Improving the Purifying Effect of the Kristalbad

A Civil Engineering Bachelor Thesis

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WATERSCHAP vechtstromen

UNIVERSITY OF TWENTE.

Preface

Dear reader,

This report is part of my bachelor thesis for the study Civil Engineering at the University of Twente. From May until July 2022, I have done research on the functioning of the Kristalbad, a water harmonica located in Enschede. I have sought possible improvements to the Kristalbad by studying literature, conducting a model study and gathering experiences from experts.

I would like to thank all who have helped me during the months in which I did my research. In particular, I want to thank my external supervisors Anke Durand and Alberta Groteboer, who helped me get familiar with aquatic ecology and guiding me through the learning process that comes with a thesis. I also want to thank my supervisor from the UT Thomas van Veelen who guided me through the practical side of a bachelor thesis and helped me with his feedback on the thesis proposal and concept report. My thanks also go to René Nij Bijvank for proofreading my thesis report. I further want to thank the ecologists and hydrologists of the Expertisecentrum of Waterschap Vechtstromen for their enthusiasm with which they shared their knowledge. Lastly, I want to thank Peter Westerbeek and Ewald Hannink for a tour through the Kristalbad and Oscar van Zanten for a tour around Waterpark Groote Beerse, both giving useful insight in the working of water harmonicas.

Of course, I also want to thank my girlfriend, family and friends, who helped me personally during the thesis and helped me get to the point where I am able do this thesis.

I hope you enjoy reading it as much as I enjoyed writing this report.

Ruben Bralts

Enschede, 06-07-2022

Abstract

Nitrogen emissions have become a pressing issue in the last twenty years. The Kaderrichtlijn Water (KRW) is a piece of European legislation which all member states must abide by. Waterschap Vechtstromen maintains a water harmonica called the Kristalbad which is constructed in part to purify water. The performance of the Kristalbad is lower than expected however and the effluent of the Kristalbad does not achieve the goals set for several parameters, among which total nitrogen is the most pressing issue. The target value of total nitrogen in the Elsbeek, of which the Kristalbad is part, is 2.2 mg/l. The effluent of the Kristalbad currently contains 5.2 mg/l total nitrogen on average.

This research investigates how the purifying effect of the Kristalbad can be improved. This is done by conducting a model study, studying literature and gathering experiences from other water harmonicas.

From the model, it can be concluded a total nitrogen reduction of 43% is possible, as opposed to 6% for the current situation in the model. This is done by making sure a mix of emergent macrophytes and submerged macrophytes live in the Kristalbad. The macrophytes should be present in the six basins in the last two columns of the Kristalbad. They should be sufficiently dense and cover the entire basins.

From literature, it can be concluded the water level is currently too high in the Kristalbad. The water level needs to be sufficiently low to allow the emergent macrophytes to live and spread. An Expert from Waterschap the Dommel further advises to intervene in time when floating algae spread in the summer. This should be removed ones a basin is around 50 percent covered with floating algae. In addition, the expert from Waterschap de Dommel stresses the importance of well-structured management of a water harmonica. Assigning final responsibility to one person or department will make sure issues are handled properly, everyone knows who to approach with regards to issues with the Kristalbad and experience gained in the management of the Kristalbad stays with the person or department who is responsible.

From this research several recommendations are made. First, it is recommended to plant extra submerged and emergent macrophytes under favourable conditions. This should be done in the spring with a sufficiently low water level. Research needs to be done on what intervention could best lower the water level in an effective and cost-efficient way. Second, the water quality should be monitored better. The most effective way of improving the performance of the Kristalbad is by getting insight in the current performance. It is recommended to measure the water quality of the inflow and outflow and in each basin of the Kristalbad. This makes it possible to compare the performance of each basin and each street, making it possible to find differences and improve the purifying performance of the Kristalbad according to these findings. It can also detect any drop in performance of a basin or street, making it possible to intervene in time. It also enables experiments to be conducted. An experiment could be set up in one street, while the two other streets function as control. Third, the advice by the expert from Waterschap de Dommel to restructure the management of the Kristalbad differently is recommended. The advice to intervene timely to remove floating algae is also recommended. Lastly, the wastewater treatment plant and the Kristalbad should work together to improve water quality. Goals should be set for both systems to get the optimal performance of the two systems combined. Especially the Kristalbad currently has no clear goals in terms of water quality parameters. These goals should be set. Setting these goals will make it easier to design and maintain the Kristalbad as there are benchmarks which should be reached. These goals make it clear what to work towards and makes it clear to the management what interventions can help achieve this goal.

Table of Contents

Table of figures

Table of tables

List of abbreviations

FWS	Free water surface
DWD	Dry weather discharge
KRW	Kaderrichtlijn Water

1. Introduction and Context

1.1. Introduction

In the year 2000 the Kaderrichtlijn Water (KRW) was put in effect by the European Commission. As a result of this, the water boards in the Netherlands are tasked with achieving the new water quality goals set in the KRW of which the deadline is in 2027. In the east of the Netherlands, Waterschap Vechtstromen is responsible for a water harmonica which is built, in part, with the KRW goals in mind. This water harmonica is known as the Kristalbad. Since the construction of the Kristalbad has been completed, Waterschap Vechtstromen has noticed that the expected reduction of some water quality parameters is not as good as expected in the Kristalbad. Most importantly, the reduction of total nitrogen and total phosphorus is not as expected. To improve the purifying effect of the Kristalbad, Waterschap Vechtstromen wants to get an insight in what causes the water harmonica to underperform.

Figure 1: The Kristalbad (Tubantia.nl, 2021)

Before explaining the aim of the research, it is necessary to understand the working of the Kristalbad. This is explained in Section 1.2 and Section 1.3. The problem statement, aim, scope, research questions and research method are described in Sections 1.4 until 1.8. More information on the parties involved in the construction and management of the Kristalbad can be found in Appendix A: Overview of involved parties.

1.2. Study area

The Kristalbad is a water harmonica located in the west of Enschede on the border with Hengelo. The construction started in 2009 and was completed in 2014 (Groenblauw Enschede, n.d.). The Kristalbad is built with multiple functions in mind.

First and most importantly, it can store up to 187.000 cubic metres of water in case of heavy rainfall. This contributes to the protection from flooding in Hengelo as rainwater from Enschede flows to the lower situated Hengelo. The Kristalbad functions as a buffer to store rainwater temporarily to spread out the rainwater, lowering the peak discharge flowing through Hengelo. Rainfall events heavy enough for using the Kristalbad as a water buffer occur around once a year (Groenblauw Enschede, n.d.).

Secondly, the Kristalbad has the goal to purify water biologically in the Elsbeek. Most water in the Elsbeek originates from the wastewater treatment plant in Enschede. This is 'lifeless' water, as it shows unnatural characteristics like not having a day-night cycle of the oxygen concentration. The Kristalbad is built to improve the ecological and chemical quality of the water flowing through the Elsbeek. This is part of the country-wide goal to have good quality water suitable for drinking water companies, farming, fishing, industry, nature and recreation (Rijkswaterstaat, n.d.).

The Kristalbad is located between two nature reserves: Driene and Twekkelo. Before the construction, the area mostly consisted of farmland and a smaller area in the southwest was a marsh as can be seen in Figure 2. The Kristalbad forms a bridge between Driene and Twekkelo giving the diverse group of animals living in the area the opportunity to traverse more easily between the two nature reserves (Waterschap Vechtstromen, n.d.).

Figure 2: Google Earth image of the Kristalbad area before construction, April 2009

Lastly, the Kristalbad is a recreational area. People can go to the area to take a walk and visit the two watchtowers to have a view of the entire area. It even provides a pleasant view when travelling from Enschede to the rest of the Netherland by train. The current situation of the Kristalbad can be seen in Figure 3.

Figure 3: Google Earth image of the Kristalbad, September 2020

1.3. The Kristalbad

1.3.1. Layout of the Kristalbad

The Kristalbad is divided into three streets. In Figure 4 these streets are depicted as street I, II and II, flowing from the right to the left side of the figure. Each street consists of three basins with a different function, referred to as basin A, B and C. The basins have the same functionality for each street. Water enters the Kristalbad in the distribution channel on the east side of the Kristalbad. From now on, basins will be referred to as basin A1, for the basin in column A and street 1, and so forth.

