Investigating water quality improvement options in lake Volkerak

An area-specific analysis of the effectiveness of wetlands and floodplains

By

C.P. Janse

June 10th, 2021

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Final Thesis

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PREFACE

Before you lies the dissertation ''Investigating water quality improvement options in lake Volkerak – An area-specific analysis of the effectiveness of wetlands and floodplains''. It has been written to fulfill the graduation requirements of the Watermanagement course at HZ University of Applied Sciences. I was engaged in conducting the research and writing this report from February to June 2021.

The research was initiated at the request of ARK Natuurontwikkeling, where I undertook an internship. The basis of this research is to conduct research on the effectiveness of wetlands and floodplains on nutrient removal, the effects on local biology and investigating area-specific locations suitable for potential developments. This project is can be considered rather future-oriented and conceptual, but with the right tools and help from my supervisors Leo Linnartz and Gijs van Zonneveld, I was able to answer the questions that were identified.

Firstly, I would like to thank my in-company supervisors Leo Linnartz and Gijs van Zonneveld for providing me with the research project and guidance throughout the research period. I also would like to thank Gwenaël Hanon, who was involved in progress meetings and provided me with some valuable advice. I also would like to thank other numerous people that have been involved in completing this dissertation. Your help benefited me in various ways and all your different areas of expertise enabled me to see certain topics from a different point of view.

I am excited to implement the knowledge that I gained during this internship into my future professional career. I am also curious to see to what extent the proposed measures will be carried out in the future.

I hope you enjoy reading this report.

Coen Janse

Poortvliet, June 10th, 2021

ABSTRACT

Ever since lake Volkerak got its status as a partially closed-off lake in the late '80s, excessive (cyanobacterial) algae blooms in the summer period have been a consistently occurring problem.

This research aims to investigate the location-specific effectiveness of wetlands and floodplains in nutrient removal. By developing these natural areas in the areas upstream of lake Volkerak, nutrients are partially removed, resulting in a decrease in frequency and intensity of algae blooms.

Wetlands and floodplains are known for their provision of various ecosystem services. This makes them an excellent choice for implementation, as they utilize natural processes and are capable of providing various benefits to plants and animals living in the area. Nutrients in these natural areas can be removed in various ways, including plant uptake and soil accretion. Factors such as plant species and abundance, oxygen availability and water retention time may affect the efficiency of nutrient removal.

Wetland and floodplain design types are analyzed and put into context of the specific research area. The resulting locations of interest are summarized in chapter 4 – Results. The selection of these locations is based on morphological and hydrological characteristics, elevation levels, proximity to the main river and presence of existing natural features. Analyses of nutrient concentrations, a nutrient balance and water levels provide more supporting theoretical context and are used for location selection.

The resulting thirteen locations and areas of interest in chapter 4 provide the basis for future similar research. Along the river *Steenbergse Vliet*, a total of six locations are assigned. In the river system *Mark-Dintel*, a total of six locations are assigned as well. Directly adjacent to lake Volkerak, one location is assigned in close proximity to the *Hollands Diep*.

The information and conclusions that are provided in this report can be used for the potential realization of the project in the near future. It is expected that the total surface area of the thirteen described locations is insufficient to reach the desired nutrient removal. Nevertheless, the proposed developments in these areas can contribute to habitat provision, various ecosystem services and (local) water quality improvements.

Future similar research should aim to focus on the expected effects of the proposed developments on biological and ecological aspects of the area, taking into account the area-specific characteristics.

SAMENVATTING

Sinds het Volkerak eind jaren '80 de status kreeg als gedeeltelijk afgesloten meer zijn perioden met hevige (blauw)algenbloei in de zomermaanden een consistent voorkomend probleem.

Dit rapport onderzoekt de locatiespecifieke effectiviteit van doorstroommoerassen en vloedvlaktes op het verwijderen van nutriënten. Door deze natuurlijke gebieden aan te leggen in de bovenstroomse gebieden van het Volkerak kunnen deze nutriënten gedeeltelijk verwijderd worden, wat resulteert in een vermindering in frequentie en intensiteit van perioden met algenbloei.

Doorstroommoerassen en vloedvlaktes staan bekend om hun verscheidene ecosysteemdiensten. Dit maakt deze gebiedstypen bijzonder geschikt als keuze voor ontwikkeling, omdat ze natuurlijke processen gebruiken en ze verscheidene voordelen bieden aan plant- en diersoorten die in het gebied leven. Nutriënten in deze gebieden kunnen verwijderd worden op verschillende manieren, onder andere opname door planten en bodemafzetting. Factoren als gebruikte plantensoorten en hoeveelheid planten, zuurstofbeschikbaarheid en waterretentietijd kunnen de effectiviteit van nutriëntenopname beïnvloeden.

Designtypes van doorstroommoerassen en vloedvlaktes zijn geanalyseerd en in de context van het specifieke onderzoeksgebied geplaatst. De resulterende locaties zijn samengevat in hoofdstuk 4 – Resultaten. De achterliggende keuze van deze locaties is gebaseerd op morfologische en hydrologische kenmerken, hoogteligging, afstand tot de rivier en de aanwezigheid van bestaande natuurlijke kenmerken. Analyses van nutriëntenconcentraties, een nutriëntenbalans en waterhoogtes geven meer theoretische context en zijn gebruikt voor het kiezen van de geschikte locaties.

De resulterende dertien locaties, beschreven in hoofdstuk 4, vormen de basis voor verder toekomstig gelijkwaardig onderzoek. Langs de rivier *Steenbergse Vliet* zijn zes locaties aangewezen. In het riviersysteem *Mark-Dintel* zijn ook zes locaties aangewezen. Direct aangrenzend aan het Volkerak is één locatie aangewezen, dichtbij het *Hollands Diep*.

De informatie en de conclusies die dit rapport bieden worden gebruikt voor de potentiële realisatie van het project in de nabije toekomst. Het totale areaal van de beschreven dertien locaties is waarschijnlijk te klein om de gewenste nutriëntenreductie te bereiken. Desalniettemin kunnen de voorgestelde ontwikkelingen op deze locaties nuttig bijdragen aan habitatvoorziening, verschillende ecosysteemdiensten en lokale toename in waterkwaliteit.

Het wordt aangeraden dat toekomstig gelijkwaardig onderzoek zich richt op de effecten van de voorgestelde ontwikkelingen op biologische en ecologische aspecten van het gebied, waarbij rekening wordt gehouden gebiedsspecifieke kenmerken.

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Photo front page: Volkerak near Dinteloord (RWS Beeldbank, 2014)

GLOSSARY

English	Dutch	Definition
Affluents	Zijrivieren	Secondary river channels
Bifurcations	Vertakkingen	Morphological characteristic formed when a single stream separates into two or more separate streams
Buffer-strip	Faunarand	Area of land maintained in (permanent) vegetation, found between the river and (agricultural) land
Carrs	Broekbossen	Type of waterlogged area, representing a succession stage between the original wetland and the formation of forest
Cyanobacterial algae	Blauwalgen	Type of algae that are found to be toxic and are capable of causing damage to living organisms
Drainage-tiles	Drainagebuizen	Drainage system that redirects excess water from (agricultural) soil to other nearby areas
Ecosystem services	Ecosysteemdiensten	The benefits organisms obtain from ecosystems, including provisioning, regulating, cultural and recreational services
Eurytope fish	Eurytope vissen	Fish species with a wide ecological preferred range that are not dependent on a specific water type
Floodplain	Vloedvlakte	Area of land adjacent to a river, which is subject to periodic inundations due to high water levels or high discharge, typically serving as a spawning ground of various fish species. The water retention time in a floodplain in the context of this report is longer than the water retention time in a wetland
GEP	Goed Ecologisch Potentieel	Ecological goal relevant for strongly altered/modified water bodies
Inundations	Overstromingen	Floodings
Limnophilic fish	Limnofiele vissen	Fish species that prefer stagnant water with rich vegetation
Lock complex	Sluizencomplex	Complex of locks that can initiate or stop the inflow and outflow of water to another waterbody
Macrophytes	Waterplanten	Plants found (partially) living in the water
Rheophilic fish	Rheofiele vissen	Fish species that prefer (fast-)flowing water
Rhizosphere	Rhizosfeer	Portion of the soil around the roots of living plants
Riparian zone	Riparische zone	The area between the river and the land
Wetland	Doorstroommoeras	Area that is subject to periodic inundations that allows the flowthrough of water, capable of partially removing nutrients

1. INTRODUCTION

The following chapters 1.1 to 1.4 give an overview of the project area and its history, the issues that it is facing and the objective and research questions of this research.

1.1 AREA DESCRIPTION

The project area that is covered in this research has an extent of approximately 63 km², including the low-elevated grasslands near the shores that are subject to periodic flooding.

The project area is situated in the southwestern delta area in the Netherlands. It borders the *Hollands Diep* to the north-east and the *Grevelingenmeer* and the Eastern Scheldt on the west. Lake *Volkerak* is considered to be a partially closed-off lake, with the *Grevelingendam* and the *Philipsdam* on the west side and the *Volkerakdam* on the east side. It is connected to the *Zoommeer* to the south by the *Schelde-Rijnkanaal*, which serves as a shipping route.

The area that consists of the Volkerak and the Zoommeer is referred to as the *Volkerak-Zoommeer*. Figure 1 below gives an overview of this area. The area that will be focused on in this report consists of the northern part of this area, which is referred to as lake Volkerak.

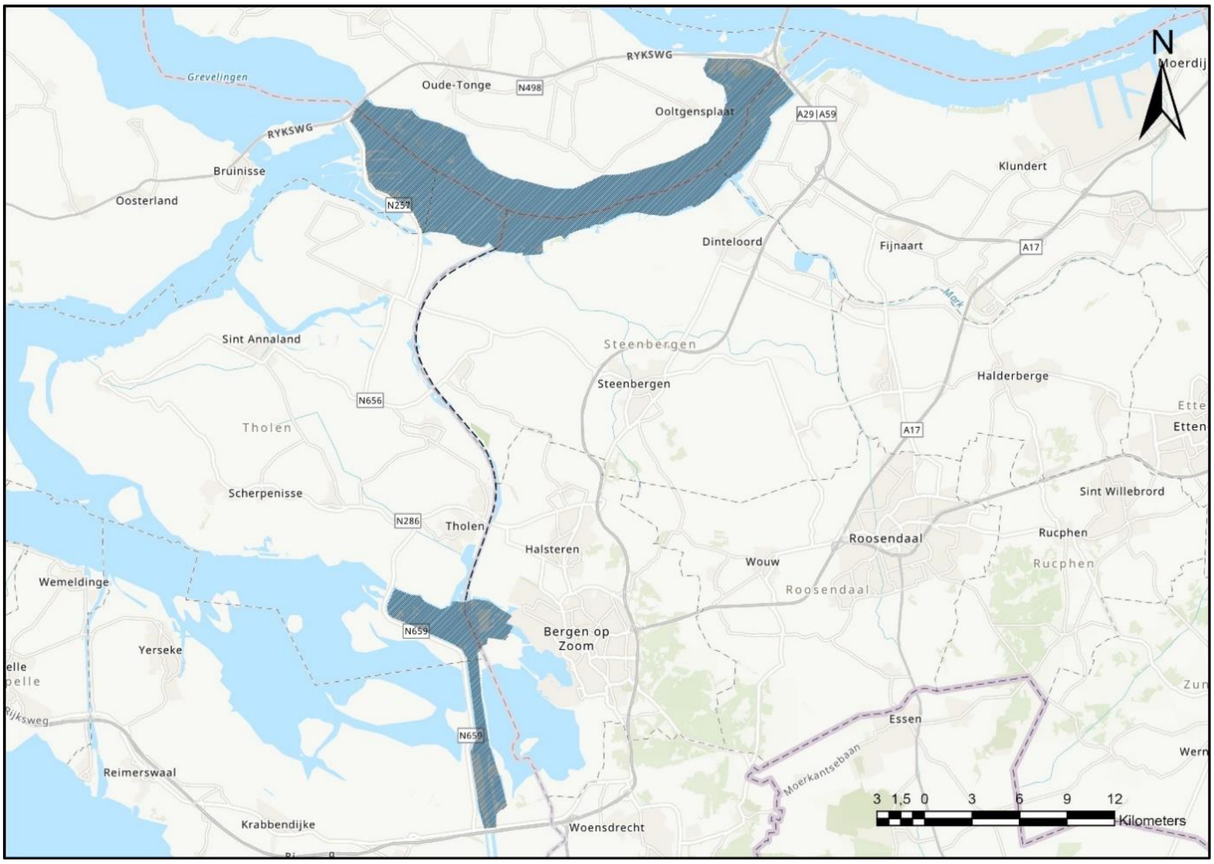

Figure 1. Overview of the location of the Volkerak-Zoommeer in the southwestern delta area in the Netherlands. (Own source, map created in ArcGIS)

A series of lock complexes, the *Krammersluizen* and the *Volkeraksluizen*, the latter referred to in this report as the Volkerak lock complex, play a role in supplying and discharging water to and from lake Volkerak. Water from the Volkerak is discharged via the *Bathse Spuisluis* to the Western Scheldt when the water level in lake Volkerak exceeds +0,15 m NAP. When the water level exceeds +0,50 m NAP, water is also discharged to the Eastern Scheldt via the Krammersluizen. When the water level in lake Volkerak is lower than -0,10 m NAP and/or when the salinity of lake Volkerak exceeds 450 mg Cl/l, water from the Hollands Diep, having an average salinity of 50 mg Cl/l, is discharged into lake Volkerak by the Volkerak lock complex. These measures ensure that there is a balance in water level and salinity (Planviewer, n.d.). The role of the Volkerak lock complex in nutrient inflow is discussed in chapter 2.2 – Nutrient inflow.

Current salinity values in lake Volkerak range from 200 to 400 mg Cl/l. Highest values are found in the south of the Zoommeer, due to saltwater leakage from the *Bergse Diepsluis*, on the border with the Eastern Scheldt. Up to 1994, at depths under -18 m NAP, salinity values of up to 10.000 mg/l were recorded. The extent of this stratification has now slightly decreased, but stratification of salinity gradients still occurs (Tosserams, Lammens, & Platteeuw, 2000).

According to these salinity values, lake Volkerak can be considered to be a moderately freshwater lake. Consistency in salinity values is important for irrigation of agricultural land. For example, the municipality *Tholen* (bordering the province of *Noord-Brabant*), pumps water from the Schelde-Rijnkanaal into its polders, where the water with relative low salinity values can be used for irrigation purposes. It is evident that this water needs to have a low salinity to ensure that no crops are damaged and the agricultural soils do not become saline over time (De Vries & Postma, 2013).

Most of the areas located within a radius of approximately 100 m within the river are characterized by relatively high elevation levels. This steep elevation gradient makes it challenging to initiate any natural developments of wetlands and floodplains, as this would require a less steep gradient between the water level in the river and the elevation of the surrounding land. The development of this morphological characteristic dates back to the time when the dikes were not present and the areas were subject to periodic flooding. During each flood, a layer of clay was deposited, resulting in a slow but steady increase of elevation levels. After land reclamation, this process was halted and the soil slowly subsided.

South of the city *Breda*, the river banks are characterized by a lower elevation, as inland dikes are not as abundant, resulting in lower elevated areas near the river Mark. The river here is characterized by smaller meanders and a smaller channel width, potentially enabling more natural developments.

1.1.1 Biology

The marshes near the shores of lake Volkerak have a total surface area of approximately 17 km^2. These marshes host a variety of bird species.

The desalinization of lake Volkerak resulted in an increase of population of water plant-eating bird species such as the *greylag goose* (*grauwe gans)* and the *common coot* (*meerkoet)* (Tosserams, Vulink, & Coops, 1999). In addition to that, the marshes and sparsely overgrown sandbanks temporarily served as a very important nesting area for bird species such as the *common ringed plover* (*bontbekplevier*), *Kentish plover* (*strandplevier*) and *pied avocet* (*kluut*). After that, the water quality deteriorated and cyanobacterial algae blooms started to dominate.

Nowadays, the overall breeding success of these bird species is low, as most of these areas are now characterized by more vegetation and the water has lower salinity levels. Currently, *quagga mussels* consume most of the algae and the water quality has started to improve again. As a result, large areas of submerged water plants started growing and attracted young fish and many birds (Natura 2000, n.d.).

Lake Volkerak is home to a variety of fish species. Most commonly found are the *common perch* (*baars*), the *European eel* (*paling*) and the *zander* (*snoekbaars*). These eurytope species are known to have no specific favorite habitat and can live and breed in a variety of different habitats (De Vries & Postma, 2013). Investigation by the waterboard *Brabantse Delta* in the rivers upstream of lake Volkerak (the Mark-Vliet river system) concluded that the species *common perch* (*baars*), *common bream* (*brasem*) and *common roach* (*blankvoorn*) are most common in this river system in the years 2006 to 2019. A complete overview of documented fish species is shown in Appendix I.

Additional data from the waterboard Brabantse Delta indicates that most common plant species around lake Volkerak are *common reed* (*echt riet*), *great manna grass* (*liesgras*) and *reed canary grass* (*rietgras*), based on the period 2016 to 2019. Other species include various riparian plant species, most notably the species *yellow flag* (*gele lis*) which is known for its water-purifying capabilities. Most water plant species are found submerged in lake Volkerak, most notably water plants of the genus *Potamogeton* (*fonteinkruid*). These take up most of the biomass of the total amount of macrophytes in and around lake Volkerak, Currently, geese and other (water) bird species strongly suppress the presence of vegetation near the shores. A full list of observed macrophytes is shown in Appendix II.

Lake Volkerak, including its marshes, are part of the *Natura 2000* network. It includes the *Vogelrichtlijn* and the *Habitatrichtlijn*. The Vogelrichtlijn aims for the conservation of bird species living in the wild and the Habitatrichtlijn focuses on guaranteeing biodiversity by maintaining or improving habitats of animal- and plant species. The fact that lake Volkerak is part of the Natura 2000 network makes it even more important to maintain and improve its current nature values.

The shores of lake Volkerak consist of various nature reserves. The *Slikken van de Heen* and *Dintelse Gorzen* on the south form an important habitat for a variety of plants and animals. The majority of these areas are permanently dry. Common plant species in these areas are *common reed* (*riet*), *goat willow* (*boswilg*) and *blackthorn* (*sleedoorn*). Other nature reserves are located in the north of lake Volkerak, namely the *Hellegatsplaten* and *Anthoniegorzen*.

As a result of the decrease in tidal ranges in lake Volkerak, there is currently a limited water exchange between lake Volkerak and the gullies present in these areas.

1.1.2 Historical developments

Lake Volkerak has been subject to a variety of morphological and hydrological changes in the past. The great flood of 1953 led to the development and implementation of the *Deltaplan*, in which the closing of tidal channels in the southwestern delta area of the Netherlands was proposed. This way, the delta area would be protected from future flooding disasters.

