that is calculated is not entirely accurate. If more research is done into this application of filters the effectiveness of the filter at lower concentration will have to be researched.

The second discussion point is the current water quality. The measurements that were used in this research are quite old and for phosphorous no data was even available at the inlet points. This also impacts the cost-effectiveness calculation as a filter could be much more or less cost-effective than currently calculated. However, no extra measurements were made since these are quite expensive and this was only an exploratory study into the possibility of filtering inlet water. The old data was therefore good enough, however, when more research is done the quality of the inlet water should be measured for accuracy.

The third point of discussion is the cost-effectiveness calculation. Besides the points mentioned earlier that have an impact on the accuracy of the cost-effectiveness calculation, the cost-effectiveness calculation also assumes all water is filtered and that it is all filtered with the high removal rate that is possible. This is unlikely to reflect the actual situation. All the shortcomings of the cost-effectiveness calculations should be taken into account if this application is researched in the future.

Lastly, the removal of algae was not assessed. Since this study was focused on the removal of nutrients. If more research into the filtering of inlet water is done this should be included. There are some interesting technologies for the removal of algae from the water such as the waterned installation (Waterned, 2023) and a water drone that sucks up algae (H2O, 2023). These could be further analysed in further research.

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14. Appendix

14.1. Cost calculations

For the yearly payment of the borrowed money for the construction of the filter Equation 8 is used.

Equation 8: Formula for annuity

$$J = \frac{i}{1-(1+i)^{-n}} * T$$

With

- T: Borrowed amount of money
- n: number of periods
- J: Amount to be paid (including the interest rate)
- i: Interest rate

$$Annuity\ aerated\ helophyte = \frac{5}{1-(1+5)^{-30}} * 2.824.500 = 183.738$$

$$Annuity\ continuous\ sand = \frac{5}{1-(1+5)^{-30}} * \ 928.369 = \ 60.392$$

14.2. AHP Calculations

Table 27: Normalized matrix

Normalized	N-removal	P-removal	Cost	Maintenance	Space	Electricty use
N-removal	0,17	0,17	0,17	0,19	0,16	0,18
P-removal	0,34	0,34	0,34	0,38	0,32	0,29
Cost	0,17	0,17	0,17	0,19	0,16	0,18
Maintenance	0,09	0,08	0,09	0,10	0,16	0,12
Space	0,17	0,17	0,17	0,10	0,16	0,18
electricty use	0,06	0,07	0,06	0,05	0,05	0,06

$$Weighted\ sum = 0{,}17 * \begin{pmatrix} 1 \\ 2 \\ 1 \\ 0{,}5 \\ 1 \\ 0{,}33 \end{pmatrix} + 0{,}34 * \begin{pmatrix} 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}25 \\ 0{,}5 \\ 0{,}2 \end{pmatrix} + 0{,}17 * \begin{pmatrix} 1 \\ 2 \\ 1 \\ 0{,}5 \\ 1 \\ 0{,}33 \end{pmatrix} + 0{,}10 * \begin{pmatrix} 2 \\ 4 \\ 2 \\ 1 \\ 1 \\ 0{,}5 \end{pmatrix} + 0{,}16 * \begin{pmatrix} 1 \\ 2 \\ 1 \\ 1 \\ 1 \\ 0{,}33 \end{pmatrix} + 0{,}06 * \begin{pmatrix} 3 \\ 5 \\ 3 \\ 2 \\ 3 \\ 1 \end{pmatrix} = \begin{pmatrix} 1{,}05 \\ 2{,}04 \\ 1{,}05 \\ 0{,}63 \\ 0{,}95 \\ 0{,}34 \end{pmatrix}$$

$$\frac{Weighted\ sum}{Weights\ criteria} = \frac{\begin{pmatrix} 1{,}05 \\ 2{,}04 \\ 1{,}05 \\ 0{,}63 \\ 0{,}95 \\ 0{,}34 \end{pmatrix}}{\begin{pmatrix} 0{,}17 \\ 0{,}28 \\ 0{,}17 \\ 0{,}11 \\ 0{,}21 \\ 0{,}06 \end{pmatrix}} = \begin{pmatrix} 6{,}08 \\ 6{,}08 \\ 6{,}08 \\ 6{,}05 \\ 6{,}02 \\ 6{,}05 \end{pmatrix} (Average: 6{,}06) \rightarrow \lambda_{max} = 6{,}06$$