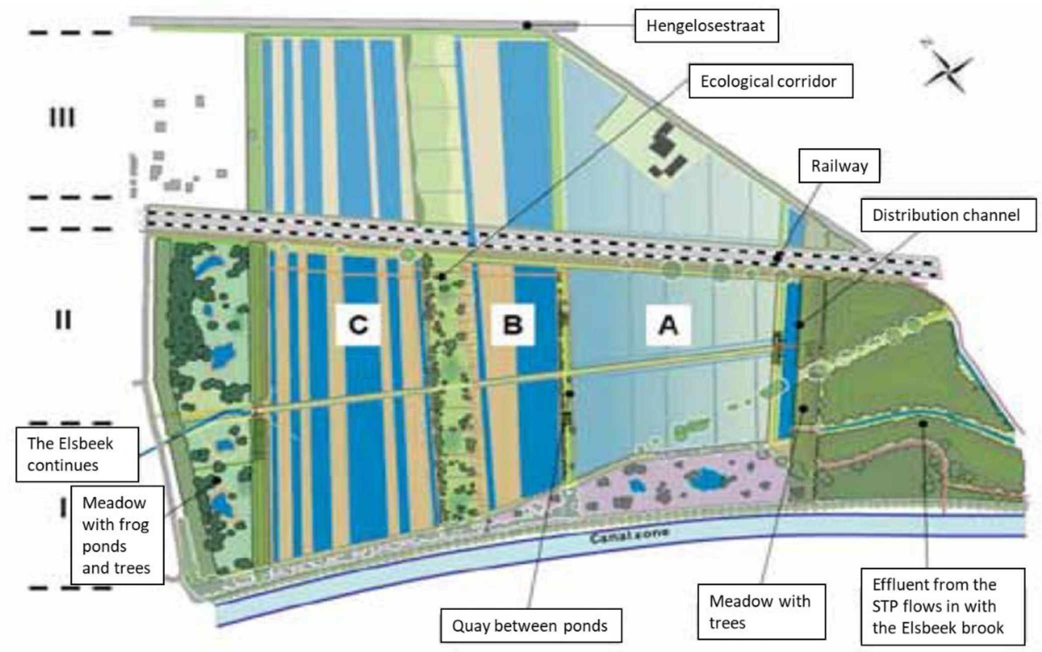

Figure 4: Top view sketch of the Kristalbad (Kampf & Van den Boomen, 2013)

1.3.2. Distribution channel

When water enters the Kristalbad, it does so in the distribution channel. In the distribution channel there are three weirs each connecting the distribution channel to one settling basin. One weir is opened at the time filling meaning one settling basin is being filled at any moment in time. Currently, a weir is open for 20 hours. This is an automatic process. The timing of this can be changed if desired.

1.3.3. Settling basins

The first set of basins, the basins in column A, is a settling basin. The purpose of the settling basin is to remove suspended solids and pathogens (Kampf & Van den Boomen, 2013). These particles are heavy enough to sink to the bottom of the basin when given the time. Because the Kristalbad has three separate streets there are three separate settling basins. This allows the management of the Kristalbad to fill and empty one settling basin at a time. This allows the water to stand still for a third of a cycle before being emptied. This improves the sedimentation process. In addition, in another third of the cycle the basin is empty of water. This gives the sludge time to settle into the soil on the bottom of the settling basin.

According to Kampf and Van den Boomen (2013), it is advised to let suspended particles settle for at least three days. In addition to this, it is recommended to remove sludge to avoid resuspension of the particles. Currently, the retention time in the settling basins is estimated to be eight hours. The sludge is never removed from the Kristalbad. In part because of this, part of the particles in the sludge will be able to re-enter the water in a process called resuspension.

Because the settling basins are filled and emptied, the soil in these basins is naturally aerated. This improves the removal of total nitrogen (Langergraber & Dotro, 2019). This is further discussed in Section 2.2.2.

1.3.4. FWS constructed wetlands

The basins in columns B and C are free water surface (FWS) constructed wetlands. A FWS constructed wetland is a basin containing submerged and/or emergent aquatic plants, also known as macrophytes. Emergent macrophytes allow bacteria to flourish which clean the water by means of nitrification, denitrification and by removing phosphorus as the water flows through the strip of emergent macrophytes (Vymazal, 2007). In addition, the emergent macrophytes take up nutrients, further purifying the water (Vymazal, 2007). In the Kristalbad, the strips with emergent macrophytes are 0.5 meters deep at DWD (dry weather discharge). Emergent macrophytes like reed (Phragmites australis) and bulrush (Typha) are suitable for this application. Figure 5 shows how water flows through an FWS constructed wetland filled with emergent macrophytes. In Figure 4, the yellow strips in the basins depict the parts where emergent macrophytes are planted. Currently, the emergent macrophytes have difficulty growing and spreading in the Kristalbad, as emergent macrophytes are currently only found at the sides of the basins and on part of the emergent macrophyte strips in basin C1.

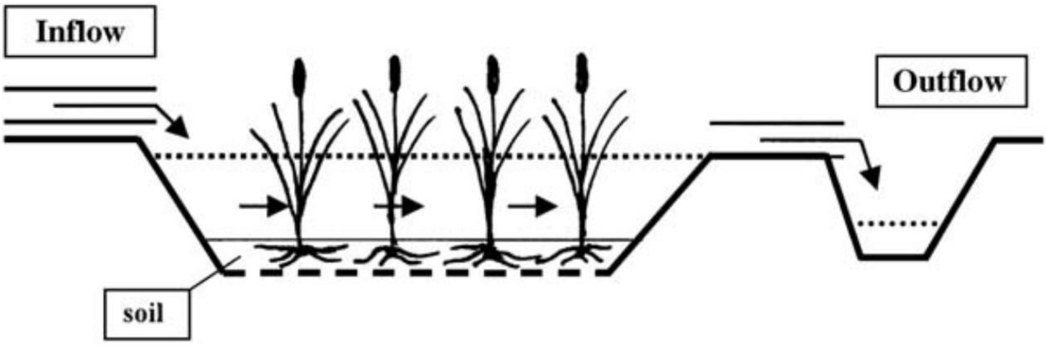

Figure 5: FWS constructed wetland with emergent macrophytes (Vymazal, 2007)

Next to the emergent macrophytes, the basins in columns B and C contain strips where submerged macrophytes grow. Submerged macrophytes, like emergent macrophytes, also remove nutrients by means of nitrification, denitrification and nutrient uptake. The strips in which these plants grow are deeper in the Kristalbad, being 1,5 meters deep at DWD.

1.4. Problem statement

Waterschap Vechtstromen has the goal to improve the water purifying effect of the Kristalbad. The current status of the purifying effect of the Kristalbad can therefore be seen as the problem in this research. Measurements of the current situation of six water quality parameters is shown in Table 1. The problem can be split up into multiple sub-problems. These are listed and explained briefly below.

Table 1: Measured concentration of six water quality parameters in the inflow and outflow of the Kristalbad compared to the KRW R5 norm

	Inflow	Outflow	Norm
Total N (mg/l)	6.3	5.2	<2.2
Total P (mg/l)	0.7	1.1	<0.1
Oxygen (%)	66.4	110.4	70-120
pH	7.5	8.4	5.5-8.5
Cu (µg/l)	6.3	7.4	<3.8
Zn (µg/l)	47.0	45.8	<10.6

1.4.1. Removal of nitrogen and phosphorus

In 2020, Aqualysis measured the performance of the Kristalbad at the request of Waterschap Vechtstromen. One of the findings of this experiment was that the effluent of the Kristalbad did not meet the KRW water quality norm R5 for total nitrogen and total phosphorus content. Norm R5 is the norm for water bodies like the Elsbeek, the water body the Kristalbad is part of. The total nitrogen content was measured to be 5.2 mg/l in the effluent of the Kristalbad. Although this is 17 percent lower than the influent, it is still too high as the norm is a maximum 2.2 mg/l total nitrogen. Vymazal (2007) states a FWS constructed wetland is capable of removing 41 percent of the total nitrogen in the inflow of the system. This is a 24 percent difference between what is possible according to literature and the actual performance of the Kristalbad. The total phosphorus content in the effluent was measured to be 1.1 mg/l. This is an increase of 60 percent compared to the influent. This is eight times higher than the norm which is 0.11 mg/l. According to Vymazal (2007), a reduction of 48.8 percent is possible in a FWS constructed wetland.

1.4.2. Copper and zinc

Two metals which are measured as well are copper and zinc. Both exceed KRW, as can be seen in Table 1. They could therefore be seen as a problem depending on what the exact goal of the Kristalbad is.

1.4.3. Maintenance issues

Apart from the two points stated above, smaller, but impactful maintenance issues have occurred in the Kristalbad. For example, in October 2021, Waterschap Vechtstromen confirmed cases of botulism in the Kristalbad area. Botulism is a disease caused by bacteria which kills birds, but can also affect fish, dogs and humans. The advice was given by Waterschap Vechtstromen to not touch dead animals or the body of water in which it is found (Waterschap Vechtstromen, 2021a). A second maintenance issue is the growth of floating algae. This is mostly a problem in the summer months. The situation in basin C1 can be seen in Figure 6.

Figure 6: Basin C1 is filled with floating algae. June 29th, 2022

1.5. Aim of the research

The aim of this research is to get an insight in why the purifying function of the Kristalbad is not as expected and what interventions could be undertaken to improve the purifying function of the Kristalbad. This will be done using a model of the Kristalbad which will be made as part of this research. The water quality parameter which will be looked at in the model is total nitrogen concentration as this is the most critical parameter. Part of this research will focus on the impact of this cycle time and investigate if it is possible to improve the purifying function by extending the cycle time of filling the settling basins. Next to this, the performance of the FWS constructed wetland could be lower than expected. Another aim of this research therefore is to find if the coverage and type of macrophytes in the FWS constructed wetland basins affects the purifying effect of the Kristalbad. Lastly, the aim is to find advice on how to improve the management and maintenance of the Kristalbad. This is done during the literature study and by gathering advice from experts.

1.6. Research scope

This research will look at the Kristalbad only. This means results of this research only give insight in the functioning of the Kristalbad and cannot directly be used for other water harmonicas. Further on, there is a limited amount of time to work on this research. This means not all water quality parameters can be investigated. The parameter looked at for this research is the total nitrogen level. The reason this is the only parameter researched is, because the concentration of total nitrogen is the most pressing issue in the entire water system Bornse Beek, which the Kristalbad drains into. Despite being primarily focussed on water quality, the total storage will be considered as well. This is necessary, as interventions improving the purifying cannot significantly harm the water buffering capability of the Kristalbad. In addition, potential management issues will be investigated.