After the construction of the Grevelingendam in 1965, the Volkerakdam in 1969 and finally the Philipsdam in 1987, lake Volkerak was formed and got its current status as a partially closed-off lake. A fixed water level was set, which resulted in the marshes near the shores to permanently stay dry (Van Rooij, Groen, Röling, Slager, & Stoffer, 1996). As a result of the closing-off, tidal influences were reduced to almost zero.

Only about five years after the closing-off of lake Volkerak, the occurence of harmful algae blooms in the area was first considered to be an issue, both for the present and for the future, since it would be very difficult to convert lake Volkerak back into a salt water lake. A first measure by *Rijkswaterstaat Zeeland* at that time included the controlled release of *pike* (*snoek*). This measure ended up to be inefficient in resolving the issue of algae blooms. In addition to that, foreshores with islands were developed with the aim to protect the old shores from erosion due to the constant and invariable water level.

The following years after, the ecological state of lake Volkerak was considered to be insufficient, characterized by widespread harmful cyanobacterial algae blooms, high mortality of bird- and fish species, odor nuisance and the inability of the water to be used for irrigation purposes (Rijkswaterstaat, Waterdienst, Deltares, Royal Haskoning, Arcadis, 2012).

After that period, the water quality improved due to algae-eating mollusks. Although the quality can currently be considered quite good, there are still too many nutrients in lake Volkerak. If the mollusks would decline in abundancy again, the cyanobacterial algae would immediately return. Only an decrease in the nutrient availability would permanently improve the water quality and would decrease its dependency on one single mollusk species. Major sources of nutrient input are amongst others the smaller rivers flowing from *Brabant* into lake Volkerak and pumping stations, supplying water with an excess amount of nutrients.

1.2 PROBLEM STATEMENT

The prominent issue in the Volkerak-Zoommeer is the occurrence of algae blooms during mid- and late summer months. The presence of harmful cyanobacterial algae blooms poses a threat to a variety of macrophytes, animal species and (recreational) water users. Additionally, it renders the water unable to be used for irrigation purposes. A more in-depth analysis of the algae blooms and the effects of quagga mussels is provided in chapter 2 – Theoretical framework.

Nutrients are discharged into lake Volkerak from the rivers that extent into sandy soils where nutrients are washed away from agricultural land after periods of heavy precipitation. The nutrient balance that is set up in chapter 2.2.1 addresses the significance of the contribution of the Volkerak lock complex to nutrient inflow.

In short, the main problem is the excessive inflow of nutrients from the upstream rivers into lake Volkerak, resulting in periodically occurring harmful (cyanobacterial) algae blooms. The research on the effectiveness of wetlands and floodplains in removing these excess nutrients will provide more insights in an attempt to solve this issue.

The main rivers flowing into lake Volkerak are the *Mark/Dintel* and the *Steenbergse Vliet*, see Figure 2 on the next page. The river system consisting of the *Mark-Vlietkanaal*, *Roosendaalse Vliet* and *Kleine Aa* (orange line in Figure 2) connect both rivers to each other. The upstream areas of these rivers extend inland to sandy soils, including Flemish territory.

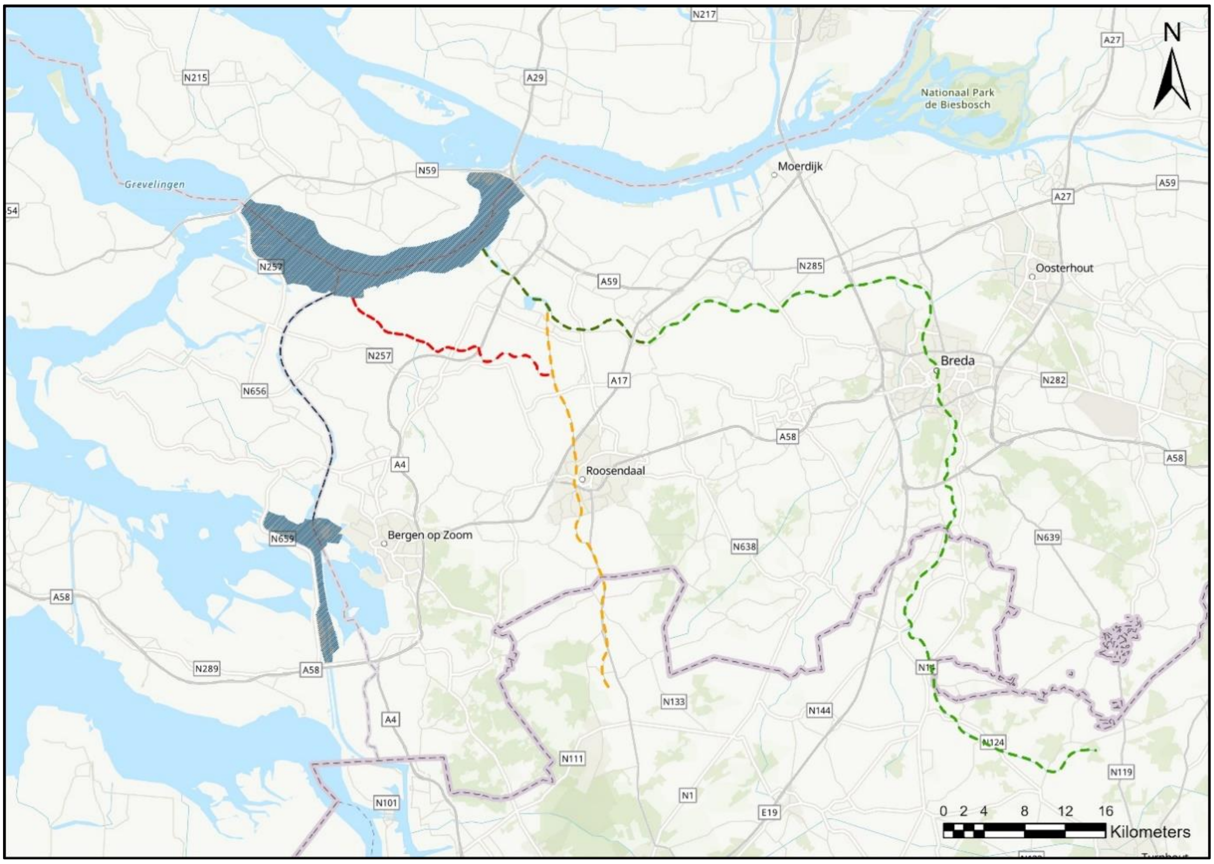

Figure 2. Location overview of the Volkerak-Zoommeer (dark blue) and the rivers flowing into lake Volkerak. Red: Steenbergse Vliet; Orange: River system Mark-Vlietkanaal, Roosendaalse Vliet and Kleine Aa; Dark green: Dintel; Light green: Mark. (Own source, map created in ArcGIS)

1.3 RESEARCH OBJECTIVE

The main objective of this research is to conduct a scientific analysis on the effectiveness of nutrient removal and area-specific applications of wetlands.

The aim of these wetlands is to reduce nutrient inflow into lake Volkerak, resulting in lower frequency and intensity of harmful algae blooms in lake Volkerak. The report will also cover the application of floodplains and their area-specific potential implementation scenarios. However, the main focus of this report will be on wetlands.

The findings of this research are translated into an advisory part, in which the different potential scenarios will be summarized and an advice will be given on how to most effectively implement the proposed scenarios.

The concept of nutrient removal by wetlands are analyzed in the theoretical framework, in addition to the effects on local biodiversity. Supported by a nutrient balance (chapter 2.2.1), data analysis of water levels (chapter 2.6) and scientific literature, the areas of interest and their area-specific opportunities for wetlands and floodplains are discussed. The advisory part takes into account the area-specific effectiveness, sustainability, and expected effects of the floodplains and wetlands on local organisms and biodiversity.

1.3.1 RESEARCH BOUNDARIES

This report covers the area-specific opportunities for wetlands and floodplains, taking into consideration a variety of aspects and preconditions. A list of these aspects and the corresponding substantiating research is covered in chapter 2 – Theoretical framework.

Because of time limitations, the general importance of setting boundaries is taken into account when setting up this report. Because of this, the results of this research are based on scientific literature, leaving out considerations of some practical aspects. These practical aspects include difficulties in construction of wetlands and floodplains due to limited cooperation of land owners, spatial limitations (presence of adjacent (agricultural) plots and nature protection areas), conflicting policies and/or laws, restricted financial viability and potential disturbance of cultural and recreational values and activities.

Even though these practical aspects are not taken into account, this research report will still aim to provide the essential fundamentals of the research topic. The findings and conclusions from this research can help future similar research to dive into the practical aspects (as mentioned above) and potential implementations.

Chapter 7 will provide more explanation on this particular topic.

1.4 RESEARCH QUESTIONS

The main research question of this research is as follows:

''Which wetland design types are most effective* in optimizing nutrient balances in the waterbodies upstream of lake Volkerak resulting in the reduction of frequency and intensity of algae blooms in lake Volkerak?''

**Most effective is defined as the most nutrient removal while still maintaining the presence of natural processes that do not negatively impact local biology and ecology. Measurable indicators for this include phosphorus and nitrogen concentrations, biodiversity and water quality parameters such as water transparency.*

Sub-questions in this research are as follows:

''Which wetland and floodplain design type functions in the most natural processes?''

''What are the area-specific opportunities for the construction of wetlands and floodplains?''

''What is the expected reduction in phosphate and nitrogen concentrations in the waterbodies upstream of lake Volkerak resulting from the implementation of wetlands?''

''What is the effect of the constructed wetlands and floodplains on the biodiversity and population of fish in the rivers and lake Volkerak?''

2. Theoretical framework

2.1 Algae blooms in lake Volkerak

Algae blooms are known to occur in water bodies with relative high temperature, low salinity and high water retention times. Lake Volkerak suits this description well. Inevitably, the first harmful algae blooms were observed only about five years after its closing off from the surrounding water bodies in 1987 (lake Grevelingen, Hollands Diep and the Eastern Scheldt).

The most dominant algae species present during algae blooms in lake Volkerak is *Microcystis*. Data from August 2003 concludes that cyanobacterial algae species account for between 80% and 100% of the total algae composition, with Microcystis being the most common species, followed by *Merismopedia*, see Table 1 below (Wolfstein, 2003).

More recent research (Weeber, et al., 2018) also concludes that Microcystis is the dominant species, followed by the species *Coscinodiscophyceae*, *Dichotomococcus*, *Cyanodictyon*, *Aphanothece* and Merismopedia. Even though this particular source lists different species, no clear trend can be concluded on a shift in species composition. Microcystis seems to remain the most abundant species throughout time.

Table 1. Percentage cyanobacterial algae present and dominant cyanobacterial algae species at four different locations around lake Volkerak in August 2003 (Wolfstein, 2003)

Location	% cyanobacterial algae	Dominant cyanobacterial species
Plaat van de Vliet (sub-surface)	78	1. Merismopedia; 2. Microcystis
Speelmansplaten (sub-surface)	87	Microcystis
Oude Tonge (sub-surface)	93	Microcystis
Dintelse Gorzen (sub-surface)	98	Microcystis
Plaat van de Vliet (surface)	87	1. Merismopedia; 2. Microcystis
Speelmansplaten (surface)	100	Microcystis
Oude Tonge (surface)	96	Microcystis
Dintelse Gorzen (surface)	89	Microcystis

The occurrence of harmful algae blooms poses a threat to a variety of macrophytes, animal species and (recreational) water users. Additionally, it renders the water unable to be used for irrigation purposes.

During periods of algae blooms, patches of floating layers of algae dominate the water surface. Cells of the Microcystis algae species are composed of vesicles filled with air. Having a lower density than water, these cells float to the surface, forming floating patches. Especially during periods of calm weather, the water column is unable to mix, resulting in the algae cells floating to the surface layer (Verspagen, Boers, Laanbroek, & Huisman, 2005). Besides relatively insignificant negative effects such as odor nuisance, excessive algae blooms are capable of posing a significant threat to bird species.

During the late summer months of 2002, widespread bird mortality took place. Over a two-month period on various locations around lake Volkerak, a total of 5.125 dead birds were observed and collected for research. No ecological catastrophes with the same extent have taken place after 2002, but it can be expected that similar catastrophes will take place in the near future. Analysis showed that these birds had relatively high concentrations of microcystines in their livers and brains, up to 113 µg/g. The general conclusion from this research is that cyanobacterial algae blooms can greatly contribute to bird mortality, although other factors may place a role as well (Wolfstein, 2003).

2.1.1 THE EFFECTS OF QUAGGA MUSSELS

Since 2005, the water quality of lake Volkerak has been showing a positive trend: cyanobacterial algae blooms occur less often and overall transparency of the water has increased, see Figure 3 below.

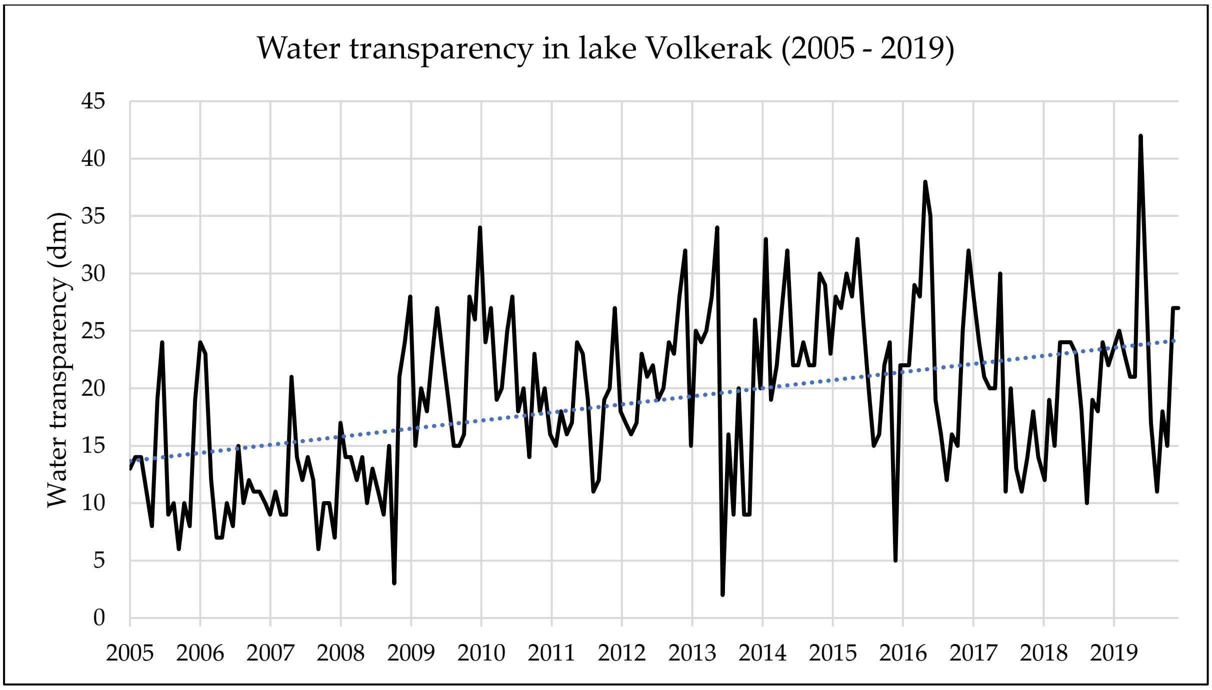

Figure 3. Water transparency in lake Volkerak from 2005 to 2019, based on data retrieved from waterinfo.rws.nl. A positive trend in increase of water transparency can be concluded.

Even though the water quality has improved, harmful algae blooms still occur, although less frequently. A hypothesis for this increase in water quality is lower phosphate concentration from the upstream rivers being discharged into lake Volkerak. This decrease in phosphate loading can only be partially ascribed to this effect.

Another hypothesis mentioned in the research was the emergence of *quagga mussels* (*Dreissena rostriformis bugensis*). However, these assumptions (lower phosphate loading and the emergence of quagga mussels) were only based on theoretical assumptions and were not physically tested at that time (De Vries & Postma, 2013).

A more recent research from 2017 concludes that a reliable link can be established between the presence of quagga mussels and an increase in water quality. Since 2008, the population of quagga mussels has reached an equilibrium. Analysis of data from the time period 2011 to 2016 concludes that the highest amounts of quagga mussels were observed in 2013, with values of 10,7 g organic dry weight per m^2. Populations were quite evenly spread throughout lake Volkerak, with most quagga mussels settling in depths of 4 to 6 meters.

The importance of future research on this topic was addressed during a convention in February 2018. For example, gaps in knowledge are present when looking at the mechanics of filtering nutrients by quagga mussels. Additionally, more research is needed on the effects of weather patterns on the frequency and intensity of cyanobacterial algae blooms (Zuidwestelijke Delta, 2018).

The presence of quagga mussels also seems to favor the presence of macrophytes, as seen in Figure 4 on the next page. Abundance of quagga mussels has been monitored since 2011, so no earlier data was available. Due to a higher transparency of the water as a result of filtration by quagga mussels, macrophytes are more abundant. This would also favor the presence of bird species that benefit from the presence of macrophytes (Weeber, et al., 2018).

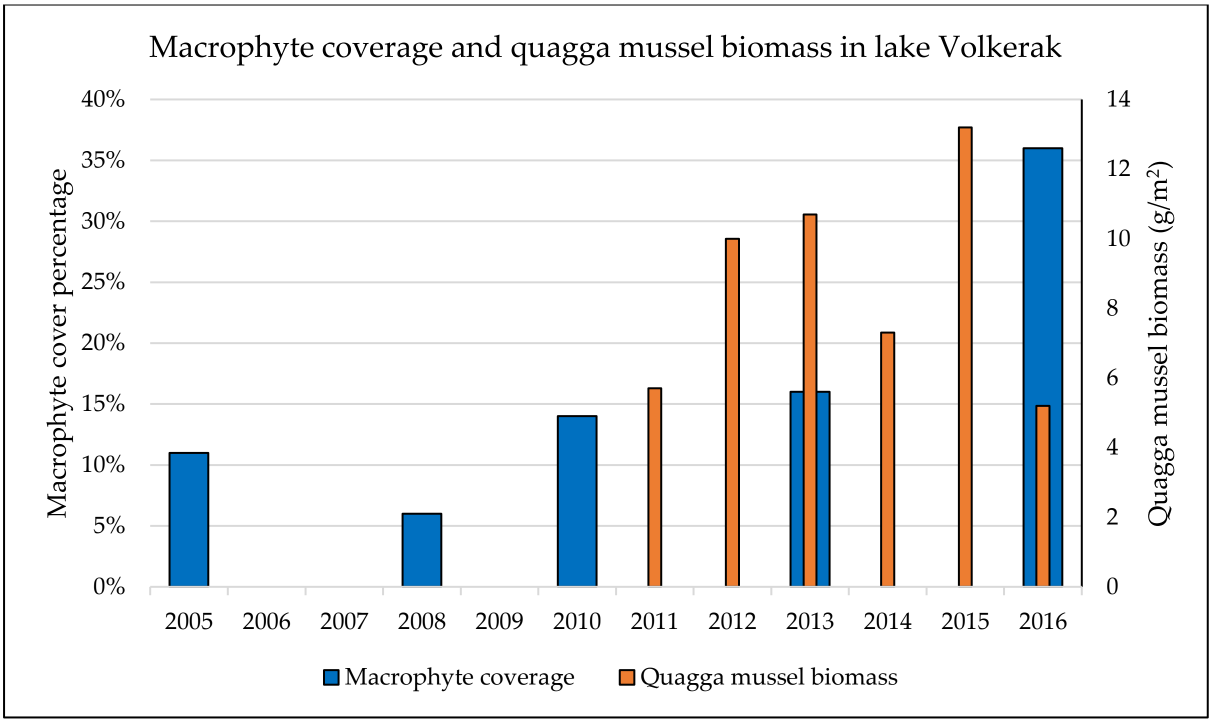

Figure 4. Development of macrophyte coverage in lake Volkerak during the period 2005 to 2016. (Weeber, et al., 2018)

2.2 Nutrient inflow

No significant increase in phosphate inflow throughout the years can be observed, seen in Figure 5 on the next page (Weeber, et al., 2018). However, a seasonal pattern can be observed with peaks occurring in autumn months. Even though no significant increase in phosphate concentrations can be observed, the phosphate concentrations are still observed to be significant enough to cause periodically occurring excessive algae blooms.

The following chapter 2.2.1 provides more information on the source of nutrient inflow. The data that is used for this nutrient balance was retrieved from the waterboard Brabantse Delta and the *WTZ-viewer* on *waterberichtgeving.rws.nl*.[1]

[1] https://waterberichtgeving.rws.nl/wbviewer/wtz_viewer.php

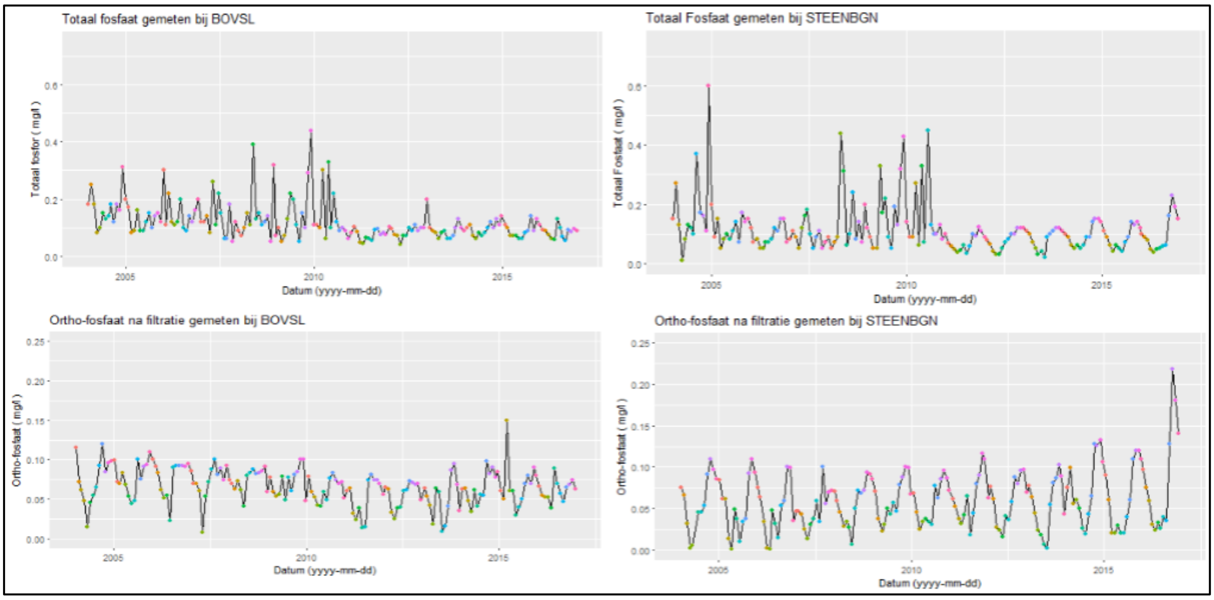

Figure 5. Inflow of total phosphorus (top left and top right) and orthophosphate (left bottom and right bottom) during the period 2006 to 2018 at the locations Volkeraksluizen and Steenbergen. (Weeber, et al., 2018)

2.2.1 NUTRIENT BALANCE

In order to support and further elaborate on the theory of excess nutrient inflow into lake Volkerak, a nutrient balance was set up. Data on flow rates and nutrient concentrations were combined to calculate the corresponding nutrient inflow values. Figure 6 on the next page provides an overview of the location of the datapoints used to set up the nutrient balance. Data on flow rates and nutrient concentrations at locations Benedensas and Dintelsas were requested from the waterboard Brabantse Delta. Similar data from the third location, the Volkerak lock complex, was retrieved from the *WTZ-viewer* on *waterberichtgeving.rws.nl*.

The corresponding data was obtained and analyzed and the results are shown in chapter 2.2.1.2, where average annual inflow of nutrients are calculated, including the relative (percentage) contribution from each of the three datapoints.

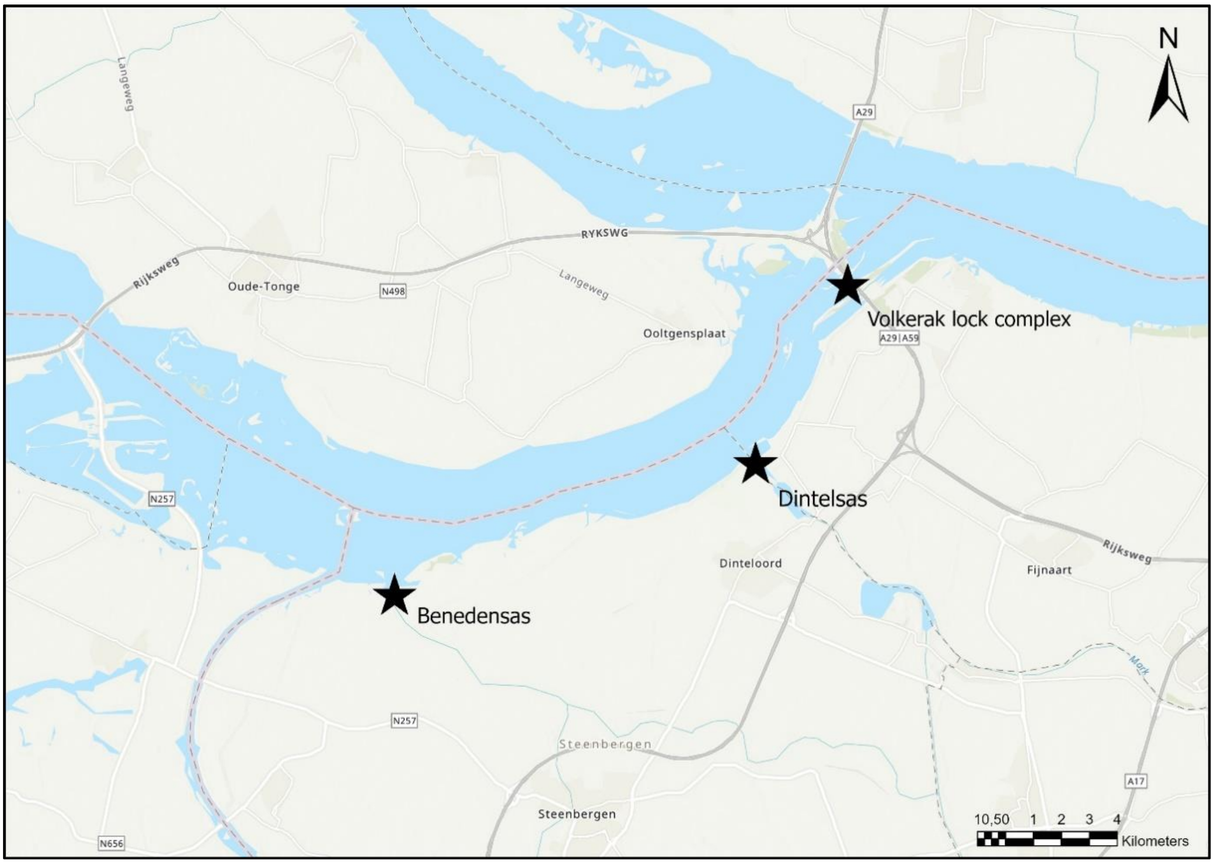

Figure 6. Overview of the three datapoints used in the nutrient balance. (Own source, map created in ArcGIS)

2.2.1.1 ANNUAL FLOW RATES

Due to limited availability of data from the Volkerak lock complex, the following period was used to calculate the values: January 1st, 2018 to January 1st, 2021. Using this three-year measurement timeframe for all locations, it is guaranteed that the data is reliable and is consistent with each other.

Table 2 below shows average annual rates of water inflow into lake Volkerak for each location and their individual contribution to the total average annual water inflow from these three sources (864.659.881 m^3). Data on inflow of nutrients is shown in the next chapter.

Table 2. Overview of average annual flow rates (based on the period January 1st, 2018 to January 1st, 2021) and percentage contribution to total inflow from each datapoint

	Benedensas	Dintelsas	Volkerak lock complex
Average annual inflow (m^3)	70.956.000	342.480.960	451.222.921
Percentage contribution to total inflow	8,2%	39,6%	52,2%

2.2.1.2 NUTRIENT CONCENTRATIONS

The average annual inflow of the following nutrients was calculated:

- Ammonium (NH_4^+)
- Total Kjeldahl nitrogen (TKN; the sum of organic nitrogen, ammonia (NH_3) and ammonium (NH_4^+))
- Nitrite (NO_2^-)
- Nitrate (NO_3^-)
- Phosphate (PO_4^{3-})
- Total phosphorus (TP; the sum of all phosphorus compounds, both dissolved and particulate)

Based on the values of average annual inflow and the average nutrient concentrations at the three locations, the total amount of nutrient inflow was calculated for each location. Figure 7 and Figure 8 below show these results, with Figure 8 showing the relative (percentage) contribution to nutrient inflow. For the circle chart shown in Figure 8, the average annual inflow values of individual nutrients mentioned above are added up and the corresponding calculated percentages are linked to the locations.

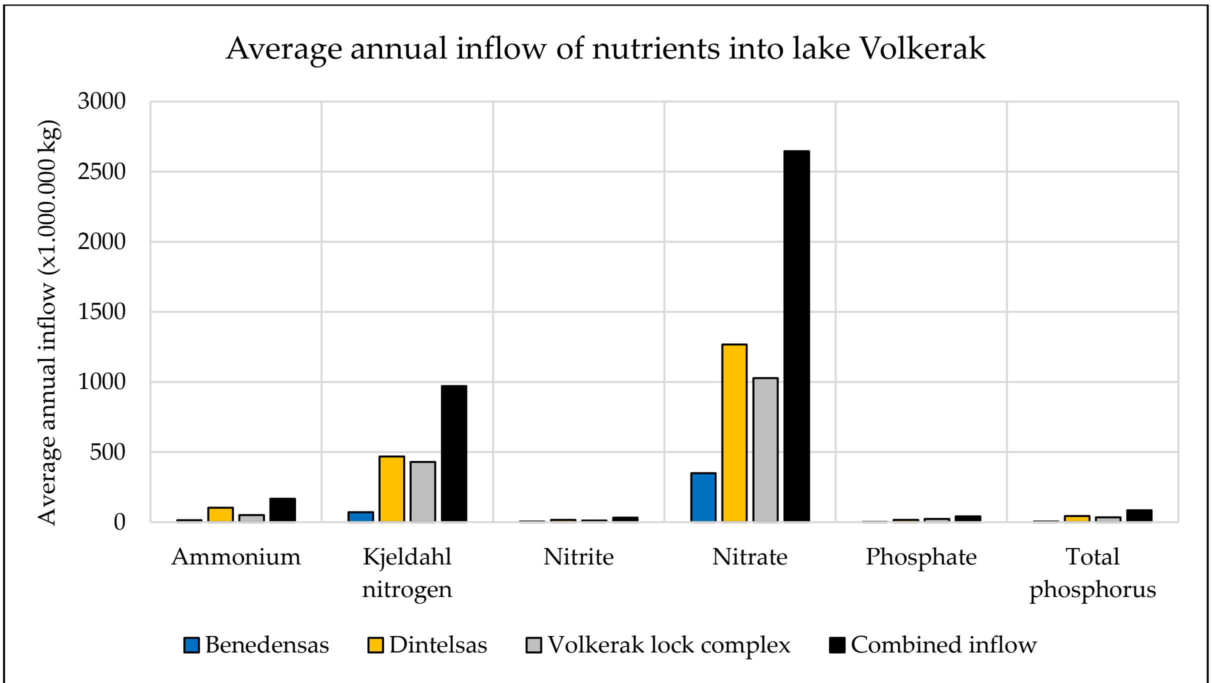

Figure 7. Average annual inflow (x1.000.000 kg) of various nutrients into lake Volkerak from Benedensas, Dintelsas and the Volkerak lock complex, based on the period January 1st, 2018 to January 1st, 2021.

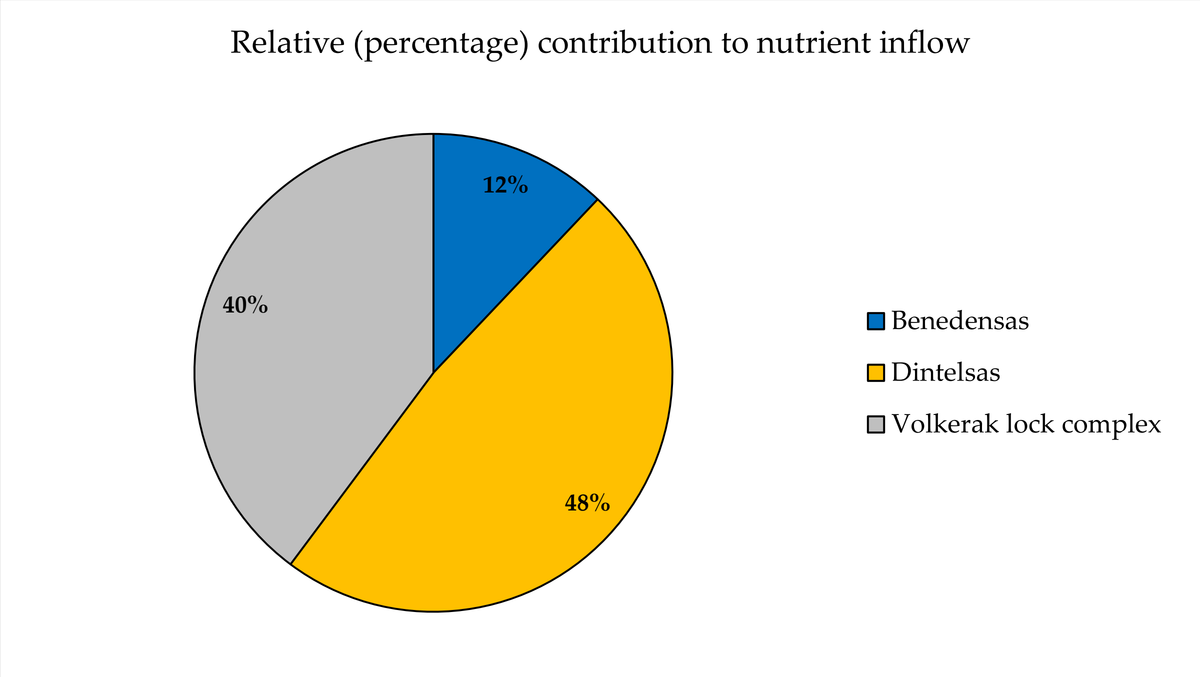

Figure 8. Percentage contribution to inflow of combined nutrient amounts, based on the period January 1st, 2018 to January 1st, 2021.

Comparing the findings shown in Figure 7 and Figure 8 with literature (Kouer & Griffioen, 2003), it can be made clear that the percentage contribution to nutrient inflow from location Volkerak lock complex is relatively high during this period (January 1st, 2018 to January 1st, 2021). Findings in literature show average values of 55%, 15% and 30% for the locations Dintelsas, Benedensas and the Volkerak lock complex respectively. However, annual fluctuations are present and these fluctuations can be explained by precipitation amounts.

The share of the river Dintel is shown to be high in years with high precipitation amounts as a result of washout of nutrients from agricultural soils. The share of nutrient inflow of the Volkerak lock complex tends to be relatively high in years with low amounts of precipitation. These literature findings line up with own findings when precipitation amounts of the years 2018 to 2020 are looked at. With annual national average precipitation amounts of 607, 783 and 785 mm for the years 2018, 2019 and 2020 respectively, these years are all considered to be dry, with a yearly average value of 847 mm, based on period 1981 to 2010 (KNMI, n.d.).

Average phosphate inflow concentrations from the three locations shown in Figure 6 is approximately 0,095 mg P/l. This value is very similar to the value of 0,093 mg P/l at a datapoint located approximately in the middle of lake Volkerak. Combining this value with data on discharge values at location Bathse Spuisluis, this results in an estimated yearly average outflow (to the Western Scheldt) of 150.000.000 kg P.

It is determined that approximately 38,5% of phosphorus and 60% of nitrogen originates from upstream Flemish soils. Investigation by the waterboard Brabantse Delta concluded that reductions of 15% and 30% for phosphorus and nitrogen concentrations respectively in the rivers upstream of lake Volkerak is needed to meet the *good ecological potential* (*GEP*; Dutch: *Goed Ecologisch Potentieel*) (Besselink, 2019). This would mean a total reduction of 290.857.875 kg N and 12.736.269 kg P. Based on data from literature on removal rates, this would indicate that a total wetland surface area of approximately 16.000 ha is needed, which is significant.

2.3 FUNCTIONS OF WETLANDS

2.3.1 NUTRIENT REMOVAL

The major function of (constructed) wetlands is the removal of nutrients and pollutants from the water. This makes the application of constructed wetlands interesting in wastewater treatment sites, where excessive amounts of nutrients and pollutants are inevitably present. Constructed wetlands can however also be applied in more natural environments, where excessive inflow of nutrients can result in problematic effects. The effectiveness of nutrient removal by wetlands is determined by a variety of factors, including the design and morphology of the wetland. The effects of different wetland design types on nutrient removal is discussed in chapter 2.4 – Wetland design types.

A study from 2009 (Kadlec & Wallace, 2009) reports average nitrogen removal values of 1.730 kg N/ha/year and 100 kg P/ha/year. Evaluation of average nitrogen removal rates in wetland systems in the Netherlands concludes values of between 1.280 and 2.200 kg N/ha/year. The same study concludes average phosphorus removal rates of 450 kg P/ha/year (Schomaker, Otte, Blom, Claassen, & Kampf, 2005).

The two major nutrients, nitrogen and phosphorus, are discussed in the following chapters 2.3.1.1 and 2.3.1.2. Wetlands are associated primarily with reduction of nitrogen loading rather than a reduction of phosphorus loading as a result of various factors.