1.7. Research questions

From the aim and scope of the research in Section 1.5 and Section 1.6, four research questions can be derived:

1. How can the water purifying processes in the Kristalbad be translated into a model?
2. How does the cycle time of filling the settling basins affect the purifying effect?
3. How do macrophyte coverage and the type of macrophyte filter affect the purifying effect?
4. What lessons can be learned from literature and other water harmonicas?

1.8. Research method

This research will be conducted by constructing a Python model of the Kristalbad. The exact design of the model is described in Section 3. The water quality calculations are based on literature covered in Section 2.3. This model will give insight in what effect the various processes taking place in the Kristalbad have on total nitrogen concentrations. Further on, a literature study and a tour around water harmonica Waterpark Groote Beerze with an expert will help gain knowledge on how to improve the purifying function of the Kristalbad.

1.9. Reading guide

Chapter 2 will go into the theoretical background necessary to understand the processes occurring in the Kristalbad and to understand the design of relevant types of constructed wetlands. Chapter 3 explains how the model is designed, what its limitations and assumptions are and it explains how the biological processes are modelled. The results of the model study and experiences from a water harmonica expert can be found in Chapter 4. In addition, the validation of the model can be found in Chapter 4. In Chapter 5 the outcome of the research is discussed. Chapter 6 contains conclusions and recommendations based on the outcome of this research.

2. Theoretical Background

2.1. Nitrification and denitrification

2.1.1. Nitrification

Two important processes in purifying water are nitrification and denitrification. These two processes are part of the nitrogen cycle and are executed by nitrifying and denitrifying bacteria (Vymazal, 2007). These bacteria live in water bodies and the soil below. In addition, nitrifying bacteria flourish on the roots of macrophytes which release oxygen which the nitrifying bacteria utilise for nitrification (Gray, 2017).

Nitrification is defined as a two-step process in which ammonia (NH_3) or ammonium (NH_4^-) reacts with oxygen to form nitrite (NO_2^-) after which nitrite reacts with oxygen (O_2) or water (H_2O) to form nitrate (NO_3^-). Nitrifying bacteria are at the core of the nitrifying process. There are multiple species capable of nitrification, one of which is the Nitrosomonas. Nitrosomonas bacteria turn ammonium to nitrite using oxygen gas as can be seen in Equation 1 (Sloots, 2014).

$$4NH_4^+ + 6O_2 \rightarrow 4NO_2^- + 8H^+ + 4H_2O \qquad \textit{Nitrosomonas}$$

Equation 1

The second step of nitrification is the process of forming nitrate from nitrite. The Nitrobacter is an example of a species forming nitrate from nitrite. In Equation 2 the reaction equation of the process executed by the Nitrobacter is shown (Sloots, 2014).

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad \textit{Nitrobacter}$$

Equation 2

Both steps in nitrification require oxygen, making nitrification an aerobic process.

2.1.2. Denitrification

Denitrification is the process of turning nitrite and nitrate to nitrogen gas (N_2). This is an anaerobic process conducted by denitrifying bacteria. There are multiple intermediate reactions when turning nitrite or nitrate to nitrogen gas, but the combined reaction equation could be as follows:

$$5(CH_2O) + 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O$$

Equation 3

Denitrification requires a low oxygen concentration. If the oxygen concentration is low, other particles start to function as the oxidiser in redox reactions. One of the first particles to replace oxygen in water and the soil below is nitrate (Sloots, 2014). This redox reaction is called denitrification. Because the oxygen concentration is lower deeper in water, denitrification mainly takes place close to the bottom of the water body and in the soil.

2.2. Constructed wetlands

Constructed wetlands are designed to purify and 'ecologise' water from various sources. There are many different types of constructed wetlands which can be applied depending on the available space, the hydraulic load and depending on the type of treatment is focussed on. Some of the most well-known constructed wetlands are horizontal flow wetlands, vertical flow wetlands and free water surface wetlands. Langergraber and Dotro (2019) give an overview and advice on different treatment types for which constructed wetlands can be used and gives practical information on how constructed wetlands should be designed and maintained.

2.2.1. FWS constructed wetlands

For this research FWS (free water surface) wetlands are most interesting. This is, because the Kristalbad is a FWS constructed wetland system. In addition, it is also a water storage, making it uninteresting to implement any subsurface flow constructed wetlands as this significantly decreases the buffering capacity of the system.

FWS wetlands are basins filled with vegetation which purify water in different ways, depending on the type of vegetation. Nutrient removal through nitrification, denitrification and nutrient uptake are the most common and always occur in such wetlands (Vymazal, 2007). Langergraber and Dotro (2019) advice FWS systems have a retention time of 2-3 days, a water depth of 0.1-0.6 and a length-to-width ratio of 2:1 to 5:1. Reed and Brown (1995) further advise having 65 to 75 percent of the wetland covered with emergent vegetation, depending on the density of the vegetation.

For reed to grow and spread well, the water level needs to be 10 cm in the initial stages of growth between the end of May and the beginning of April. This should be increased to 15 cm at the stage of rapid growth from the end of June to the end of August (Wang, Zhang, Guan, Qi, & Tong, 2017).

A water quality consultant at Waterschap Vechtstromen explains a mix of vegetation improves the resilience of an ecological system. This is important to consider when designing a water harmonica as it is less likely for the ecological system to collapse if it is more diverse.

2.2.2. FWS fill-and-drain constructed wetlands

The first basin of the Kristalbad is a special type of constructed wetland which is not mentioned in literature. A type of wetland showing similarities with the first basin of the Kristalbad is the fill-and-drain wetland. Fill-and-drain wetlands are a subsurface flow system which goes through a continuous cycle of filling and draining the basin. This is done to create a cycle of aerobic and anaerobic phases, improving total nitrogen removal (Reed & Brown, 1995). This is linked to the nitrogen cycle discussed in Section 2.1. In the Kristalbad the same cycle applies. Instead of it being a subsurface flow system it is a FWS system. It could therefore also be considered a FWS fill-and-drain constructed wetland, instead of just a settling basin. The goal of this system is to improve the total nitrogen removal without impacting the buffering capacity. There is no literature however which shows such a system works in practice. To understand with a degree of certainty what the effect of this type of system has on water quality, more research must be conducted.

2.3. Nutrient removal using macrophytes

Macrophytes are water plants which grow in an aquatic environment, partially or fully submerged. Macrophytes use nutrients like nitrogen and phosphorus to grow. When macrophytes grow, they extract these nutrients from the soil or water they live in. This interaction between macrophytes and their environment can be applied as a method to remove nutrients from water. Suitable types of macrophytes for this application are macrophytes which can live in waters which are rich of nutrients and can grow at a fast rate to absorb nutrients at a fast rate. A good example of an effective submerged plant for nutrient uptake is waterweed (*elodea*), which removes up to 50 percent of phosphorus and 90 percent of nitrogen present in the body of water (Ozimek, Donk, & Gulati, 1993). A research by Zhou et al. (2016) compares the effect of nutrient uptake of seven types of macrophytes on water quality. Figure 7 shows the results of the measurements of the total nitrogen concentration of seven tanks filled with a different type of macrophyte over time. This research shows the brittle naiad (*Najas minor*), curled pondweed (*Potamogeton crispus*) and western waterweed (*Elodea nuttallii*) are the most potent in removing total nitrogen.

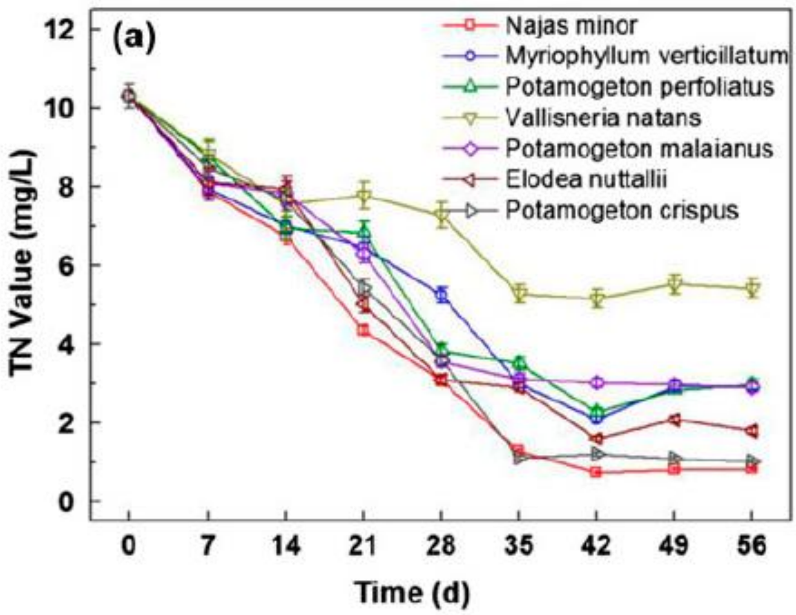

Figure 7: Total nitrogen concentration over time in seven tanks with individual submerged macrophytes (Zhou et al., 2016)

Toet et al. (2005) did research on the effect of retention time on water quality in the water harmonica Everstekoog on Texel, the Netherlands. This water harmonica is filled with a mix of emergent and submerged macrophytes. The same processes take place in a water harmonica with a mix of macrophytes as one filled with submerged macrophytes.