Firstly, it is known that the efficiency of nitrogen removal is not affected by the amount of time the wetland has received nitrogen pollution, whereas the ability of a wetland to remove phosphorus is known to decline by time. This is most likely due to limited sorption/uptake capacity over time (Vymazal, 2004).

Secondly, wetlands characterized by waterlogged sediments are known to release phosphorus into overlying water bodies. It can then be easily exported from the wetland, but in relatively stagnant waters, this would simply result in a cycle of phosphorus transport, not removal (also see Figure 11 on page 21) (Fisher & Acreman, 2004).

Oxygen availability in the sediment is the most mentioned factor influencing nutrient removal efficiency. Oxygen availability positively affects nutrient removal efficiency in aerobic processes such as ammonification and nitrification. Denitrification on the other hand requires low oxygen concentrations in order to be effective. Alternating periods of inundation and drying up can thus result in an effective reduction of nitrogen (resulting from alternating periods with high and low oxygen concentrations), where gaseous nitrogen is released into the atmosphere. Figure 9 below gives an overview of the most important factors influencing nutrient retention or reduction capabilities of two types of wetlands.

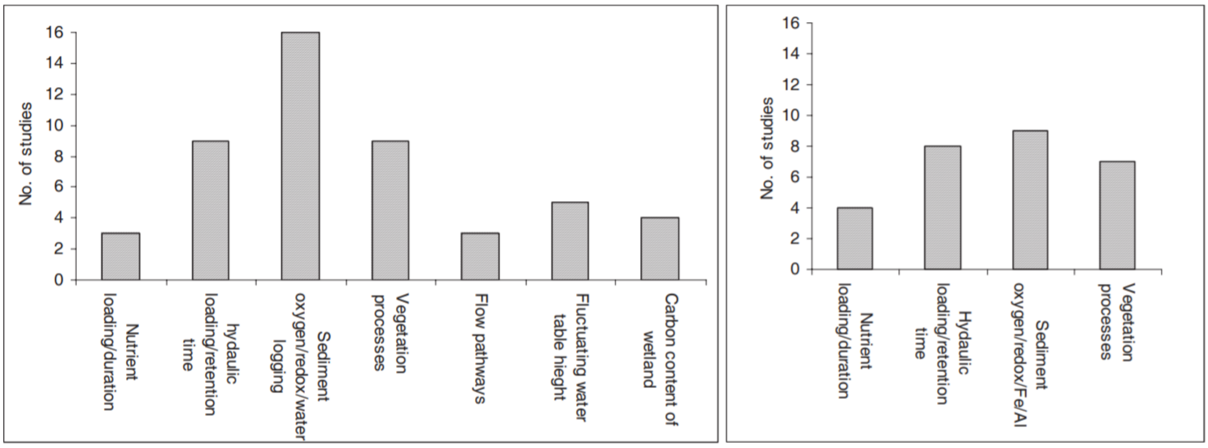

Figure 9. Overview of the most important factors influencing nutrient retention or reduction capabilities of swamps and marshes (left) and riparian zones (right). Swamps and marshes are characterized by higher water retention time. Riparian zones are usually more stretched out but are also less wide (one to a few dozen meters). (Fisher & Acreman, 2004)

2.3.1.1 NITROGEN

Nitrogen compounds include a variety of organic and inorganic forms that are essential for all biological life. For example, nitrogen can be found in proteins, enabling the functioning of various essential biological processes. Important inorganic forms of nitrogen include ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-).

The nitrogen cycle consists of three major consecutive processes (also see Figure 10 on the next page for a schematic overview):

- Ammonification (or mineralization): NH_2 (organic nitrogen) → NH_4^+ (ammonium)
- Nitrification: NH_4^+ (ammonium) → NO_2^- (nitrite) → NO_3^- (nitrate)
- Denitrification: NO_3^- (nitrate) → N_2 (gaseous nitrogen)

In the first process, ammonification, organic nitrogen is biologically converted into ammonium. This process can be either aerobic or anaerobic. Certain soil bacteria and fungi called decomposers are capable of breaking down organic nitrogen, releasing ammonium ions which are then converted to other nitrogen compounds. The rate of ammonification is the fastest in the oxygenated zone, which is usually found in the top layer of the water.

The second process, nitrification, tends to proceed slower than ammonification. This aerobic process is defined as the oxidation of ammonium to nitrite and nitrate. The nitrifying bacteria in this process derive energy from the oxidation of ammonia. Ammonia is transformed into nitrite by bacteria of the genus *Nitrosomonas* and this compound is then transformed into nitrate by bacteria of the genus *Nitrobacter*.

In the third process, denitrification, nitrate is anaerobically converted into nitrogen gas where it can be released to the atmosphere. This process takes place under anoxic conditions and is mediated by microbes. The efficiency of this process is depends on various factors, including temperature, pH value, alkalinity, inorganic carbon source, microbial population and ammonium concentrations. The most limiting factor, however, is oxygen availability. The latter could in theory be easily affected by the presence of macrophytes, as the presence of macrophytes influences oxygen concentrations of the substrate in the rhizosphere (the portion of the soil found adjacent to the roots of plants) (Fisher & Acreman, 2004). The minimum temperature for nitrification to take place is 4 °C (Vymazal, 2007) (Mihelcic & Zimmerman, 2014).

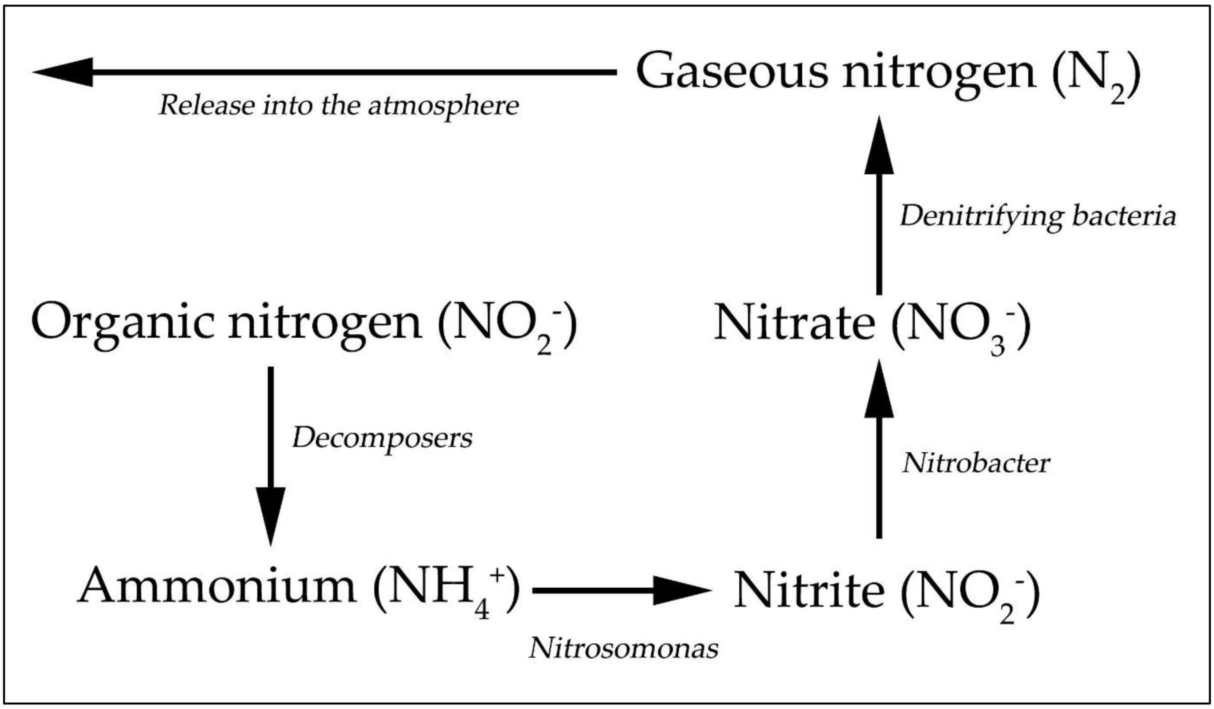

Figure 10. Schematic overview of the major processes in the nitrogen cycle. (Own source)

The uptake capacity of nitrogen of emergent plants (plants that are rooted under water but with stems and leaves extending to above the water surface) is estimated to be approximately 135 g N/m²/year, which corresponds to 1.350 kg N/ha/year. It has been reported that under optimum conditions, the amount of nitrogen removed by plant uptake does not exceed 10% of the total removed nutrients (Wallace & Knight, 2006). Similar values of 5% – 6% are reported in an older study (Arends, 1977). The remaining nutrient removal is mediated by decomposers and bacteria of the genera Nitrosomona and Nitrobacter.

2.3.1.2 PHOSPHORUS

Phosphate compounds are usually present in relatively small concentrations compared to nitrogen compounds because of the low solubility of phosphorus-bearing minerals. This results in phosphorus compounds usually being particle-bound. These concentration differences can also be observed in the nutrient balance in chapter 2.2.1, where total phosphorus concentrations are only 1,6% of nitrate concentrations. This usually makes phosphorus the limiting nutrient for algae growth in water bodies, resulting in the need to focus more on phosphorus removal rather than nitrogen removal.

Phosphorus can be transformed or removed in wetlands by the following mechanisms:

- Soil accretion
- Adsorption
- Precipitation
- Plant/microbial uptake
- Fragmentation
- Mineralization

The first two mechanisms, soil accretion and adsorption, are found to control long-term phosphorus transformation and removal.

Precipitation refers to the reaction of phosphate with metallic compounds such as Fe, Al, Ca and Mg. These reactions typically only occur when the concentrations of these metallic compounds are relatively high. As a result, this removal mechanism does not typically result in significant amounts of phosphorus transformation/removal.

Uptake of phosphorus by macrophytes and microbes is usually highest during the early stage of the growing season in early spring. Phosphorus can be taken up by plant roots and absorbed by leaves and shoots, the latter being restricted to submerged plant species. Aboveground phosphorus values are reported to be up to 6,8 g P/m^2 (Johnston, 1991), 11 g P/m^2 (Vymazal, 1995) and 15 g P/m^2 (Brix & Schierup, 1989) (Vymazal, 2007).

Growth, death and decay of plant biomass results in a cycle of phosphorus loading (see Figure 11 on the next page). Plants absorb phosphorus and eventually die and decay, releasing the phosphorus back into the water and sediment. This might seem counter-intuitive to be applied into a system that revolves around nutrient removal. However, most of the phosphorus load is taken up during the growing season, in early summer. Most of it is released again in the winter period. This might still be an effective method concerning the problem of algae blooms, because those are known to occur in late summer months. Additionally, the parts of the plants extending above the water can be harvested in late summer to permanently get rid of the accumulated phosphorus. This issue does not arise with some particular species, most notably *Schoenoplectus lacustris* (*mattenbies*), because the stem dies from top to bottom, so accumulated phosphorus is not deposited into the water in large amounts (Arends, 1977).

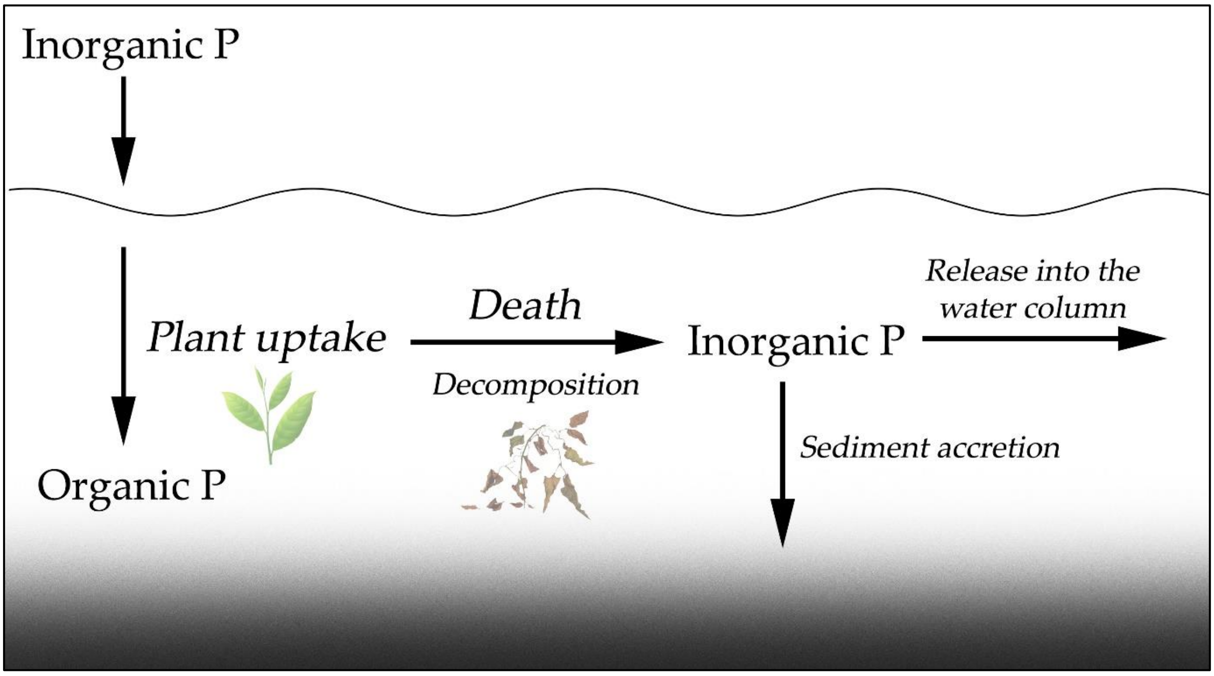

Figure 11. Schematic overview of vegetation-mediated phosphorus cycling in a water column. (Own source)

When phosphorus is released into the sediment, the term sediment accretion is used. The rate of sediment accretion is dependent on phosphorus loading, wetland size, climate (temperature) and vegetation type. Review of current literature indicates a mean removal rate of approximately 1 g/m²/year for sediment accretion (Wallace & Knight, 2006).

The uptake capacity of phosphorus of emergent plants is estimated to be approximately 9 g P/m²/year, which corresponds to 90 kg P/ha/year. Comparing this value with uptake of nitrogen (1.350 kg N/ha/year; chapter 2.3.1.1), this value is considerably lower.

2.3.2 Ecosystem services

Ecosystem services can be defined as follows (*Millennium Ecosystem Assessment*):

''The benefits organisms obtain from ecosystems, including provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling.''

The most important ecosystem services of wetlands include:

- Provisioning of habitat
- Water purification and waste treatment
- Climate regulation

Total global coverage of wetlands is approximated to be 12,1 million km^2 and wetlands account for 40,6% of the total global ecosystem services value. Even though wetlands play an important role in the delivery of global ecosystem services, they are among the most threatened ecosystems. Since 1970, anthropogenic interventions have resulted in a 35% loss of the global wetland extent (Xibao, Chen, Yang, Jiang, & Zhang, 2020). Most common contributors to global wetland loss include (Mihelcic & Zimmerman, 2014):

- Agricultural activities
- Residential and commercial development (urbanization)
- Construction of roads and highways

2.3.2.1 Climate change

Eutrophication in various ecosystems has an increasing trend worldwide due to the effects of climate change. Besides that, an increase in anthropogenic activities also contributes to this issue (Cheng, Zhu, Shutes, & Yan, 2021).

A recent study from 2020 highlighted the effects of climate change on sediment resuspension to shallow lakes. This would in turn lead to more eutrophication. In addition to that, the increase in microplastics due to an increase of runoff, could increase mineralization (the conversion of organic compounds into inorganic compounds) which would lead to more eutrophication (Zhang, et al., 2020).

The effects of climate change, most notably the rise in global temperatures, give rise to an increase in necessity to focus on resolving issues around eutrophication, as eutrophication is expected to increase when temperatures rise.

The ecosystem services of wetlands are capable of reducing the extent of the negative effects of climate change, for example by providing habitat to animal species that are endangered due to the effects of climate change. This makes the research topic that is covered in this report sustainable and future-oriented.

2.4 WETLAND DESIGN TYPES

Eiseltová (2011) describes four major methods for stream restoration in the agricultural landscape:

- Buffer-strips
- Alteration of tile-drainage
- In-channel modifications
- Creation of riparian wetlands and ponds

Each restoration method involves a different design with different key elements present. A summary of the key elements of each restoration method will be included in the following chapters 2.4.1 to 2.4.4.

2.4.1 BUFFER-STRIPS

The term *buffer-strip* is used to refer to a permanently vegetated zone between the agricultural fields and the river, which can also be referred to as the riparian ecotone or vegetated buffer zones. Figure 12 on the next page gives a visual representation of a buffer-strip.

Water enters the river either directly from precipitation or via the adjacent buffer-strip. Water can enter the buffer-strip via one of five pathways:

- Surface runoff
- Seepage
- Shallow subsurface flow
- Deep subsurface flow (i.e. groundwater)
- Through drainage tiles

The physical and biogeochemical properties of the buffer-strip influence the flow of the water and any nutrients or pollutants it contains. The riparian ecotone is a valuable part in river restoration as it usually consists of a surface area equal or larger than the river (Eiseltová, 2011).