Because of the setup of both the research by Zhou et al. (2016) and Toet et al. (2005), the effect of nitrification and denitrification by bacteria living in symbiosis with the macrophytes is also measured, in addition to the nutrient uptake by the macrophytes for growth. For this research this is convenient as nitrification and denitrification occur in the Kristalbad as well and do therefore not have to be measured and calculated separately.

3. Model

To get insight in the impact of potential interventions in the Kristalbad on its purifying effect, a Python model is designed. In this section the working of the model is explained and the assumptions and limitations of the model are described. The validation of the model can be found in Section 4.5.

3.1. Model description

The model will be a deterministic discrete-time model, meaning the outcome is an exact value and the model is time-based. Each basin of the Kristalbad is modelled as a separate entity. The in- and outflow, amount of water and total nitrogen content are determined at each time step for each basin and for the outflow of the Kristalbad. The time step used is one hour. This is short enough to have representative results and model the filling of the settling basins correctly without having unnecessarily long calculation times. The conceptual model can be seen in Figure 8 and is based on the design of the Kristalbad, shown in Figure 4. The water flows in the direction of the arrows, starting in the distribution channel which can be seen on the left of Figure 8. The water flows through the basins and eventually reaches the outflow point of the Kristalbad as seen on the right. An overview of the inputs, outputs and processes in each type of basin can be found in Table 2.

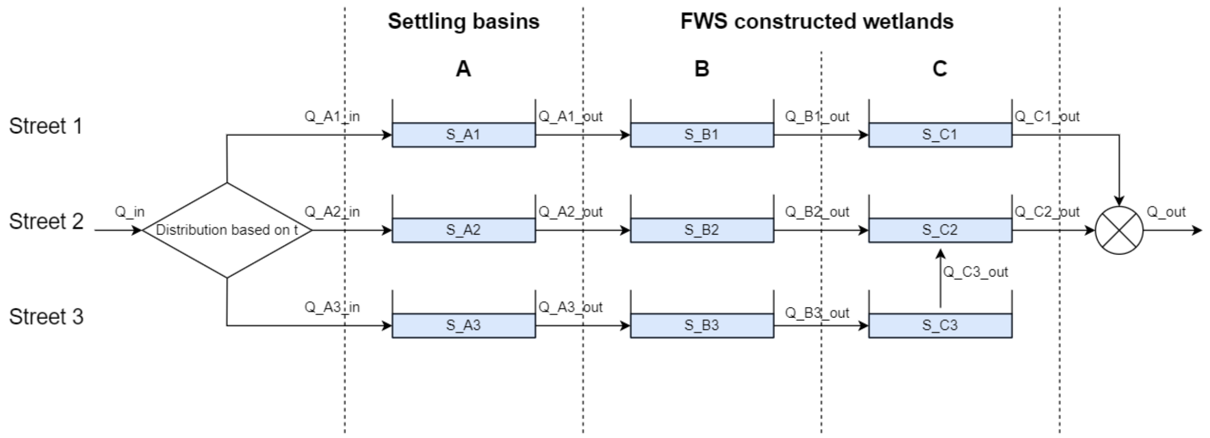

Figure 8: Conceptual model of the Kristalbad

Table 2: Overview of model inputs, processes and outputs of each type of basin

Basin	Input	Processes	Output
Settling basins	Inflow (m^3/s) Total N in inflow (mg/l)	- Change in total N due to mixing of present water with inflow*	Outflow (m^3/s) Total N in outflow (mg/l)
FWS constructed wetlands	Inflow (m^3/s) Total N in inflow (mg/l)	- Change in total N due to mixing of present water with inflow - Total N reduction by macrophytes	Outflow (m^3/s) Total N in outflow (mg/l)

* In the current version of the model the total nitrogen concentration in the inflow is constant, meaning there is no change in total nitrogen concentration in the settling basins.

3.2. Assumptions and limitations

Assumed no short-circuit flows in the system. Short-circuits in any of the basins would harm the performance of the Kristalbad as part of the water has a lower retention time while other parts of the basin would have a low flow rate and therefore a higher retention time. This has a negative impact on the overall decrease in nutrient content. In addition, short-circuit flows can occur, because vegetation partially or fully blocks the flow in other places. This means the part through which the short-circuit flow with a higher hydraulic load flows is not in contact with vegetation as much as is desired, further decreasing nutrient removal using macrophytes.

Water quality is the same throughout each basin. This allows the model to consist of basins on which calculations are made. If this is not the case, a large dynamic hydrological model needs to be designed in which water flows within each basin is calculated as well. This is far too complex for the scope of this research. This assumption could under- or overestimate the performance of the purification as new inflow in a basin is assumed to be mixed immediately with the water already in the basin.

No influence by maintenance issues. Issues like growth of duckweed or floating algae could hamper the processes which need light. This is not considered in this model and it is therefore assumed there is no obstruction of natural light.

Assumed data from research by Toet et al. (2005) and Zhou et al. (2016) applies to the Kristalbad. This assumption is made as there is no information on how the data might change as other variables like temperature and water quality of influent change.

3.3. Distribution of water

In the model, the distribution channel is not modelled as a separate basin. Instead, the inflow is determined based on the moment in time. As explained in Section 1.3.2, a weir is open for 20 hours. This means after 20 hours the total inflow into the Kristalbad at a time step is switched to the next settling basin. After filling for 20 hours it will empty in the following 40 hours, after which it will start filling again.

3.4. Settling basin

The settling basins do not contain any purifying processes in the model. This is first of all, because the sedimentation seems to be limited according to a senior employee water system and an area manager, both working for Waterschap Vechtstromen. Because exact data is not available, it is assumed there is no significant decrease in total nitrogen due to sedimentation.

As discussed in Section 2.2.2, the soil in the settling basins is naturally aerated. This process could also remove total nitrogen. There is no available data however to prove this. It is therefore not considered in the model.

3.5. Mixed macrophyte filter

The mixed macrophyte filter is modelled as a FWS constructed wetland filled with an equal mix of emergent macrophytes and submerged macrophytes. Toet et al. (2005) researched the effect of retention time on pollutant removal of the FWS constructed wetland Everstekoog on Texel. Because this research measures performance over time it is possible to plot a trendline of the results which can be implemented in the model. Figure 9 shows the comparison between the trendline and the data retrieved from Toet et al. (2005), on which the trendline is based. Because there are only five data points in the used data, a simple linear trendline is chosen to avoid overfitting. The first part of the trendline is based on the first four data points with which a trendline is determined using excel. This fit has an R^2 value of 0.9621. The second part of the trendline is a flat linear function the data suggests the effect of retention time on total nitrogen decreases as the retention time becomes higher. The flat line has the same total nitrogen concentration value as the last data point from Toet et al. (2005). The data used is based on a practical scenario. This has the advantage all processes occurring in a field of macrophytes are included in the data.

To calculate the reduction in total nitrogen for a time step in the model using the trendline in Figure 9, first, it is determined if the total nitrogen level is higher than 2.25 mg/l. If this is the case, the total nitrogen level will be lowered by taking a step of one hour forward in time. Translating this to the function used in the model, this means determining the x-value based on the total nitrogen value, the y-value, to than calculate the y-value for the next step in time by increasing the determined x-value by 1/24. 1/24 represents one time step forward as this is equal to one hour. For a linear function it is also possible to simply determine the reduction of y when increasing x by 1/24 at any arbitrary point on the line as the reduction is always the same. Calculating the reduction in total nitrogen using the method used however, makes it easy to introduce more complex functions which do return different values for the reduction based on the input value of total nitrogen.

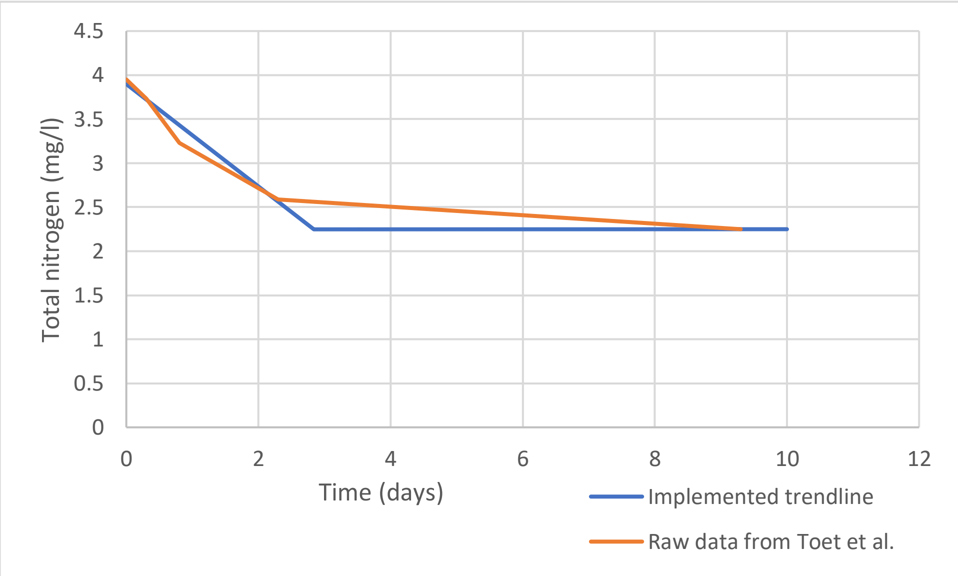

Figure 9: Comparison of data from the research by Toet et al. (2005) and trendline implemented in model

A constant c is introduced in the calculation of the reduction in total nitrogen. This decreases or increases the step forward on the x-axis when determining the new value of total nitrogen. This lowers or increases the effectiveness of the vegetation. This constant is an estimation based on vegetation coverage, vegetation density and presence of short-circuit flows in the basin compared to a basin full of healthy macrophytes. Because this constant cannot be measured, Experts from Waterschap Vechtstromen did an estimation of the constant for each basin based on visuals. This was done partly by experts on location and experts who used pictures and video. The estimation of the experts can be found in Table 3.