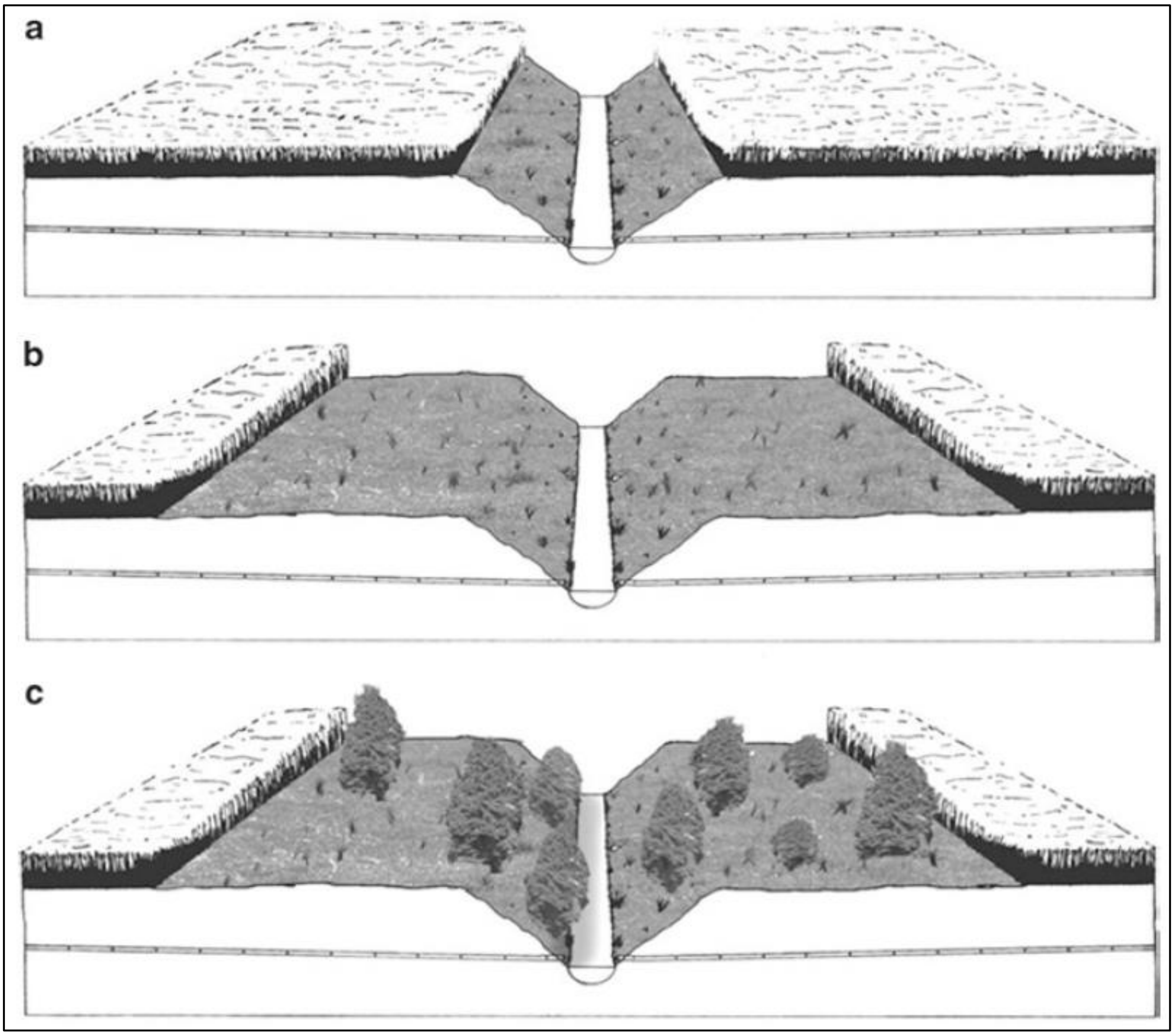

Figure 12. Buffer-strips along streams: a. As it commonly looks today in the agricultural landscape; b. A wide grass buffer-strip; c. A wide tree buffer-strip.

The presence of buffer-strips along the river channel is capable of reducing both the volume and timing of water entering the stream. Because of this, peak flows are reduced in intensity and frequency.

Besides being capable of reducing peaks in water flows, buffer-strips are also capable of reducing nutrients from water runoff. An experiment on using buffer-strips as pesticide filters was conducted (Syversen & Bechmann, 2004) and the results support the hypothesis of nutrient removal. A vegetated buffer zone was constructed with a slope of 14% and a width of 5 m. Vegetation consisted of various grass species: *Cirsium arvense* (*akkerdistel*), *Elytrigia repens* (*kweek*), *Phleum pratense pratense* (*timoteegras*), *Deschampsia cespitosa* (*ruwe smele*) and *Festuca pratensis* (*beemdlangbloem*). Results from this experiment show average removal efficiencies of 39%, 71%, 32% and 62% for *glyphosate*, *fenpropimorph*, *propiconazole* and soil particles respectively.

The overall effectiveness of pollutant trapping in buffer-strips is dependent on the slope of the buffer-strip, water transit time, vegetation type and amount and season. Considering the geomorphological characteristics of the research area, the development of buffer-strips has the greatest potential in the areas around the rivers further upstream. The riparian zones in the areas further downstream usually have a higher elevation than the surrounding polders, making it more difficult to initiate natural developments of buffer-strips.

Figure 13 below shows the reduction rates of total phosphorus and nitrate by buffer-strips, based on compiled data from literature. Highest reduction percentages are observed in buffer-strips with widths of more than 20 m. This amount seems to be the threshold value, as the reduction efficiency does not statistically increase above this value. It indicates that buffer-strips do not need to be very wide in order to function properly.

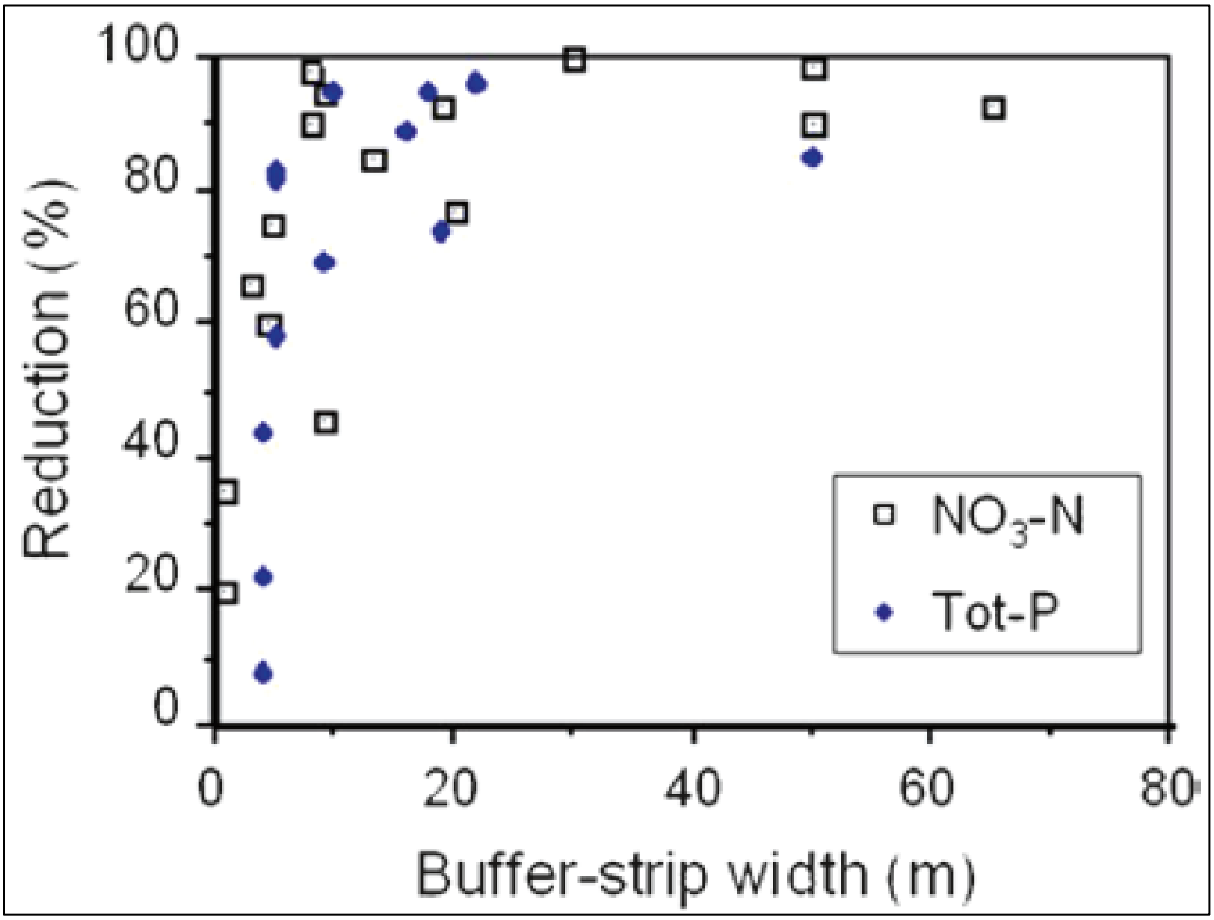

Figure 13. Reduction rates (%) of total phosphorus (Tot-P) and nitrate (NO3-N) in buffer-strips with various widhts. (Eiseltová, 2011)

2.4.1.1 EFFECTS OF BUFFER-STRIPS ON BIODIVERSITY

As seen in Figure 12c, buffer-strips can be forested which has various positive effects. The extensive root systems are capable of stabilizing stream banks and provide habitat for fish and invertebrates, given the right conditions. Another result is that they provide shade, reducing water temperatures, which leads to lower eutrophication rates and algae growth in the stream.

The presence of trees along a stream can alter macro-invertebrate communities, either directly through physical changes or through changes in detritus source. A mixture of tree species generally leads to a higher diversity and abundancy of macro-invertebrates compared to a monoculture, consisting only of one or very few different tree species (Rios & Bailey, 2006).

In addition to positively affect macro-invertebrate communities, trees along a stream can be beneficial in removing nutrients as well. Firstly, trees can be partially harvested, which permanently removes the nutrients. Secondly, the nutrients taken up by the trees are stored in the leaves, which are carried further downstream by the stream. These leaves serve as a food source for various water organisms, but not for (cyanobacterial) algae.

Findings in literature show different conclusions on the effects of buffer-strips on fish. A research from 1977 concluded that clear-cutting areas in forested streams in the USA resulted in the increase in both biomass and density of cutthroat trout (*Oncorhynchus clarkii/roodkeelforel*). This increase could be explained by a greater abundance of food in these sections. Other early research (1945 and 1954) shows the opposite effect: the removal of natural cover decreases abundance of trout because it allows summer temperatures to rise too high. The extent of the effects of buffer-strips on fish is however dependent on location and climate.

This leads to a general recommendation on the implementation of buffer-strips: the vegetation on the buffer-strip should ideally provide moderate shading to the river.

The key benefits of improving buffer-strips along streams are summarized below:

- Reducing peak flows through reduction of runoff volume and velocity
- Reducing the amount of nutrients and pollutants entering the stream
- Improving stream-bank stability through root systems
- Decreasing stream temperature during warm weather through shading
- Reducing macrophyte growth in the stream by decreasing light penetration
- Enhanced environment for flora and fauna in and around the stream

In the area of the research, enhanced environment for fauna is particularly relevant for the beaver. Forested buffer-strips provide a habitat for this species and the beaver itself has a direct impact on local vegetation and water levels.

2.4.2 Alteration of tile-drainage

Drainage-tile networks (Dutch: *drainagebuizen*) are widely applied in agricultural lands, especially in low-elevated areas where efficient water drainage is difficult. The constructed drains carry water that usually contains high concentrations of nutrients and pollutants. The natural filtering systems surrounding the streams are effectively bypassed with this method. Additionally, they are responsible for higher input of water, resulting in higher peak flows.

The approach that will be discussed here focuses on opening up drainage pipes before they enter the stream. This can be done in several ways, depending on the morphology of the stream and its banks, the main factor being the slope of the river bank. Moderate slopes allow for more extensive modifications, such as drainage tiles opening at the top of the slope, flowing through the riparian zone before entering the stream. This would be more easily initiated in the areas further upstream, as slopes in the riparian zones in these areas are generally less steep. The rivers flowing into lake Volkerak however are characterized by relatively steep slopes. This is not a significant problem in the sandy soil further upstream, as excavations could potentially be economically beneficial as a result of the obtainment of valuable sandy soils.

An analysis was done at the locations Benedensas, Dintelsas and De Hillen (see Figure 20 on page 38) by using *Vastgestelde Legger Waterschap Brabantse Delta*.[2] Stream banks located near these locations have slope values ranging from 1:2 (°45) to 1:3 (~°70), which can be considered to be steep, leaving only a tiny riparian zone to purify the drainage water. Alternatively, excavations of agricultural soils would solve this issue, but this option would be more challenging and complex, taking into account practical challenges such as legislative issues.

Eiseltová (2011) mentions two methods for alteration of tile-drainage that are considered suitable for areas with river banks characterized by moderate slopes:

- Opening drainage pipes
- Riparian wetland horseshoes

The first method focuses on opening drainage pipes at the top of the valley (or at the top of the river bank). This method allows drainage water from agricultural lands to filter through the riparian zone before entering the river. This method is similar to the method of buffer-strips (chapter 2.4.1), however the method of opening pipes mainly focuses on altering the location of the drainage pipes. This method is only applicable if a sufficient riparian zone is already present or the development of a riparian zone can be realized.

[2] https://www.brabantsedelta.nl/legger/

The disadvantage of this method is that the flow path of the drainage water is highly dependent on the morphology and vegetation on the buffer-strip, so additional measures would need to be taken into consideration. For example, the drainage water could create preferential flow paths that simply flow through the riparian zone without major nutrient removal taking place.

In order to combat this concern, riparian wetland horseshoes can be implemented. They are defined as excavations within the buffer-strip to expose drainage-tile outflow. This method is more suitable for areas where the topography is too flat to open up pipes at the top of the valley, which is what the area around lake Volkerak is characterized by. A visual example of both methods is provided in Figure 14 below.

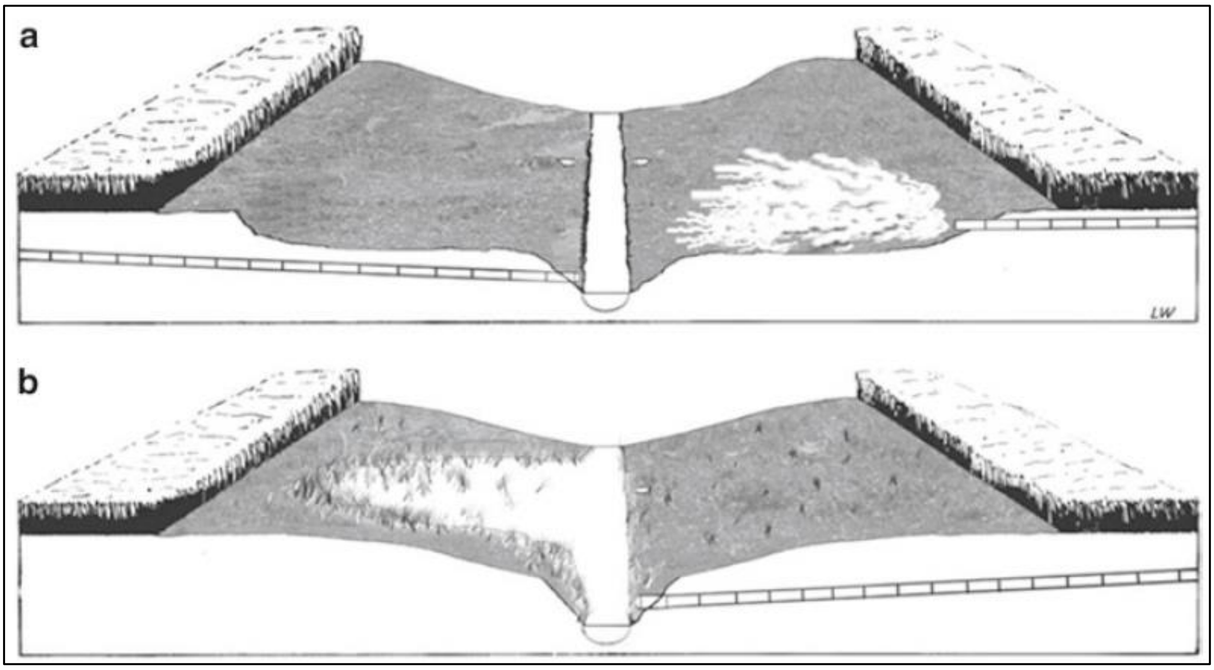

Figure 14. Visual representation of two methods that can be applied in tile-drainage alteration: a. Drainage-tiles opened up at the top of the stream valley; b. Drainage-tiles opened up into a horseshoe built within the riparian zone.

2.4.3 IN-CHANNEL MODIFICATIONS

Methods for in-channel modifications include:

- Side slope reduction
- Riffle-pool sequences
- Recreating meanders

Reducing bank slopes has various positive consequences. The risks of bank failures are reduced, resulting in a reduction of the amount of soil entering the stream. This, in turn, also results in less phosphorus entering the stream, as most phosphorus that enters the water is either bound into, or adhering to particulate matter. Secondly, bank slope reduction increases the width of the stream, resulting in an area that functions like a narrow floodplain. Water velocities are reduced which decreases erosion risks and particle deposition into the water, eventually resulting in a reduction of nutrient transport into the stream. Additionally, increase in width of the stream enables more development of vegetation, without significantly affecting water-discharge capabilities of the stream. Next to that, the water-storage effectiveness of the stream also increases.

The second method (riffle-pool sequences) focuses on increasing physical complexity in a stream by the introduction of large rocks in the stream, resulting in the development of natural riffles and pools. The theory behind this method is that the presence of large rocks in a stream increases bottom roughness and turbulences, which in turn reduces the overall water velocity. This method is however not applicable in the main watercourses in the rivers flowing into lake Volkerak, as these watercourses are used for recreational boating.

The third method (recreating meanders) focuses on recreating (or restoring) meanders in the river. This stable channel configuration controls water velocity by increasing the total length of the river but maintaining the same slope. Additionally, bed roughness is increased.

In the '60s and '70s, the river Mark was canalized and natural meanders were partly removed. This led to a faster discharge of water and besides that, the size of the river (width, length and depth) was increased significantly. The fast discharge of water resulted in higher flood risks in low-lying parts in the catchment area (Vereniging Markdal, n.d.).

Meandering rivers also have the capability of delaying the flux of inorganic and organic nutrients. In more or less straight-flowing rivers, nutrients are more likely to be just flushed through instead of being utilized, transformed or deposited elsewhere. This capability is referred to as the retention capacity. It is influenced both by physical properties of the river (mainly length) but also by biological properties such as vegetation present.

Reconstruction of meanders is difficult and requires expert hydrological and geomorphological advice. There have however already been successful attempts in restoring meanders in the river Mark. Around 1990 and later around 2004, various meanders were restored in the area near the Belgian border. Various characteristic plant species were found on excavated soils such as the *Juncus ensifolius* (*dwergbies*) and the *Ranunculus sceleratus* (*blaartrekkende boterbloem*). Additionally, the *Riparia riparia* (*oeverzwaluw*) has been observed to nest in the steep edges of the riverbank (see Figure 15 on the next page).

Figure 15. The Riparia riparia (oeverzwaluw), observed in the Schelde-Rijnkanaal, located south of lake Volkerak. (Dekker, 2021)

2.4.4 CREATIONS OF RIPARIAN WETLANDS AND PONDS

The benefits of creating wetlands and ponds along stream valleys include increase in hydraulic storage, retention time and sediment trapping, which is known to significantly reduce particle-bound phosphorus. Additionally, build-up of organic matter in these areas enhances denitrification, a process described in chapter 2.3.1.1 on page 18.

A pond and wetland along a river is visualized in Figure 16 on the next page. Ponds can be excavated along the stream where the water can be diverted from an upstream location and returned to the stream after residing in the pond for a period of time. It is usually not possible to raise the groundwater level to the required height as the impact of this process would be too high on surrounding (agricultural) fields. Additionally, the water flowing into these constructed ponds is not limited to water from the river, but can also originate from other surrounding soils.

The effects on (local) biodiversity are known to be significant, especially when combined with reintroduction or restoration of vegetated buffer-strips (see chapter 2.4.1) (Thiere, 2009).