Table 3: Type of macrophytes and of c of each basin containing macrophytes estimated by experts

Basin	Type of macrophytes	Constant c
FWS constructed wetland B1	Submerged	0.25
FWS constructed wetland B2	Submerged	0.25
FWS constructed wetland B3	Submerged	0.25
FWS constructed wetland C1	Mixed	0.4
FWS constructed wetland C2	Submerged	0.25
FWS constructed wetland C3	Submerged	0.25

3.6. Submerged macrophyte filter

The submerged macrophyte filter is modelled as a field filled with submerged macrophytes. This is done using data from Zhou et al. (2016) covered in Section 2.3. The change in total nitrogen is modelled using a trend line of the average of the seven species researched. This approach is chosen as it can be applied to a time-based model. The average of seven species is chosen as there are multiple species of submerged macrophytes present in the Kristalbad. Using the average gives the mix of macrophytes in the Kristalbad a more reliable representation of how much total nitrogen the average species of macrophytes removes over time.

The reduction in total nitrogen is calculated using the same method as for the mixed macrophyte filter as is explained in Section 3.5. First, it is determined if the total nitrogen level is higher than 2.4714 mg/l. If this is the case the trendline shown in Figure 10 will be used to calculate the new total nitrogen level. The value of the flat line is the average of the last three data points which are 2.29, 2.6 and 2.53 for 42, 49 and 56 days, respectively. The constant c is also used in this calculation, similar to the mixed macrophyte filter.

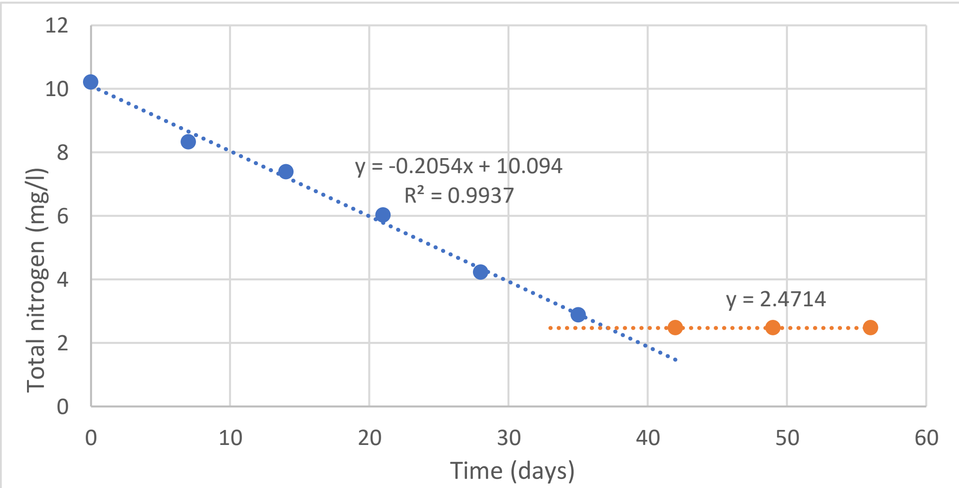

Figure 10: Trend line of decrease in total nitrogen content over time based on data from the research by Zhou et al. (2016)

Like the mixed macrophyte filter, the data used to establish trend is based on measurements of a real system. This means all processes occurring in a field of submerged macrophytes are included in the data.

4. Results

4.1. Cycle time of filling the settling basins

The way the model is currently modelled, the cycle time has no influence on the purifying function of the Kristalbad. This can be seen in Figure 11. A change in the cycle time does not cause a change in the total nitrogen content in the outflow of the Kristalbad. This is most probably not realistic, however. This is further discussed in Section 5.1.

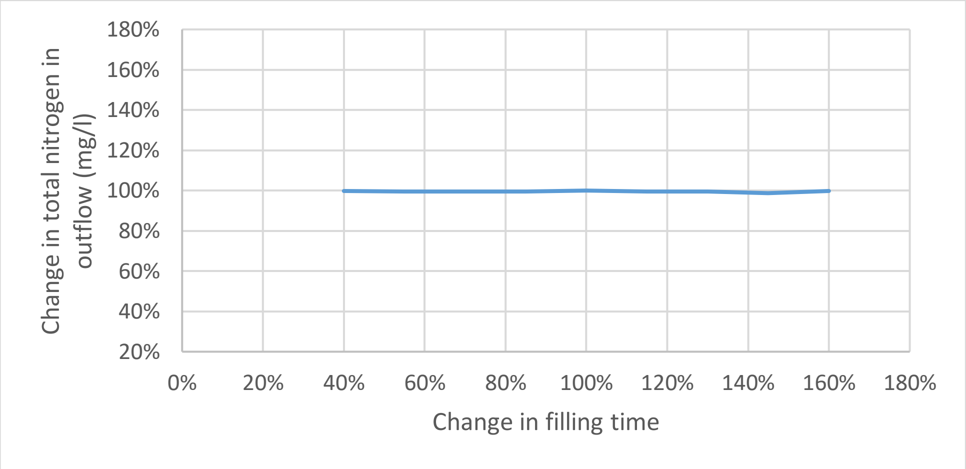

Figure 11: Change in total nitrogen relative to change in filling time

4.2. Macrophyte coverage and type of macrophyte filter in the Kristalbad

Figure 12 shows how much the total nitrogen in the outflow changes relative to the constant c used in the functions for calculating the total nitrogen reduction by macrophytes. This shows the mix of macrophytes is more effective at removing total nitrogen than the basin with only submerged macrophytes. This effect can also be seen in the average total nitrogen concentration of the three FWS constructed wetland basins in column C in Figure 13. basin C1 contains the mix of macrophytes, while basins C2 and C3 do not and basin C1 contains significantly less total nitrogen compared to the other two basins, indicating a mixed macrophyte filter is more effective.

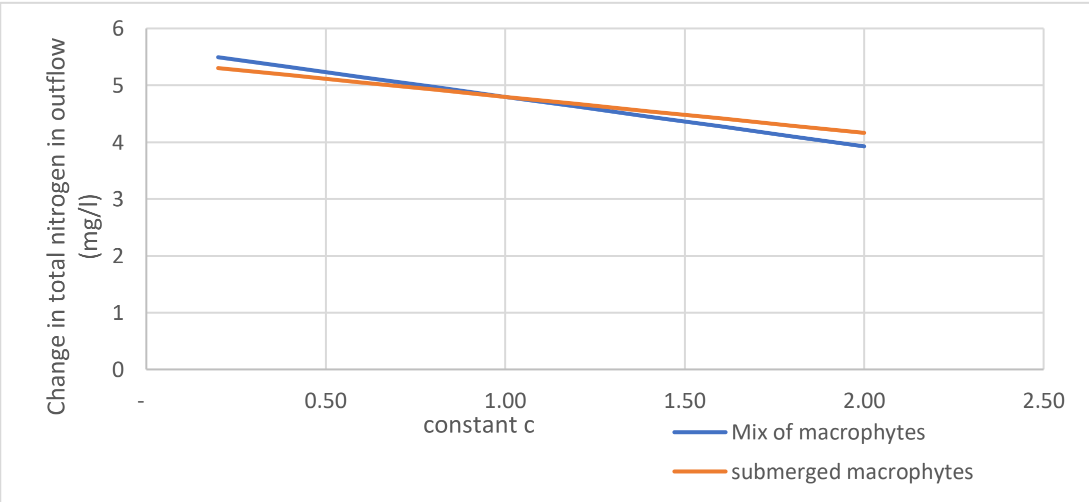

Figure 12: Relation between change in constant c in macrophyte functions and the total nitrogen in the outflow

Figure 13 shows the average concentration of total nitrogen. This makes it clear the settling basins do not have any effect on the total nitrogen concentration as there are no processes affecting the total nitrogen concentration in the model as discussed in Section 3.4. In the FWS constructed wetlands in column B, the total nitrogen concentration is 0.1 mg/l lower being 6.2 mg/l. This is partly due to the submerged macrophytes not being as effective as basins filled with a mix of emergent and submerged macrophytes. It is also caused by the basin not containing as many macrophytes as the constant c for each basin with submerged macrophytes is determined to be 0.25, as established in Section 3.5 and shown in Table 3. The same is the case for basins C2 and C3. Basin C1 however has a significantly higher reduction in total nitrogen as this is reduced to 5.5 mg/l compared 6.1 mg/l and 6.0 mg/l for basins C2 and C3, respectively. This is the case, because basin C1 contains a mix of submerged and emergent macrophytes, which is more effective than just submerged macrophytes. The constant c is also higher for this basin, as can be seen in Table 3. The total nitrogen content in the outflow of the Kristalbad, being 5.9 mg/l, is closer to the concentration basin C2 than in basin C1, because the volume of outflow from basin C2 is higher. This is the case, because the outflow of basin C3 flows into basin C2, instead of flowing out of the Kristalbad directly via the collection point.

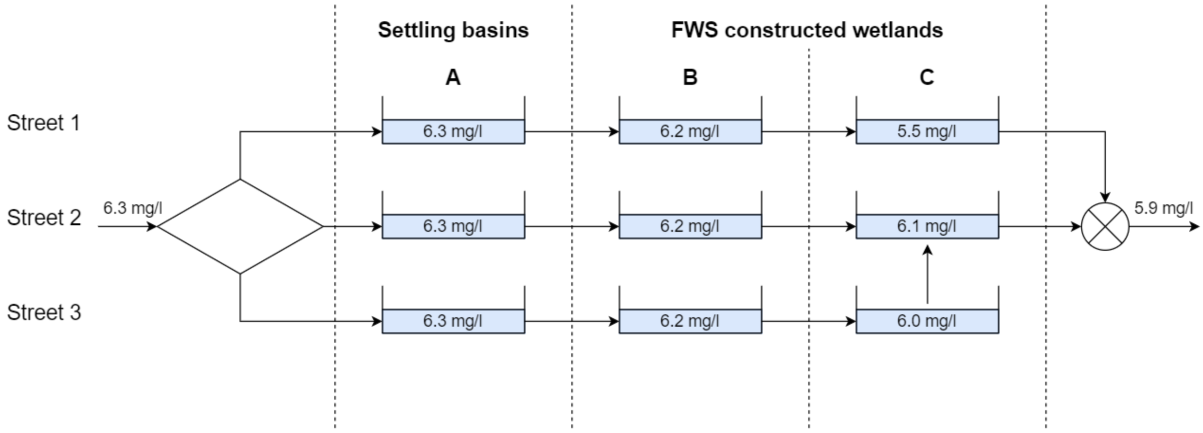

Figure 13: Overview of average total nitrogen concentration the inflow, outflow and each basin in current situation

The total nitrogen concentration in the outflow of the Kristalbad over time is shown in Figure 14. This figure shows the outflow is not constant. Instead, it shows an oscillation, repeating the same pattern every 60 hours after an equilibrium is reached. This is the case, because each 20 hours water flows through different streets in the model, combined with the fact each basin in column C has a different total nitrogen concentration, as can be seen in Figure 13. In the oscillating pattern, the concentration of total nitrogen descends below 5.8 mg/l when water from basin C1 leaves the Kristalbad. This is the case for 40 of the 60 hours in each cycle, because the emptying time of each settling basin is 40 hours, as explained in Section 3.3. The other 20 hours, only basin C2 and C3 are emptying, which have a higher average total nitrogen concentration. This causes the total nitrogen concentration in the outflow of the Kristalbad to be higher.

The first 300 hours show a higher total nitrogen concentration. This can be seen as a warm-up period as the initial total nitrogen concentration of each basin is 6.3 mg/l, equal to the total nitrogen concentration of the inflow.

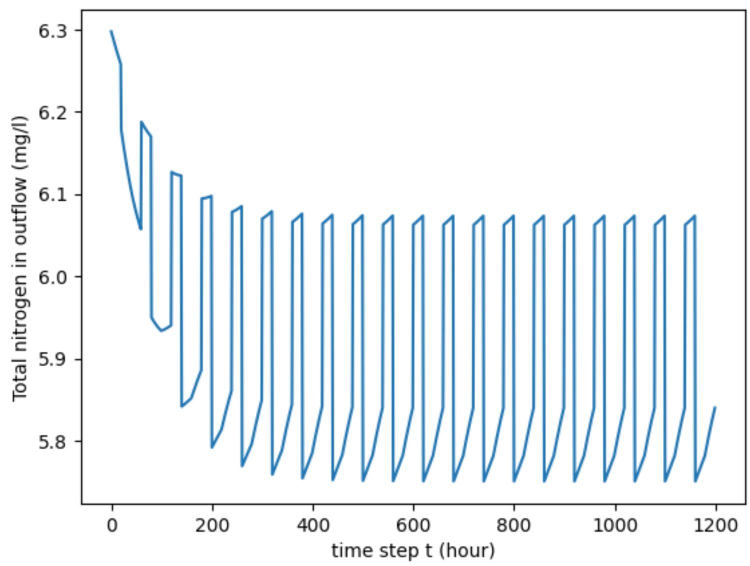

Figure 14: Total nitrogen concentration in outflow of the Kristalbad over time

The difference between the current situation and the optimal situation is measured as well. The model determined in the optimal situation of the design, where each basin is filled with a mix of healthy emergent and submerged macrophytes, the total nitrogen concentration in the outflow of the Kristalbad is reduced from 6.2 mg/l to 3.6 mg/l as is shown in Figure 15. All basins show a lower average total nitrogen concentration compared to the current situation shown in Figure 13, as is expected. basin C1 shows less reduction in total nitrogen concentration compared to the other two basins in column C. This is the case, because in the current situation the quality of the macrophytes is relatively good. This means the quality of the macrophytes changes less as the quality becomes similar in all six basins containing macrophytes.

It is also interesting to note FWS constructed wetland B3 has a significantly lower average total nitrogen concentration compared to the other two basins in the same column. This is the case, because basin B3 is larger, containing 22950 m^3 of water at DWD compared to 12900 m^3 and 13260 m^3 for basin B1 and B2, respectively. This results in basin B3 having a higher retention time, improving the effectiveness of the basin.

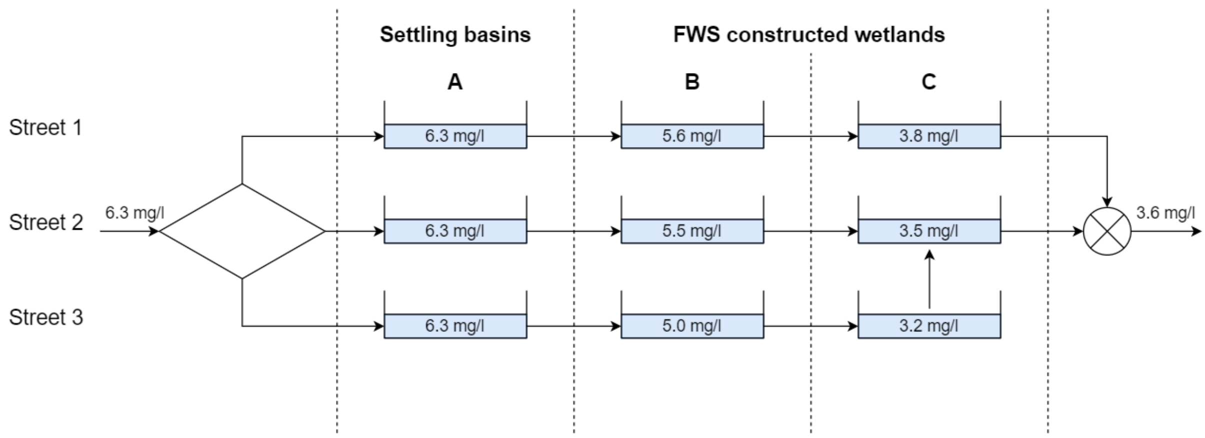

Figure 15: Overview of average total nitrogen concentration the inflow, outflow and each basin in optimal situation

4.3. Effect of resuspension on purifying performance

As discussed in Section 3.4, sedimentation in the Kristalbad seems to be limited. This is, because resuspension only occurs if there is enough sediment to resuspend. Based on the conclusion made by experts in Section 3.4, it can be concluded resuspension does not have a significant impact on the purifying performance.

4.4. Sensitivity analysis

A sensitivity has been conducted on the four main input parameters of the model. These are the constant c for the mixed macrophytes function and the submerged macrophytes formula, the total nitrogen in the inflow, the amount of inflow into the Kristalbad and the filling time of a settling basin. For these parameters it is determined how much a change in the input parameter influences the total nitrogen in the outflow of the Kristalbad. The results can be seen in Figure 16.

A comparison between the functions of a mix of macrophytes and the submerged macrophytes illustrates well how the two compare. For example, when lowering c from 1 to 0.6 for both functions the total nitrogen in the outflow increases with 7 percent for the mixed macrophytes while for the submerged macrophytes this is 5 percent. This is further discussed in Section 4.2. The other two parameters, the amount of inflow and the total nitrogen in the inflow are much more impactful, however. Especially the total nitrogen in the inflow has a large impact on the total nitrogen concentration in the outflow. It is important these two parameters are correct. The data on the amount of inflow is very reliable. The inflow of the Kristalbad originates from the wastewater treatment plant nearby. This plant measures the amount of inflow which can be used as input for the model. The total nitrogen in the inflow is a reasonably reliable value as it based on measurements taken in a period of eight months. The filling time of the settling basins has no effect on the change in total nitrogen, as is discussed in Section 4.1.