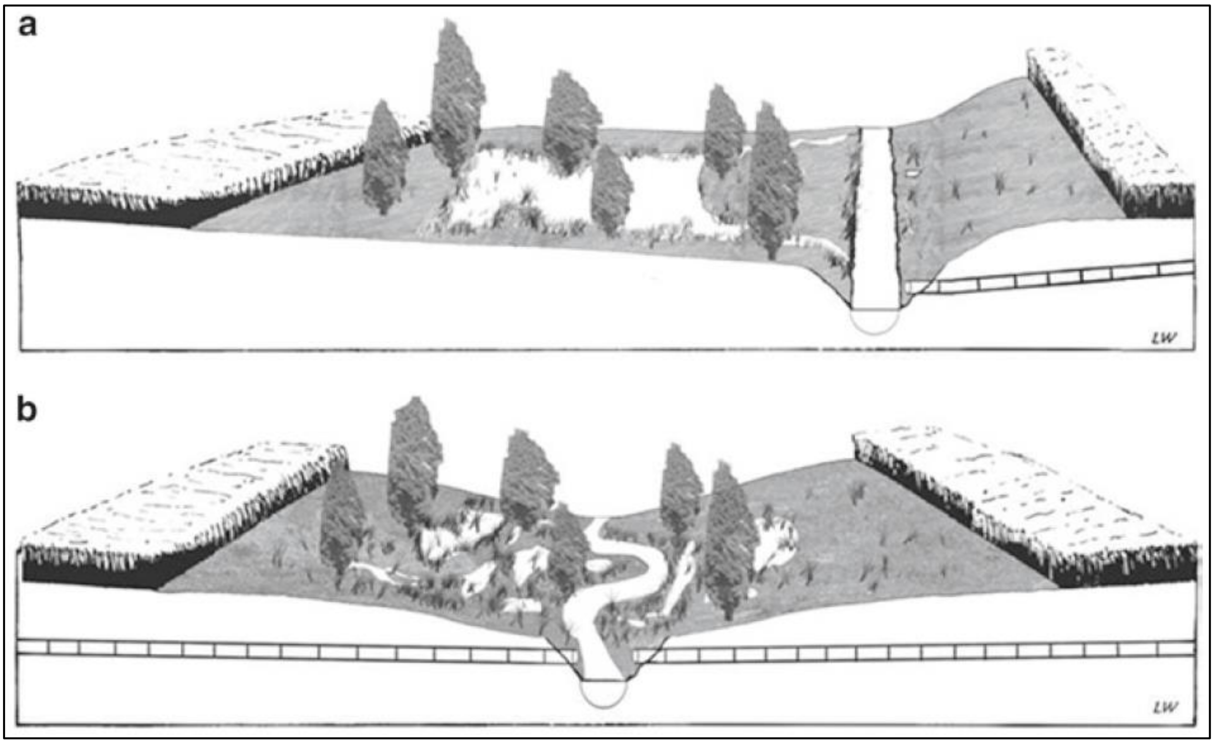

Figure 16. a. Detention pond; b. Riparian wetland.

Nutrient removal in these type of ponds can be significant, with average values of nitrogen retention of 1.770 kg/N/year and phosphorus retention values of 124 P/ha/year (Vought, Lacoursière, 2000). Vegetation in the restored area can promote a rapid build-up of organic matter. Coupled with low oxygen levels (due to water-saturated soils), these areas provide ideal conditions for nitrification to take place. The various stages in riparian wetlands are shown in Figure 17 on the next page.

Figure 17. Overview of the stages in a riparian wetland in Hörby, Sweden: a. Diversion from the main channel into the wetland; b. Sediment trap; c. First wetland; d. Connective riffle; e. Second wetland; f. Wetland outflow to the main channel. (Olsson, 2001)

The most practical and cost-effective location of riparian wetlands and ponds is in the lower part of the catchment area, in this research-specific case close to lake Volkerak. However, implementing these methods more upstream has the additional benefit of reducing peak flows. With an eye on the increasingly extreme effects of climate change, most notably extreme precipitation rates, this would reduce flooding risks in more urban areas (e.g. *Breda*).

2.4.5 Plant species selection

Many plant species are adapted to grow in wetlands, but only a relatively small amount of plant species are used in constructed wetlands with the aim to reduce nutrient concentrations. Plant species in wetlands must be capable of thriving in environments with high nutrient loads, saturated soil conditions and anaerobic environments.

Generally speaking, plant species that provide year-round structure perform better than plant species that fall below the water line when they die. Wallace & Knight (2006) conclude that the following species are most suitable for constructed wetlands: *Phragmites australis* (*echt riet*), *Typhia* (*lisdodde*) and *Scirpoides holoschoenus* (*kogelbies*). Out of these species, *Phragmites australis* is the most commonly used species in wetlands worldwide. This is because of its growth rate, root development and tolerance of saturated soil conditions.

When selecting plant species for a constructed wetland, the following factors should be taken into consideration (Wallace & Knight, 2006):

- Hydrology: water levels at both normal and peak values should be evaluated to ensure plant survival
- Climate: selected plant species must match their native climate
- Cost and availability: only plant species native to the area should be planted. The introduction of exotic species should be highly avoided
- Plant size: if small plant species are selected, plant maintenance (and thus costs) may need to be increased
- Rate of spreading: plant species that spread rapidly require less planting stock, which reduces costs and the potential for invasion of weeds
- Water quality: the selected plant species must be able to tolerate the water quality characteristics (including salinity, pH, alkalinity, nutrients etc.)
- Project goals: if the wetland is expected to provide or encourage a high-quality habitat for various organisms, a more diverse selection of plant species is favored

An older study (Arends, 1977) concludes the following species in Table 3 below to be most suitable for nutrient removal in constructed wetlands. It can be concluded that a factor 10 in effectiveness is present, comparing the first species with the last species. Per species, the amount of phosphorus uptake per kg of grown area is shown in the third column:

Table 3. Uptake of phosphorus (in g P/kg grown area) by plants, sorted in descending order of phosphorus uptake (Arends, 1977). Species indicated with an asterisk were also observed near lake Volkerak (see Appendix II). Most of these species can be found in brackish water systems

Latin name	Dutch name	g P/kg grown area
Schoenoplectus lacustris	Mattenbies	6,72
*Phragmites australis**	Echt riet*	6,27
*Iris pseudacorus**	Gele lis*	6,20
Carex elata	Stijve zegge	5,89
*Glyceria maxima**	Liesgras*	5,20
Sparganium erectum	Grote egelskop	4,99
*Acorus calamus**	Kalmoes*	4,64
*Mentha aquatica**	Watermunt*	3,70
Typha angustifolia	Kleine lisdodde	3,17
Myosotis scorpioides	Moerasvergeet-mij-nietje	0,64

2.5 FLOODPLAINS

Besides wetlands, floodplains are also known to provide a various range of ecosystem services. Floodplains (Dutch: *vloedvlaktes*), are defined as the low-lying areas along rivers that are subject to periodic flooding at intervals of varying frequency. These inundation periods used to be longer historically. Nowadays, their natural functions are limited because of limited inundation times.

The characteristics of ecosystems defined by floodplains are mainly dependent on the fluctuations of water levels. The dynamics of plant and animal communities in a floodplain are determined by the following aspects:

- Input of nutrients into the floodplain
- Sediment dynamics
- Mechanical stresses produced by water, bedload and sediments
- Groundwater table dynamics
- Exchange of organisms and the reproductive units of plants

Ecosystem services of floodplains can be divided into three main categories and twelve sub-categories (The Task Force, 2002):

- Hydrological functions
  - Flood retention
  - Sediment transport
  - Groundwater recharge
- Biogeochemical functions
  - C-N-P (carbon – nitrogen – phosphorus) cycling
  - Nutrient retention
  - Sediment retention
  - Transformation of organic and inorganic pollutants
  - Promotion of aquifer recharge
- Ecological functions
  - Habitat provision for plants and animals (spawning, growth, feeding and nesting)
  - Reservoir of biodiversity/storage of genetic resources
  - Bio-corridor
  - Bio-productivity

Groundwater recharge, all of the biogeochemical functions and all of the ecological functions are nowadays near impossible to be realized by floodplains currently present in the Netherlands due to extensive anthropogenic developments.

An analysis of four different floodplain restoration projects were evaluated (Eiseltová, 2011) and the resulting learned lessons were summarized. The first and most important result was that preliminary knowledge of the functioning floodplain ecosystem (with the river and the floodplain(s) inseparably coupled together) is required, including the various factors that influence how the ecosystem functions. This also includes an evaluation of the present status of the area, based on studies on habitat structure and function and the presence of indicator species. This aspect forms the basis for determining the degree of naturalness and the degree of modifications necessary. Another result was the importance of monitoring the success of restoration or implementation. In response to this, the following question should be asked: ''Is the (eco)system functioning in a sustainable way and are additional measures required for the system to operate in a self-regulatory manner?''

2.5.1 WATER STORAGE AREAS NORTH OF BREDA

Just north of the city Breda, five low-elevated areas that are capable of storing water (Dutch: *bergboezems*) are present, separated from each other by dikes. Figure 18 below shows the locations of these areas (indicated with the letters *A*, *B*, *C*, *D* and *E*) and their elevation levels. The total surface area of all five areas is approximately 700 ha.

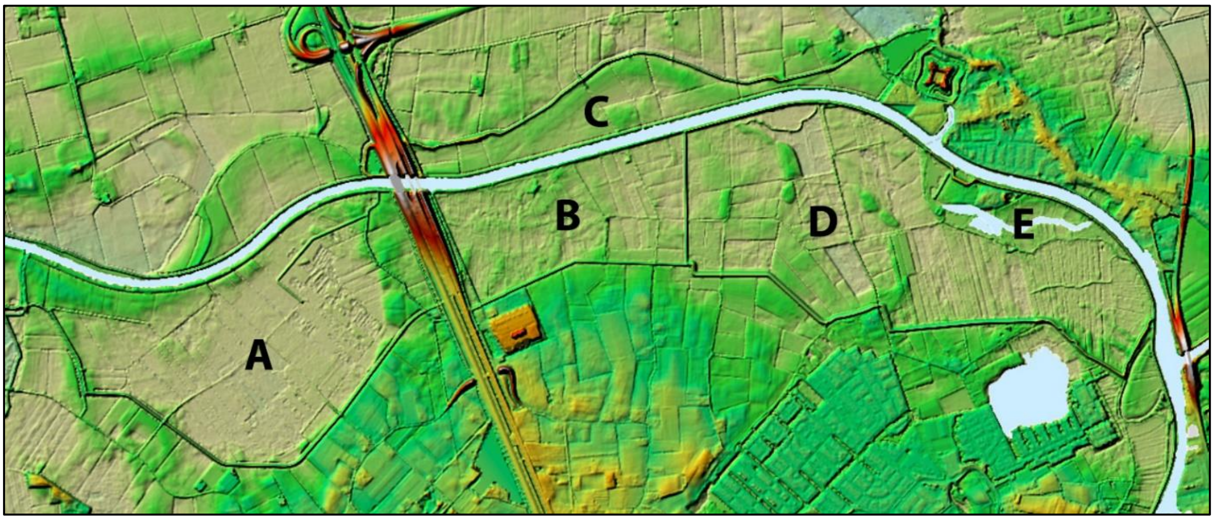

Figure 18. Elevation map of the five low-elevated areas (grey = low elevation; green = higher elevation). (Source: Esri Nederland, AHN)

The fifth area (indicated with the letter *E*) was realized in 2010 and is referred to as the *Vierde Bergboezem*. It has a surface area of approximately 28 ha and the water level in this area can be manually adjusted by weirs.

The main goal of the realization of this project is to decrease the risk of flooding by temporarily storing excess water from the river Mark. Additionally, the area provides excellent living conditions for various organisms. It is expected that in the course of time, parts of the area will develop into carrs (Dutch*: broekbossen*), which are characterized by waterlogged terrain, providing valuable and various species of flora and fauna.

This project is used as an example because it can be used as a reference for future developments in other nearby areas. The valuable services that it provides are unique and they include nutrient removal as well. Chapter 4 includes opportunities for similar projects in other areas, further upstream.

2.5.2 EFFECTS ON FISH POPULATION

Floodplains are known to have high biological and ecological value for a variety of fish species. In spring of 2006 and 2007, a research was carried out that investigated the fish species present in floodplains of the river *Volga* in Russia. Initially, only fish species that prefer flowing water were observed, referred to as rheophiles. These included *asp* (*roofblei*), *aichel* (*ziege*) and *ade* (*winde*).

Another conclusion from this research was that only a very small amount of fish originated from the main stream of the river and most of the fish species originated from either the affluents (Dutch: *zijrivieren*) or the lakes in the river catchment area. The main channel of the river seemed to only play a significant role in the supply of water, not so much in the supply of fish.

Other important conclusions from this research included that most fish species used the permanently inundated parts of the floodplain rather than the periodically inundated parts. An exception to this is the species *Prussian carp* (*giebel*). This species was observed mostly in the periodically inundated parts of the floodplain.

Additionally, a strong link was established between the presence of juvenile fish and the water temperature. When inundations occurred relatively early in the year, fewer fish were observed due to low water temperatures (Nagelkerke, 2011).

In another research, fish species were observed and recorded on three locations in floodplains along the rivers *Waal* and Rhine during the period 2017 to 2019. A total of 29 different fish species and 35.977 individual fish were observed. The relative abundance of these species was dominated by the *sunbleak* (*vetje*), *European bitterling* (*bittervoorn*) and *common rudd* (*ruisvoorn*). Figure 19 on the next page shows the full list of recorded fish species, sorted by relative abundance (Dorenbosch, Kooiman, Ploegaert, Vos, & Kranenbarg, 2020).

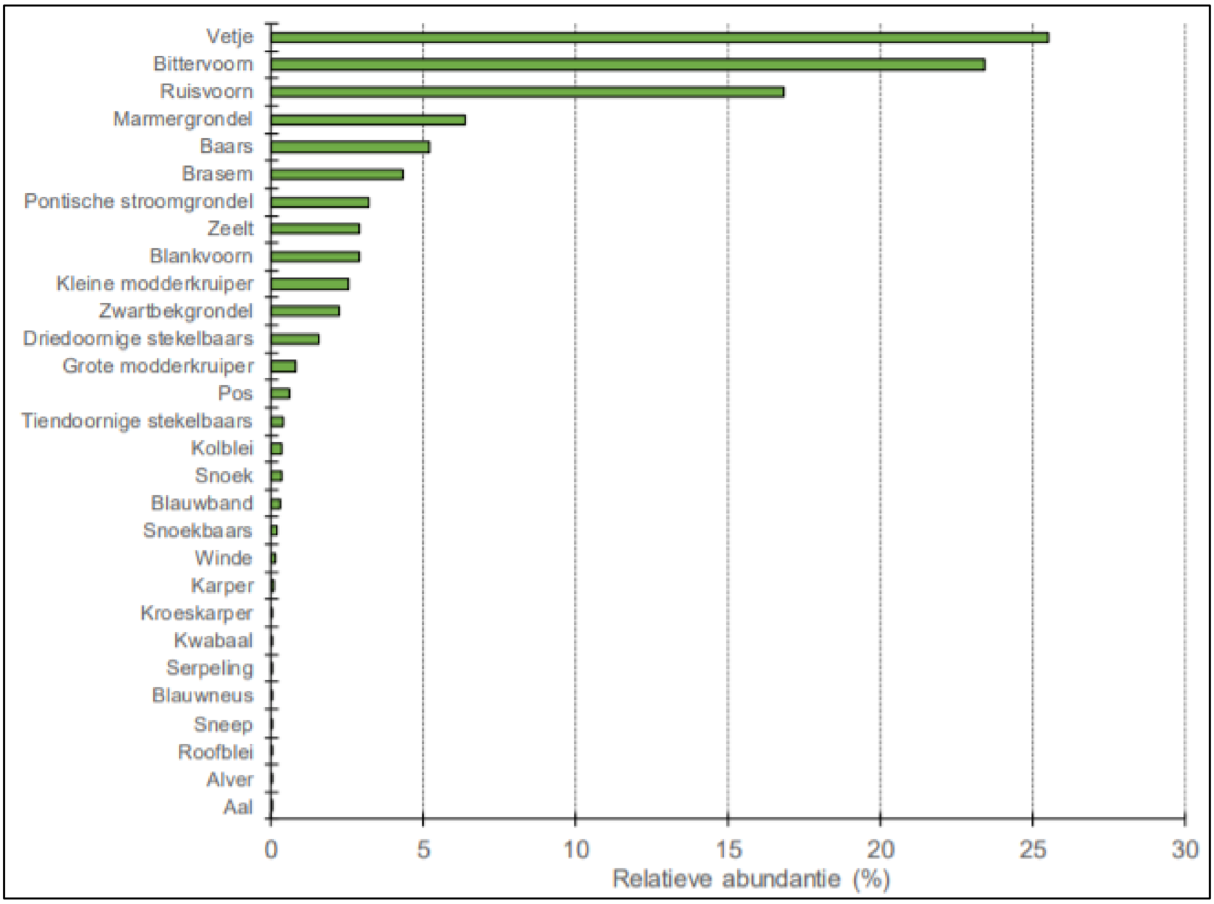

Figure 19. Relative abundance (%) of fish species in floodplains of the rivers Waal and Rhine, the Netherlands. (Dorenbosch, Kooiman, Ploegaert, Vos, & Kranenbarg, 2020)

Fish productivity was concluded to be significantly higher in robust floodplains, characterized by relatively deep water and large surface areas. The water in areas with relatively shallow water is more subject to drying up and anaerobic conditions, resulting in less favorable habitat for (juvenile) fish.

In most floodplains, fish communities are dominated by fish species strongly associated with the presence of water plants. These species include *sunbleak* (*vetje*), *European bitterling* (*bittervoorn*) and *common rudd* (*ruisvoorn*). Rheophile fish species such as *gudgeon* (*riviergrondel*), *Cottus perifretum* (*rivierdonderpad*) and *ide* (*winde*) were rarely observed.

Only two fish species were observed to use the floodplain for the whole life cycle, namely the *spined loach* (*kleine modderkruiper*) and the *weatherfish* (*grote modderkruiper*). The other observed fish species only used the floodplain during their juvenile stage (Dorenbosch, Kooiman, Ploegaert, Vos, & Kranenbarg, 2020).

A dataset from the waterboard Brabantse Delta of observed fish species in lake Volkerak and its upstream rivers is shown in Appendix I.

2.6 WATER LEVELS

Data provided by the waterboard Brabantse Delta was used to get an overview of monthly values of water levels in the water bodies upstream of lake Volkerak, based on the period January 1st, 2014 to January 1st, 2021. Figure 20 below gives an overview of the location of these datapoints, indicated with a star (left: Benedensas; middle: Dintelsas; right: *De Hillen*). Datapoint De Hillen is located approximately 25 km upstream of lake Volkerak in the river Mark. Data from upstream of the datapoint Benedensas was not available.