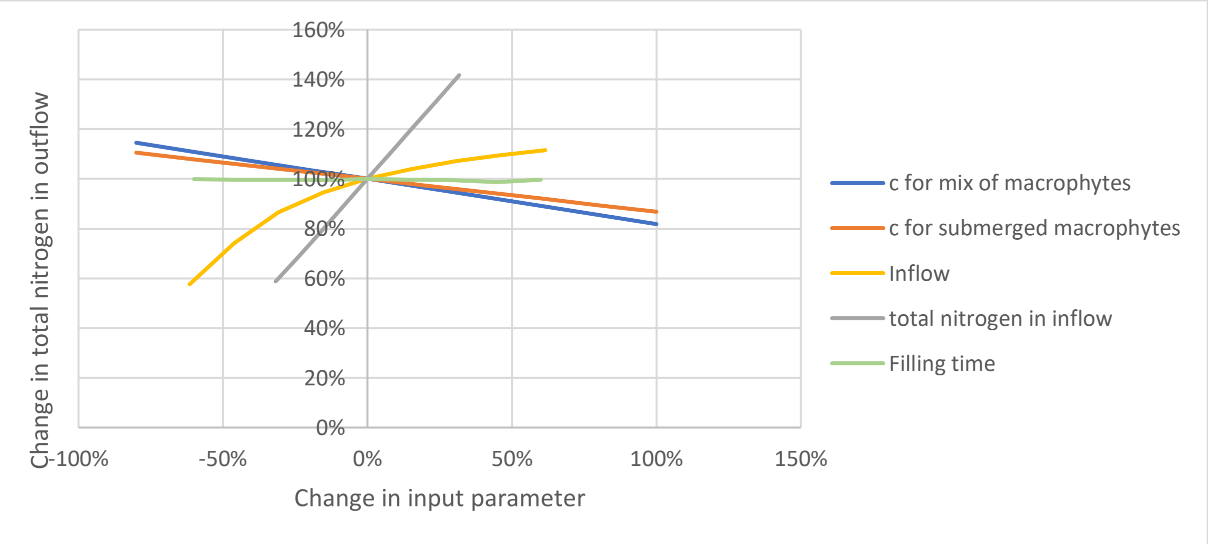

Figure 16: Sensitivity analysis of five input parameters

4.5. Validation of the model

4.5.1. Historical data validation

For historical data validation, there are two sets of data available. The first is from July 2012 until June 2014. This data is not representable, because the Kristalbad project was not fully completed at that point. In addition, the vegetation needs one to two years to develop before functioning optimally (Van de Weerd, 2014). The second set of data is from March 2020 until December 2020. Despite this not being a period of at least a year, the measurements are recent enough to declare them as representative for the current situation.

The average total nitrogen measured in the period from March until December 2020 in the outflow of the Kristalbad is 5.2 mg/l, with the inflow being 6.3 mg/l. This is a reduction of 17 percent. In the model the inflow is set to 6.3 mg/l as well. Using the estimate of the experts of the current situation given in Table 3 as input parameters, the resulting average outflow is 5.9 mg/l. This is a reduction of 6 percent. Compared to the estimation of the experts of the current situation, the actual total nitrogen reduction is 11 percent higher. This could be, because the experts underestimated the performance of the vegetation. Alternatively, it could be the case other processes like nitrification and denitrification in the first set of basins bridges the gap in total nitrogen reduction as discussed in Section 2.2.2. Both could be the case simultaneously as well.

4.5.2. Operational graphics analysis with experts

The second part of the validation process consists of showing the figures the model generates and getting the opinion of experts on the way the model is constructed. Four experts, two with a background in ecology and two with a background in hydrology, have been consulted.

Before going into the operational graphics, the correctness of the design of the model was discussed shortly. The experts all concluded the model is similar to the conceptual model, which is shown in Figure 8 and is in line with the actual situation of the Kristalbad.

The first point the experts noticed is the average value of total nitrogen in the outflow being in an accurate range. This could be a realistic value. A note is made only the average value can be used as the model does not consider any seasonal fluctuations or a day-night cycle.

Second, the experts commented several processes are missing in the model. For example, sedimentation, resuspension and the influence of rainfall and evaporation are not included in the model. This makes the model less realistic.

Third, the way the Kristalbad is set up and how the total nitrogen removal is modelled seems to be correct. This could give a representative view of how the Kristalbad functions.

Fourth, the fact a mix of macrophytes is more effective at total nitrogen removal compared to only submerged macrophytes seems logical. This is, because it is consistent with the idea in ecology a more biodiverse system is better.

Fifth, there is some uncertainty in determining the constant in the macrophytes functions. There is no calculation based on for example the amount of area covered by vegetation and the density of vegetation to determine this constant. It currently just is an estimation which can lead to inaccuracies.

Sixth, the inflow of the Kristalbad is not constant. In fact, there is a standard cycle the wastewater treatment plant goes through each day due to human behaviour. A difference in the amount of inflow could influence the effectivity of the purifying function. This behaviour should fade away as the water moves through the different basins, because of diffusion.

4.6. Experiences from a water harmonica expert

During the summer months, it often occurs floating algae grow in a FWS constructed wetland. This needs to be removed if it covers too much of a basin. A senior advisor at Waterschap de Dommel, advises to remove floating algae once it covers more than 50 percent of the basin. This will probably result in having to remove it twice every year during the summer period according to the senior advisor.

Apart from technical improvements, the senior advisor of Waterschap de Dommel stresses the importance of proper management, a clear division of tasks and a person or department responsible for the water harmonica as this can achieve large improvements to the functioning of the water harmonica. Giving a person or department the final responsibility over the water harmonica, including its purifying performance, makes sure the water harmonica is looked after better. If any problems arise, people know who to approach and from there problems can be handled properly. This ensures the person or department managing the water harmonica has the knowledge to do so effectively and any experience gained will not be lost. In addition, a regular check on the water harmonica could make sure any issues which might arise are noted in time. For example, a weekly check could avoid issues getting out of hand.

5. Discussion

5.1. Influence of filling cycle time on total nitrogen removal

The model does not consider any processes taking place in the first set of basins. It is likely the case the first set of basins does influence the purifying function of the Kristalbad. This could first of all be the case due to nitrification and denitrification in the soil. As discussed in Section 2.2.2, the aeration cycle the first basins go through could remove a significant amount of total nitrogen. If this is the case, the removal of total nitrogen is underestimated by the model.

5.2. Sedimentation

Currently there is no clear insight in how much sedimentation is present in the Kristalbad and how much this increases or decreases each year. Waterschap Vechtstromen is working on a monitoring program in which it will measure the amount of sediment over a period of time to get insight in how sediment is present and how much the amount of sediment increases or decreases. The part of the Elsbeek, upstream of the Kristalbad might also have an influence on the amount of sediment as sedimentation already takes place in the Elsbeek. This has a positive effect on the quality of the influent of the Kristalbad.

5.3. Quality of used data

As discussed in Section 3.2, it is assumed the data from the papers by Toet et al. (2005) and Zhou et al. (2016) also applies to the context of the Kristalbad. This might not be the case, however. The data from Toet et al. (2005) is measured in the water harmonica Everstekoog, which is also located in the Netherlands, meaning there is a comparable climate. In addition, the Everstekoog water harmonica has a comparable quality of the influent as this also originates from a wastewater treatment plant. There could still be a difference in the actual performance of a mix of emergent and submerged macrophytes compared to the performance measured at Everstekoog. This could for example be, because the layout of Everstekoog is not the same as the Kristalbad or because this water harmonica is closer to the sea. There are many factors which could be a cause for a different purifying performance of macrophytes. This could be a cause for under- or overestimating the performance of the mix of emergent and submerged macrophytes.

For the research by Zhou et al. (2016) the situation is more different. Experimental tanks are used, instead of a water harmonica. The temperature during the measurements ranges from 19 to 23°C and the pH is between 6 and 9. This does resemble an early summer day and could be seen as a comparable situation with regards to pH and temperature. Because the research is conducted in Beijing, it is probable the climate does differ in other regards like soil composition and humidity. The experimental tanks and the different climate might be a cause why the performance of submerged macrophytes is under- or overestimated.

A better approach to designing a model of Kristalbad would be using detailed measurement data of the Kristalbad itself from which a stochastic model could be made. This makes the model significantly more accurate and can give a range in which the quality of the effluent will be by doing a Monte Carlo simulation and finding the confidence interval of the total nitrogen concentration in the basins and effluent of the Kristalbad instead of an exact value. To have a representative data set it is advisable to have it at least cover a year, to be able to simulate all seasons and calculate averages over a full year. Gathering data of multiple years would make the averages more reliable and makes it possible to compare different years in the model.

5.4. Lack of technical knowledge about FWS fill-and-drain constructed wetlands

In literature there is no information available about the settling basins in column A of the Kristalbad. It is therefore impossible to implement the processes occurring in the basins in column A in the model. Research needs to be done on the effect of these basins to be able to implement this in the model and draw conclusions from it.

5.5. Calibration of the model

The model has not been calibrated to match the measurements of the Kristalbad. This is done on purpose as not all processes having a significant impact are modelled due to a lack of data from measurements or literature. Calibration could result in overfitting and giving un unrealistic view of how the vegetation performs in the model. To fill the gap between the measured data and the model, processes having a significant impact on the purifying effect need to be included in the model. Only after this is done, calibration could be beneficial to the accuracy of the model.