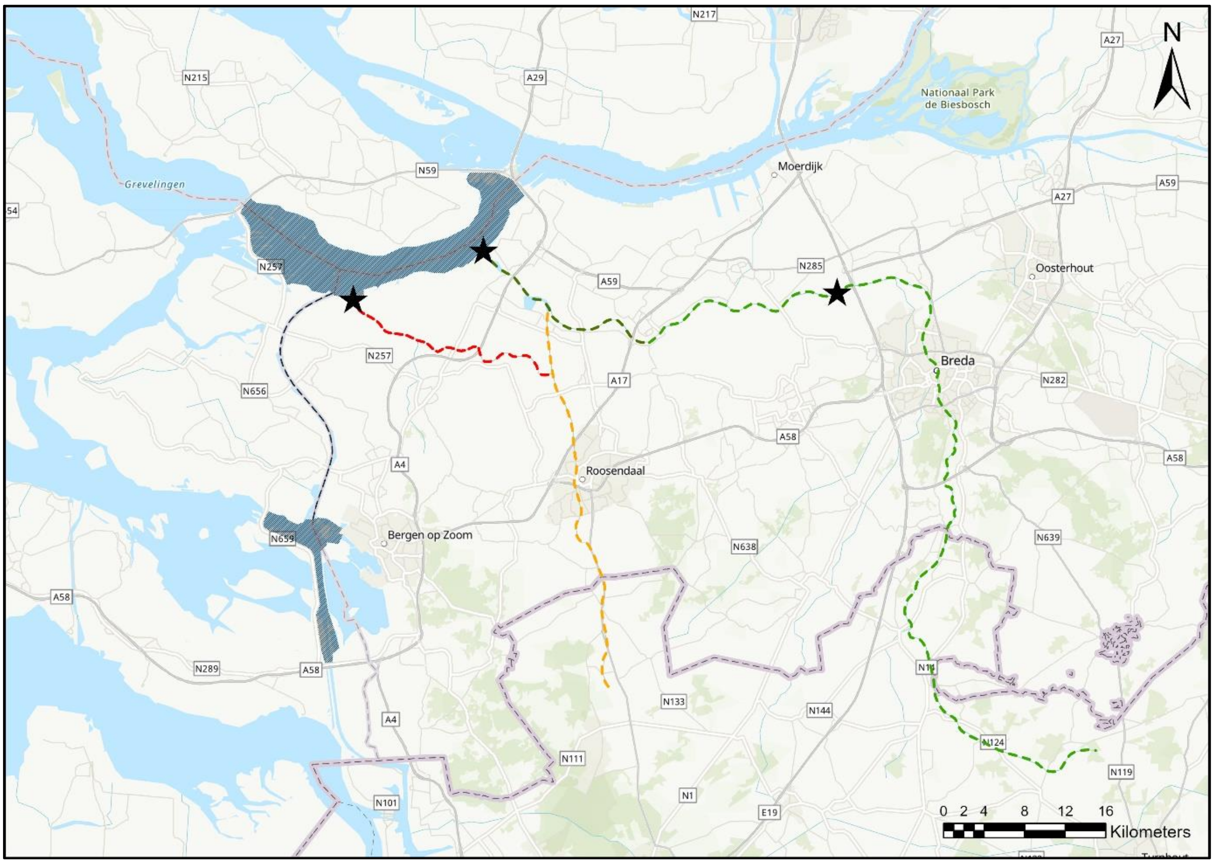

Figure 20. Overview of the datapoints Benedensas (left), Dintelsas (middle) and De Hillen (right). (Own source, map created in ArcGIS)

Figure 21 gives an overview of the monthly average water levels at the three datapoints. Average water levels are +0,031, +0,037 and +0,037 m NAP for the locations Benedensas, Dintelsas and De Hillen respectively, as shown in Table 4 on the next page.

The standard deviation for each datapoint was calculated and is also shown in Table 4. This number indicates to which extent the individual values differ from the average value. When this number is relatively high, it indicates that peak values (both high and low) are more extreme, translating to higher peak values in water levels.

Table 4. Montly average water levels (based on the period January 1st, 2014 to January 1st, 2021) and values of standard deviation for the datapoints Benedensas, Dintelsas and De Hillen

	Benedensas	Dintelsas	De Hillen
Monthly average water level (m NAP)	+0,031	+0,037	+0,037
Standard deviation	0,057	0,051	0,087

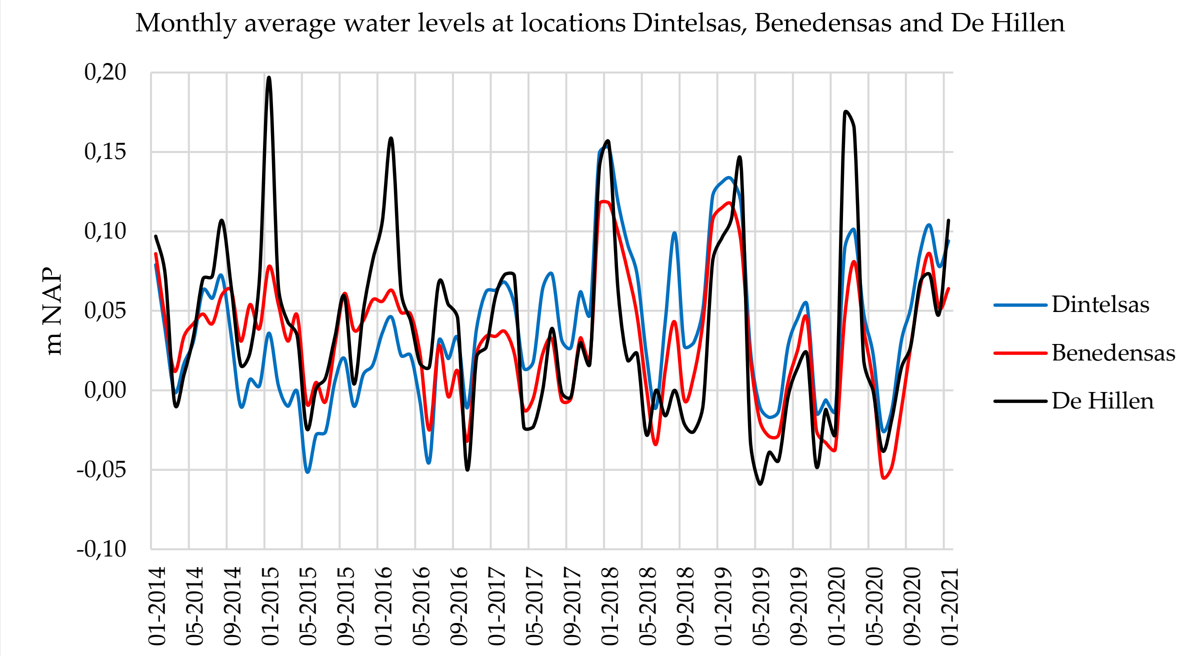

Figure 21. Montly average water levels at locations Dintelsas, Benedensas and De Hillen.

The area-specific opportunities and effectiveness of wetlands and floodplains is dependent on a variety of factors, including peak values of water levels and their frequency of occurring. In order to define 'peak values', the data of water levels was selected in such a way that 'peak values' could be defined as follows:

''The water level values (in m NAP) that correspond to the 20% highest values in the dataset.''

Table 5 on the next page shows these calculated peak values (taking into account the definition of peak values as defined above) and their annual average frequency of occurring. Note that values in the corresponding dataset were measured on a daily basis, resulting in a total of 2.558 individual measurements during the 7-year period. This results in peak values occurring on approximately 20% of the days at locations Benedensas and Dintelsas and 4% at location De Hillen.

Table 5. Average water level peak values and frequency of occuring at datapoints Benedensas, Dintelsas and De Hillen (based on the period January 1st, 2014 to January 1st, 2021)

	Benedensas	Dintelsas	De Hillen
Peak value (m NAP)	+0,069	+0,083	+0,204
Average number of days per year with peak values occurring	77	72	14

The water agreement of the Volkerak-Zoommeer that was realized in 2016 states that fluctuations in water level should be limited to values between -0,10 m NAP and +0,15 m NAP (Waterschap Scheldestromen, 2016). Based on the period January 1st, 2017 to January 1st, 2021, these values are exceeded six times per year on average.

Data on water levels in lake Volkerak was retrieved from *Rijkswaterstaat Waterinfo*[3] to get more insights on these measurements. The data was selected based on the period January 1st, 2017 to January 1st, 2021. Analysis of this data concludes the following numbers as shown in Table 6 below.

Table 6. Numbers resulting from an analysis of data on water levels in lake Volkerak from waterinfo.rws.nl, based on the period January 1st, 2017 to January 1st, 2021

Average water level (m NAP)	+0,028
Maximum observed water level (m NAP)	+0,280
Minimum observed water level (m NAP)	-0,280
Standard deviation	0,057
Peak value (m NAP)	+0,140
Average number of days per year where peak values are exceeded	34
Average number of days per year where the water level exceeds -0,10 m NAP or +0,15 m NAP (water agreement water levels)	6

2.6.1 WATER LEVEL GRADIENT

The rivers that flow into lake Volkerak originate in Flemish territory (see Figure 20 on page 38). This means that there is little to no seasonal variability in water inflow/outflow, in contrast to bigger water systems in the Netherlands such as the *Rhine* and the *Meuse* that originate in areas with relative high elevation and have seasonal variability in water discharges due to melting of snow. The water levels in the rivers that flow into lake Volkerak are highly

[3] https://waterinfo.rws.nl/

dependent on precipitation amounts. Seasonal patterns in water levels are to a smaller extent present due to water retention and usage by vegetation in summer months.

When looking at the rivers flowing into lake Volkerak, it can be concluded that further upstream, peak values of water levels are higher (see Table 5 on page 40). This might be a result of a narrower diameter of the river upstream, as at location Dintelsas the river has an approximate diameter of 80 m and 50 km upstream near the Belgian border, this diameter has decreased to 20 m. The relatively wide diameter of the river further downstream (80 m) was historically needed to store the water originating from the former tidal ranges. Further upstream, these tidal ranges were less significant. Current peaks further upstream are compensated by a wider channel further downstream.

Assuming a linear correlation and a total length of the river system Mark-Dintel of 70 km, it can be assumed that peak water levels (as defined in chapter 2.6) are approximately 5 cm higher every 10 km. Considering this linear model, it would result in peak values of approximately +0,25 m higher at the location 50 km upstream, near the Belgian border. This linear model corresponds well with river diameter, as the river diameter at location Dintelsas is 80 m, the river diameter at location De Hillen 50 m and the river diameter at the location 50 km upstream 20 m.

The areas around the rivers that flow into lake Volkerak are known to be frequently subject to (minor) flooding events, especially areas that are located further upstream (Vereniging Markdal, n.d.). This makes these particular areas interesting for the specific research topic, as natural occurring inundations do not need to be initiated via anthropogenic interventions. The areas around the river Mark south of the city Breda are more frequently subject to flooding, as the water flows faster in this part of the river. A slope of 34 m is present between the source of the river Mark (*Merksplas*, Belgium) and the city Breda, which has a trajectory length of approximately 55 km. The trajectory on Dutch ground is approximately 35 km (Planviewer, n.d.).

Figure 22 on the next page shows the calculated inundation surface in the river Mark south of Breda. The colors indicate the expected frequency of occurring (e.g. T2 means that inundation occurs once every two years on average).

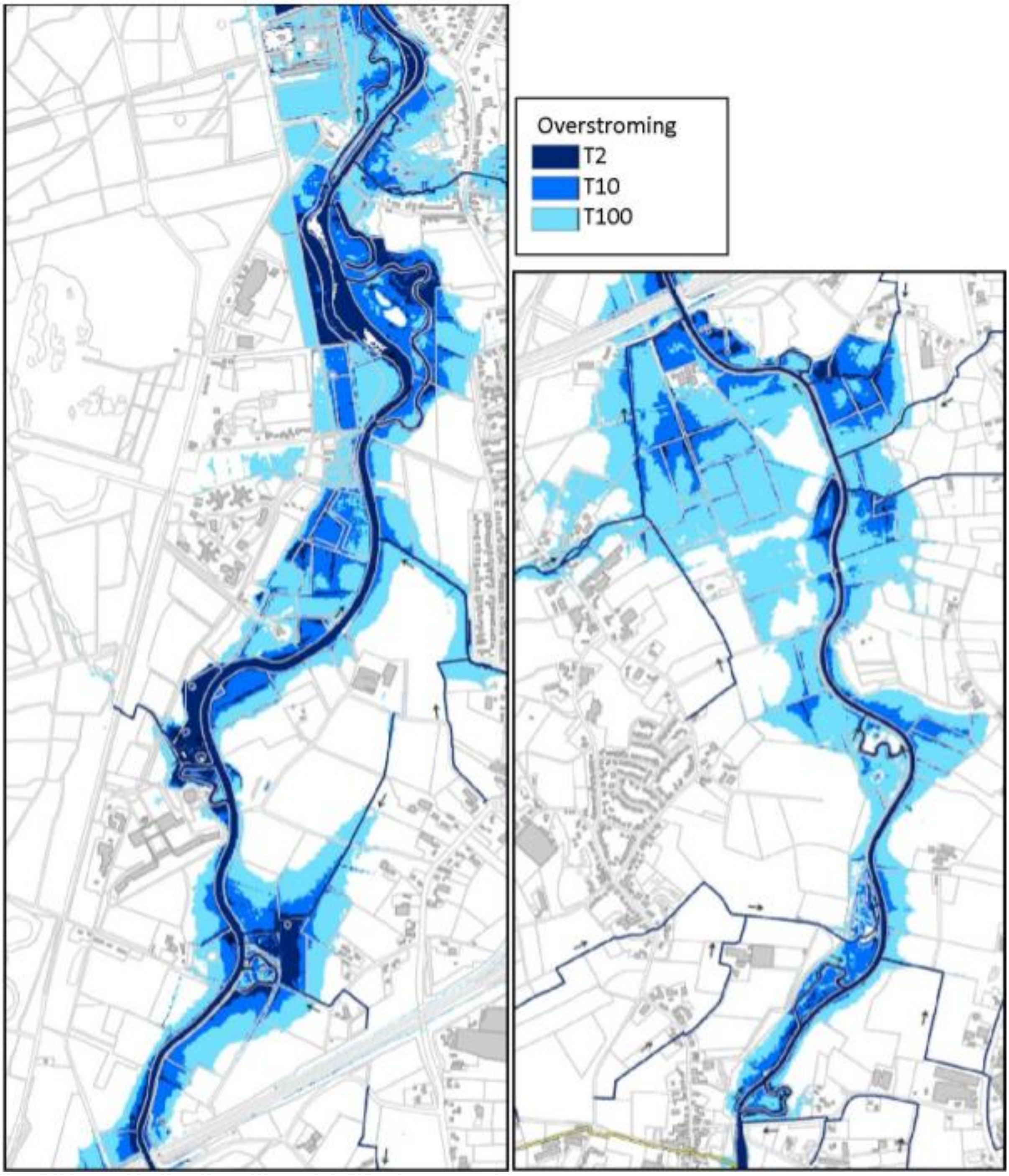

Figure 22. Calculated inundation surface in the river Mark south of Breda. Left: north of highway A58; right: south of highway A58. (Besselink, 2019)

3. METHOD

The selection of the locations listed in chapter 4 and in Table 7 on page 45 are based on various factors/criteria. Firstly, it is looked at whether the locations are currently characterized by the presence of natural characteristics of wetlands/floodplains. These characteristics are then compared to findings from literature on how effective they could potentially be at removing nutrients and/or providing ecological and biological value to the surrounding area.

Secondly, the elevation of the location and the area around it is evaluated. If, for example, a location is characterized by a relatively low elevation and is in close proximity to the main river channel, this makes the location interesting for potential future measures on wetland or floodplain development.

Based on the surface area of the location and combining this data with elevation levels, the gradient of the slope of the potential wetland/floodplain area can be determined. This is relevant for the expected health and functioning of the ecosystem, as large areas of wetlands and floodplains are more robust, self-sufficient, ecologically and biologically diverse and carry more potential for nutrient removal (see chapter 2.5 – Floodplains).

4. Results

Figure 23 below shows the locations of the areas of interest. These locations are the result of investigations on area-specific opportunities for the introduction of wetlands and floodplains.

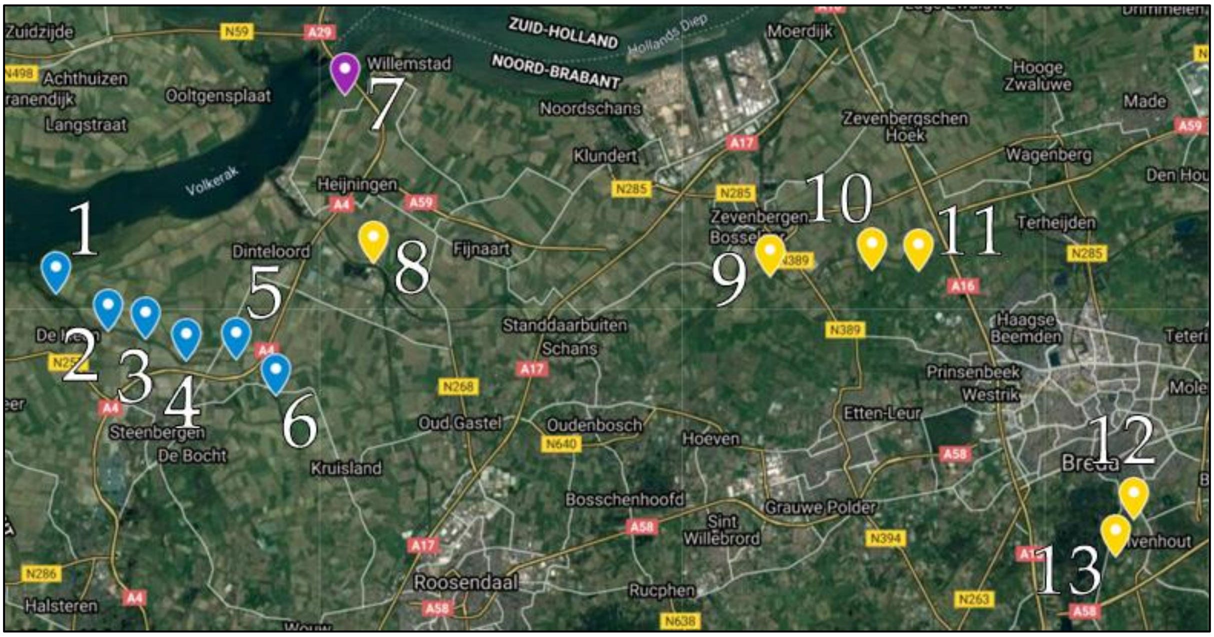

Figure 23. Overview of the locations of interest that were selected for potential wetland/floodplain development. (Source: Google Maps)[4]

1: SteenbergseVliet_1 / Saspoldertje
2: SteenbergseVliet_2
3: SteenberseVliet_3
4: SteenbergseVliet_4
5: SteenbergseVliet_5
6: SteenbergseVliet 6 / De Baak
7: Volkerak_1 / St. Anthoniegorzen
8: Dintel_1
9: Mark_1
10: Mark_2
11: Mark_3
12: Mark_4 / Meander Ulvenhout
13: Mark_5

Table 7 on the next page gives an overview of the locations and corresponding additional information. The list is sorted by priority, meaning that locations high on this list are most suitable for the proposed developments, influenced by factors such as elevation levels, expected inundation frequency, naturalness and surface area. Each location is assigned an individual appendix (III to XV) in which more in-depth information and context is provided.