5.6. Influence of sewer overflow on purifying performance

Because the sewer overflow flows into the Kristalbad around once each year, the purifying performance of the Kristalbad could be impacted. The wastewater contains more suspended particles, increasing sedimentation in the Kristalbad and the bad quality and high flow rate of the wastewater could hurt the vegetation. Sewer overflow events are not modelled in this study.

6. Conclusions and Recommendations

6.1. Conclusions

6.1.1. How can the water purifying processes in the Kristalbad be translated into a model?

This is done by designing a model in the Python programming language. A time-based model is designed and data from literature is used to model the purifying processes occurring in the Kristalbad. The exact design of the model is explained in Chapter 3.

6.1.2. How does the cycle time of filling the settling basins affect the purifying effect?

In the model, the cycle time of filling the first set of basins does not affect the purifying performance of the Kristalbad. This can be seen in Figure 11. This is probably not a realistic representation of reality, as is discussed in Section 5.1. It is necessary to do research by doing measurements of the total nitrogen concentration in the first set of basins of the Kristalbad for different cycle times to get an understanding of the effect of the cycle time of filling the basins on the purifying performance.

The cycle time of filling the settling basins could also have an influence on sedimentation in the settling basins. Currently there is not enough knowledge to make conclusions and give good recommendations on the effect of sedimentation on the purifying performance of the Kristalbad. Based on the results of the sediment monitoring program planned by Waterschap Vechtstromen, discussed in Section 5.2, it should be possible to get insight in this. Based on the outcome of the monitoring program, a recommendation should be made on whether it is necessary to dredge the Kristalbad and if so, how often this should happen.

6.1.3. How does the surface area and type of the aquatic plant filter affect the purifying effect?

Increasing the amount of vegetation improves total nitrogen removal in the Kristalbad. Planting vegetation to fill the second and third column of basins with a mix of emergent and submerged macrophytes can reduce the total nitrogen with a 3.6 mg/l total nitrogen, instead of 5.9 mg/l in the current modelled situation. This improves the total nitrogen concentration reduction from 6% to 43%, according to the model.

A mix of emergent and submerged macrophytes is better than only submerged macrophytes. Not only does it perform better, as is shown in Section 4.2, but it is also more resilient as explained in Section 2.2.1. This makes it more likely the system can handle peak discharge during a heavy rainfall event in which the Kristalbad functions as a buffer.

6.1.4. What lessons can be learned from literature and other water harmonicas?

From literature, it can be concluded the water level should be between 10 and 15 cm to create an optimal situation for the growth of emergent macrophytes, as discussed in Section 2.2.1.

Responsibility of the Kristalbad should be handed to one person or department. This improves the management of the Kristalbad, decreasing the overall impact of issues which might arise in the Kristalbad. This is discussed in Section 4.6.

6.2. Recommendations

6.2.1. Vegetation and water level

A core principle of a constructed wetlands is the use of macrophytes to purify water. Emergent macrophytes however have difficulty growing in the Kristalbad, as is briefly discussed in in Section 1.3.4. As stated in the literature study in Section 2.2.1, emergent macrophytes require water levels of no higher than 15 cm during the second half of spring and the first half of the summer to spread properly. It is necessary to lower the water height to enable reed to develop and spread properly. To achieve a lower water level, weirs could for example be installed at the outflow point of the Kristalbad or at the outflow point of basin C1 and C2 which can be used to manually lower the water level. During the period in which the emergent macrophytes spread, the water level could be lowered to support this process. Another solution could be heightening the strips on which reed is supposed to grow, effectively lowering the water level for reed. These two, and other solutions should be explored to lower the water level without impacting the buffering capacity of the Kristalbad. Advantages and disadvantages of each intervention should be explored to see if this could improve the performance of the Kristalbad without impacting the buffering capacity.

6.2.2. Measure purifying performance of the Kristalbad

Currently no data is gathered on the purifying performance of the Kristalbad. This has been done twice in the past, but only at the inlet and outlet of the Kristalbad. By doing measurements at the inlet and outlet of each basin, the performance of each basin can be monitored separately. This gives the opportunity to compare basins which could indicate a basin is not function as well as similar basins in the other streets. It also makes it possible to experiment with interventions in one basin to see if it is effective using the other two streets as benchmarks. This makes it easier to maintain and improve the purifying function. This recommendation is based on the process of designing the model, in which it became apparent there is little knowledge available about the purifying performance of the Kristalbad. In addition, measuring the performance of each basin allows research to be done on the basins in column A, the settling basins. The aeration cycle could prove effective at purifying water, but this is currently unknown. Research on the performance of the basins in column A should be conducted to get insight in the effect of this innovative design.

By installing continuous measuring devices for a select group of key performance indicators, it also is possible to get insight in how the Kristalbad performs throughout a day. This gives insight in how well the Kristalbad performs during daytime and night-time and gives insight in the difference. In addition, this gives insight in how the Kristalbad reacts to the cycle the wastewater treatment plant goes through each, which is mentioned in Section 4.5.2. Continuous measuring could also give insight in the performance during different types of extreme weather events like extended periods of drought or an extreme rainfall event in which sewer water directly goes into the Kristalbad without going through the wastewater treatment plant first.

6.2.3. Maintenance

As discussed in Section 1.4.3, floating algae can be a problem. A senior advisor of Waterschap de Dommel advises to remove floating algae when it covers more than 50 percent of a basin. This will result in removing it around twice a year, as discussed in Section 4.6. A weekly check on the Kristalbad is also advised, as this makes sure any issues are noted in time.

6.2.4. Operations management

The Kristalbad is a system which is in a grey area between the two departments Watersysteem and Waterketen of Waterschap Vechtstromen, making it unclear who is responsible for the Kristalbad. The senior advisor at Waterschap de Dommel advises to make a person or department responsible for the Kristalbad, as is discussed in Section 4.6. This makes sure issues are dealt with better and faster. In addition, people know where to go to with any issues regarding the Kristalbad, improving how fast and how well problems are dealt with.

6.2.5. Determining goals

Currently, there are no clear performance indicators for the Kristalbad. Prioritising certain water quality indicators over others and setting limits to how high this should be at a maximum could make interventions and maintenance more effective as this is done with a clear goal. This became apparent when designing the model, as there were no clear targets for the purifying performance. In addition, the goals of the Kristalbad and the wastewater treatment plant should be aligned, as they are part of one system. The wastewater treatment plant could for example focus more on reducing the number of metals and medicines in water, while the Kristalbad focusses on reducing the concentration of total nitrogen and total phosphorus. Viewing the two systems as one can improve the purifying efficiency of the combined system. In addition, it might make it possible to find more cost-efficient solutions as there are more configurations and therefore more solutions available.

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Appendix A: Overview of involved parties

Waterschap Vechtstromen

Waterschap Vechtstromen is a Dutch water board since 2014, after the fusion of the water boards of 'Velt and Vecht' and 'Regge en Dinkel'. Water boards are responsible for regulating groundwater levels, treating wastewater, managing dikes, maintaining nature in and around water and maintaining and controlling swim water quality (Rijksoverheid, n.d.). Waterschap Vechtstromen has the responsibility of 23 wastewater treatment plants, maintains 3700 kilometres of streams and ditches, maintains the groundwater level in the entire area and works on a safe living environment with regards to water (Waterschap Vechtstromen, 2021b).

The Kristalbad was an idea by Waterschap Regge en Dinkel to improve not only the protection from floods, but also the water quality in the region. Waterschap Regge en Dinkel, together with the company Eelerwoude, designed the Kristalbad to achieve these goals.

Waterschap Vechtstromen is still actively working on water quality in the region around Enschede and Hengelo. To get an understanding of the current water quality in the Elsbeek, it has done measurements after the construction of the Kristalbad and again in 2020. This research is an initiative of Waterschap Vechtstromen to get an insight in how the various biological and chemical processes in the Kristalbad exactly work and how these could be improved.

Municipality of Hengelo

The municipality of Hengelo had multiple reasons to support the project. Hengelo regularly struggled with floods after heavy rainfall events. To reduce this, a retention area was to be constructed which became the Kristalbad. Next to this, there were reports of an unpleasant smell of the Elsbeek, despite meeting legal water quality standards. This was addressed by applying the Kristalbad as a natural water purifier.

Municipality of Enschede

Despite not directly improving the water safety in Enschede, the Kristalbad still has the city a lot to offer. The municipality of Enschede is mainly interested in the ecological and recreational aspects. The Kristalbad establishes an ecological corridor between Driene and Twekkelo, improving the possibilities for nature to flourish in the north of Enschede. On both sides of the Kristalbad, two watchtowers are placed for tourists to have a pleasant view of the area. This area also connects the Twekkelo, Hengelo and Enschede for hikers.

Province of Overijssel

One of the responsibilities of Dutch provinces is to maintain and expand nature areas and allocate areas within the province for nature. In this context this means the province has the final say in the construction of the Kristalbad. The province of Overijssel itself is mainly concerned with the Kristalbad as a nature and recreational area as they write on their website. The website explains it is an important hiking area in the region, being part of 'Rondje Enschede', an initiative to have a ring of hiking areas around the city of Enschede (Provincie Overijssel, 2021).

Landschap Overijssel

Landschap Overijssel is tasked with maintenance of the Kristalbad. They mainly maintain the nature and walking paths in the area, but have not touched the basins, apart from mowing the water plants once in 2014 to resolve a blockage. Landschap Overijssel also manages the filling cycle of the settling basins.