[4] https://www.google.com/maps/d/edit?mid=1tcHGjV7hUP-RF_fTBEiZJxECkaDTJtIU&usp=sharing

Table 7. Overview of locations of interest and corresponding relevant information

Location	Km upstream	Surface area (ha)	Coordinates (x,y)	Appendix	Key characteristics	Potential measures
SteenbergseVliet_4	7	5	51.60225, 4.32822	VII	– Two waterbodies adjacent to the river with relatively deep water levels – Pumping station present – Embankments with gaps present on the river side	– Redirecting discharge water from the pumping station to the adjacent waterbodies – Increasing retention time of water by closing existing gaps in the embankments – Making water less deep, allowing macrophyte development
Mark_1	21	5	51.62758, 4.60968	XI	– Fish spawning ground present in the east – Dry grassland present in the west (elevation levels of +1,50 m NAP) – Area is directly bordering the main river	– Small-scale wetland development in the grassland area by dredging a secondary channel with bifurcations – Floodplain development by closing off outflow to the main river
Mark_4 / Meander Ulvenhout	44,5	11	51.55498, 4.78905	XIV	– No embankments present directly around the channel – Presence of meanders – Low-elevated grassland in-between the meanders	– Increase controlled inundation frequency (by excavations), allowing more macrophyte development – Wetland development between the existing meanders
Mark_5	46	3	51.54359, 4.77962	XV	– Low-elevated area to the west of the main channel – Set of meanders present in the south	– Extending meanders to the north through low-elevated areas, increasing inundation frequency which allows wetland development
Mark_2	25,5	16	51.62890, 4.66107	XII	– Low-elevated area (-0,50 m NAP to -1,40 m NAP) – Presence of a dike to the east, with a channel behind it	– Floodplain development by allowing inflow of water from the channel behind the dike to the east

					– Pumping station present in the north west – Steep elevation gradients – Approximately 50% of the area is covered with trees	– Lowering parts of the dike to initiate a more controlled inflow of water
SteenbergseVliet_3	5	4	51.60928, 4.30933	VI	– Presence of a small secondary channel – Presence of a pumping station in the north west, pumping water from the polders into the main river – Low-elevated area to the north of the pumping station	– Redirecting discharge water through the area with the secondary channel – Wetland development in the low-elevated area in the north – Opening up drainage pipes directly into the proposed wetland development location
SteenbergseVliet_2	3,5	25	51.61152, 4.29293	V	– Area with characteristics of a wetland directly adjacent to the main channel – Low-elevated area to the south of the dike (elevation levels of +0,50 m NAP)	– Development of a (low-gradient) buffer-strip by lowering or breaching the main dike – Extending the main dike to the south, initiating controlled inundation with wetland development – Opening up drainage pipes directly into the proposed wetland development location
SteenbergseVliet_6 / De Baak	11	50	51.59162, 4.37282	IX	– Waterbody with a surface area of 6,5 ha present to the south of the river – Pumping station present to the north of the waterbody – Low-elevated area present adjacent to the waterbody (0 m NAP on average)	– Wetland development directly in the waterbody by decreasing depth – Partially diverse the water from the waterbody to surrounding low-elevated areas
SteenbergseVliet_1 / Saspoldertje	0,5	11	51.62378, 4.26251	IV	– Presence of a man-made channel system with small bifurcations directly adjacent to the main river	– Increasing flow velocity by introducing a second opening in the south of the area

					– Natural area around the secondary channel characterized by various grass species – Inflow of water into this system from the north	
Volkerak_1 / St. Anthoniegorzen	0	60	51.68217, 4.40605	III	– Presence of a low-elevated area in close proximity to lake Volkerak, including various small channels and culverts and weirs – Presence of another low-elevated area to the south with low-gradient elevation levels	– Connect the first area (St. Anthoniegorzen) with the second area by partially lowering or breaching the dike to the north
Mark_3	26,5	185	51.63018, 4.68606	XIII	– A large area, functioning as a water storage area during flooding events – Low elevation levels (-0,20 m NAP) – Presence of weirs and a pumping station to the north west – Presence of embankments around the area	– Initiating controlled inundations with the use of existing weirs, resulting in an area with characteristics of a wetland, enabling macrophyte development
Dintel_1	5	11	51.63226, 4.42010	X	– Low-elevated area (+0,20 m NAP to +0,80 m NAP) north of the main river, partly consisting of agricultural soil and partly consisting of forest vegetation – Presence of a pumping station to the south east of the area	– Dredging a channel with bifurcations through the low-elevated area – Redirecting discharge water from the pumping station to the area in the north west
SteenbergseVliet_5	8,5	2,5	51.60301, 4.35336	VIII	– Presence of a low-elevated area (+0,30 m NAP) to the south of the main river	– Wetland development in the low-elevated area by lowering or breaching the dike to the north – Dredging a secondary through the low-elevated area

5. Conclusion

In this research, an answer to the following question was investigated: ''Which wetland design types are most effective in optimizing nutrient balances in the waterbodies upstream of lake Volkerak resulting in the reduction of frequency and intensity of algae blooms in lake Volkerak?'' In order to answer this question, literature research was combined with location-specific data on water levels, elevation levels and morphological characteristics.

Results from this research shows that wetland design types that are present directly adjacent to the main river provide the most suitable conditions for nutrient removal. These areas are proven to be most suitable for wetland development as they can relatively easily match the water levels in the main river and they do not require impactful methods that could potentially disturb current nature in the areas.

Ten out of thirteen of the investigated locations are located in areas where currently existing natural areas can be expanded or used for wetland development. Five locations (Appendices VI; VII; IX; X; XII) are characterized by the presence of a pumping station, allowing excess nutrients in the discharge water from the surrounding polders to be used for nutrient removal. The average potential surface area of the investigated locations is approximately 30 ha. Six locations are present in the river Steenbergse Vliet, another six locations are present in the river system Mark/Dintel and one location is present directly adjacent to lake Volkerak.

The most natural processes in a wetland are used when the elevation gradient between the land and the water level is low. This can be realized at locations with relatively large surface areas, for example in the areas described in Appendices III, IX and XIII. In the other areas, this low gradient is more challenging to realize, forcing the usage or construction of additional pumping stations or weirs.

Assuming a desired reduction of 15% and 30% for phosphorus and nitrogen respectively (considering the goals of the Good Ecological Potential; GEP) over the course of 10 years, an approximate total wetland surface area of 16.000 ha needs to be realized. This number is far higher than the combined surface area of all potential areas listed in chapter 4 (~390 ha). Based on this conclusion, it can be assumed that wetlands alone are not capable of reaching these goals. A more direct approach to reduce nutrient loading into lake Volkerak would be to directly reduce inflow of nutrients by lowering nitrogen and phosphate loading in agricultural soils. This would however require alternate policies and laws. Another proposed solution would be to completely turn lake Volkerak into a saltwater lake again. This would in theory lower eutrophication rates, potentially lowering the frequency and intensity of harmful algae blooms.

Because there is no guaranteed seasonal variability on inundations of areas around the rivers upstream of lake Volkerak, success of fish species reproduction in constructed floodplains is dependent on the timing of the inundations. If inundations occur too early in the year, water temperatures are too low for successful reproduction. This makes it more beneficial to construct floodplains characterized by high inundation frequency. So preferably, these areas are implemented directly adjacent to the river channel, as seen in the locations described in Appendices V and XI.

It is expected that the construction of floodplains favors the presence of limnophilic fish species such as *sunbleak* (*vetje*), *European bitterling* (*bittervoorn*) and *common rudd* (*ruisvoorn*). These specific fish species are also strongly associated with the presence of water plants and thus may benefit from vegetation development in floodplains and wetlands.

6. DISCUSSION

Since the topic that is covered in this research can be considered to be conceptual, correct interpretation of the results is important. The research topic can be considered conceptual because the measures that are proposed are based on theoretical information and have not been widely implemented in previous years.

The information, proposed methods and locations of interest that are provided in this report should serve as a basis for future similar research. Correct interpretation of these aspects should provide the reader with the relevant information needed to conduct more in-depth location-specific research on topics such as plant species selection, local biology and ecology and practical challenges (see chapter 7 – Recommendations).

The theoretical information that is provided in this report is derived from various sources. Quantitative data in this report is reproducible and includes data from the waterboard Brabantse Delta, the *WTZ-viewer* on *waterberichtgeving.rws.nl*[5], *AHN Nederland*[6], *Vastgestelde Legger Waterschap Brabantse Delta*[7] and scientific literature. Qualitative data in this report was retrieved from various sources, ensuring that the provided information is reliable. Some of this data contains information from real case studies, which increases viability of the results.

Generally speaking, the topic that is covered in this research is very complex, characterized by a large amount of different variables affecting the overall efficiency of the system. Extensive and detailed information on this topic is not widely available, resulting in the fact that the expected efficiency of the systems can only be based on limited data. Additionally, most of the data that is available is relevant for wetland systems designed to purify water from wastewater treatment sites.

If this research was to be replicated by using different methods and setting different requirements for the development areas, the results would most likely be different as well. Because it was not feasible to physically visit each location of interest listed in Table 7, some of these locations are expected to contain (currently unknown) features or characteristics that would either increase or decrease their potential for wetland or floodplain development.

One interesting finding in this research is the limited availability of natural features in the rivers closer to lake Volkerak, that could be potentially suitable locations for wetland or floodplain development. This makes it more challenging to conduct any developments in these areas. The areas in the rivers more upstream contain more natural features (for example meanders), making them more suitable for natural wetland or floodplain development.

[5] https://waterberichtgeving.rws.nl/wbviewer/wtz_viewer.php
[6] https://scheldestromen.maps.arcgis.com/apps/webappviewer/
[7] https://www.brabantsedelta.nl/legger

Another interesting finding in this research is that phosphorus removal is vastly different from and generally less efficient than nitrogen removal, which has implications for the design of the areas. Additionally, efficient phosphorus removal in wetlands may require more routine work, including plant harvesting. More research on this particular topic is needed.

As for plant species selection, more in-depth research is needed on the effectiveness of plant species and the effects of local organisms on the developments of this vegetation. For example, in various studies *Phragmites australis* is shown to be capable of removing nutrients, but it is also known that the presence of geese, nutria (*Myocastor coypus/beverrat*) and muskusrats (*Ondatra zibethicus/muskusrat*) result in relatively weak development of this type of vegetation, potentially reducing nutrient removal effectiveness.

7. RECOMMENDATIONS

Because this study focused on a limited amount of research-specific topics, further research is required to establish the viability of the findings.

The areas and specific locations of interest that were presented in chapter 4 provide a general overview of potential locations for initiating developments. Further research should focus on determining to what extent developments in these areas are limited by practical challenges. These practical challenges include:

- Cooperation of land owners
- Spatial limitations (e.g. presence of adjacent (agricultural) plots)
- Presence of nature protection areas
- Conflicting policies and/or laws
- Restricted financial viability
- Potential disturbance of cultural and recreational values and activities

In addition to research on these practical challenges, more research is required on location-specific characteristics. It was beyond the scope of this study to conduct research on all the location-specific characteristics such as details in morphology (water depth, flow velocity and hydrological regime), existing vegetation and historical location-specific developments. These aspects are proven to be important when initiating developments in an area, as they can greatly contribute to the viability and overall efficiency of the measures.

Additionally, since phosphorus can be considered to be the limiting nutrient for algae blooms, additional research is needed on efficient phosphorus removal, taking into account varying removal efficiency rates, depending on the salinity of the water. As shown in chapter 2.3.1.2 and Figure 11 on page 21, phosphorus removal is mediated by other processes than processes that mediate nitrogen removal. Phosphorus removal is mostly particle-bound and tends to require manual harvesting of vegetation, whereas nitrogen removal requires less intermediate maintenance. This difference indicates that further research on efficiency of permanent phosphorus removal by, for example, plant harvesting is necessary and should provide more information on this topic.

In order to guarantee successful measures, it is important to look at similar projects and monitor their developments. One specific project that comes to mind is the project around the Vierde Bergboezem in Breda (see chapter 2.5.1 on page 35). This project shares similar features with the proposed measures in this report and thus serves as an important project to be monitored. Additionally, it is exactly located in the project area.

As for literature recommendations, the following sources may provide helpful information and insights for the realization of the proposed measures and/or future research:

- Overview of documents by the waterboard Brabantse Delta that include analysis of water systems in the province of Noord-Brabant:
  Watersysteemanalyses Kaderrichtlijn Water (KRW)[8]

- Restoration of various natural water systems and case studies, with focus on self-sufficiency and usage of natural methods:
  Restoration of Lakes, Streams, Floodplains and Bogs in Europe – Principles and Case Studies (2010) by *Martina Eiseltová*. ISBN 978-90-481-9264-9

- In-depth theoretical examination of mechanisms in treatment wetlands, including historical perspectives, practical examples, case studies and different wetland design types:
  Treatment Wetlands (2008) by *R.H. Kadlec* and *S.D. Wallace*. ISBN 978-15-667-0526-4

- Report from *STOWA* (*Stichting Toegepast Onderzoek Waterbeheer*) about experiences and findings on the functioning of constructed treatment wetlands in sewage treatment plants:
  Waterharmonica – De Natuurlijke Schakel tussen Waterketen en Watersysteem (2005) by *A.H.H.M. Schomaker*, *A.J. Otte*, *J.J. Blom*, *T. Claassen* and *R. Kampf*. ISBN 90-5773-299-8[9]

- Database of numerous (historical) documents from various organizations and authors on various topics, including water system analyses and monitoring reports of nature development projects:
  Publicatieplatform UitvoeringsContent (PUC)[10]

- Report on water systems, including the Volkerak-Zoommeer, with various parameters and datasets (concept version; work in progress)
  Concept Systeemrapportage Volkerak-Zoommeer[11]

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[8] https://www.brabantsedelta.nl/watersysteemanalyses-kaderrichtlijn-water-krw
[9] https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202000-2010/Publicaties%202005-2009/STOWA%202005-18.pdf
[10] https://puc.overheid.nl/
[11] https://www.testsysteemrapportage.nl/VolkerakZM/

REFERENCES

Arends, H. (1977). *Biologische processen bij de zuivering van afvalwater in moerasvegetaties.* Rijkswaterstaat. Retrieved from https://puc.overheid.nl/rijkswaterstaat/doc/PUC_93086_31/1/

ARK Natuurontwikkeling. (2020, May 24). *Grazers brengen het landschap tot leven*. Retrieved from https://www.ark.eu/nieuws/2020/grazers-brengen-het-landschap-tot-leven

Besselink, D. (2019). *Watersysteemanalyse Mark Dintel Vliet.* Retrieved from https://brabantsedelta.overheidsbestanden.nl/Watersysteemanalyse%20Mark%20Dintel%20Vliet.pdf

Boelens, J. (n.d.). *Luchtfoto van de Philipsdam/Krammersluizen.* RWS Beeldbank, Sint Philipsland, Zeeland. Retrieved from https://beeldbank.rws.nl/MediaObject/Details/488711

Brix, H., & Schierup, H. (1989, January). *The Use of Aquatic Macrophytes in Water-Pollution Control*. (AMBIO - A Journal of the Human Environment) Opgehaald van https://www.researchgate.net/publication/230563410_The_Use_of_Aquatic_Macrophytes_in_Water-Pollution_Control

Cheng, R., Zhu, H., Shutes, B., & Yan, B. (2021). Treatment of microcystin (MC-LR) and nutrients in eutrophic water by constructed wetlands: Performance and microbial community. In *Chemosphere.* Elsevier. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0045653520323341

De Vries, I., & Postma, R. (2013, May 30). *Quick scan waterkwaliteit en ecologie Volkerak-Zoommeer*. (Deltares) Retrieved from https://www.commissiemer.nl/projectdocumenten/00000486.pdf

De Vries, I., & Postma, R. (2013, May 13). *Quick scan waterkwaliteit en ecologie Volkerak-Zoommeer*. Retrieved from https://www.commissiemer.nl/projectdocumenten/00000486.pdf

Dekker, D. (2021). Oeverzwaluw. *Oeverzwaluw.* Waarneming.nl, Schelde-Rijnkanaal, Zeeland. Opgehaald van https://waarneming.nl/photos/35659356/

Dorenbosch, M., Kooiman, M., Ploegaert, S., Vos, M., & Kranenbarg, J. (2020). *Visgemeenschappen in drie Nederlandse natte overstromingsvlakten.* RAVON, Nijmegen. Retrieved from https://library.wur.nl/WebQuery/hydrotheek/2291529

Eiseltová, M. (2011). *Restoration of Lakes, Streams, Floodplains, and Bogs in Europe - Principles and Case Studies.* Springer.

Fisher, J., & Acreman, M. (2004). Wetland nutrient removal: a review of the evidence. In *Hydrology and Earth System Sciences* (pp. 673-685). Wallingford, United Kingdom:

European Geosciences Union. Retrieved from https://hess.copernicus.org/articles/8/673/2004/hess-8-673-2004.pdf

Huggins, D., Kastens, J., Baker, D., & Freeman, C. (2017). *Conversion of existing farm ponds to wetlands in agricultural landscapes for mitigation, land use treatment and conservation with a perspective toward climate change.* University of Kansas, Central Plains Center for BioAssessment. Retrieved from https://biosurvey.ku.edu/sites/biosurvey.ku.edu/files/publishedworks/pdfs/KBSrpt189_farmpond_72845.pdf

Johnston, C. (1991). Sediment and nutrient retention by freshwater wetlands: Effects on surface water quality. In *Critical Reviews in Environmental Control* (pp. 491-565). doi:10.1080/10643389109388425

Kadlec, R., & Wallace, S. (2009). *Treatment Wetlands* (2nd ed.). CRC Press. Retrieved from https://sswm.info/sites/default/files/reference_attachments/KADLEC%20WALLACE%202009%20Treatment%20Wetlands%202nd%20Edition_0.pdf

KNMI. (n.d.). *Archief maand/seizoen/jaaroverzichten*. Retrieved March 21, 2021, from https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/

Kouer, R., & Griffioen, A. (2003). *Water- en stoffenbalans Volkerak-Zoommeer; microverontreinigingen en nutriënten 1996-2000.* Rijkswaterstaat, Dordrecht. Retrieved from https://www.deltaexpertise.nl/images/c/c8/Water_en_stoffenbalans_VZM_1996-2000.pdf

Mihelcic, J., & Zimmerman, J. (2014). *Environmental Engineering* (2nd ed.). United States of America: John Wiley & Sons Inc.

Nagelkerke, N. (2011). Leren van de Wolga; vloedvlaktes blijken belangrijk voor vis. *Visionair*, 16-19. Retrieved from https://library.wur.nl/WebQuery/wurpubs/420071

Natura 2000. (n.d.). *Krammer-Volkerak*. Retrieved from https://www.natura2000.nl/gebieden/zeeland/krammer-volkerak

Planviewer. (n.d.). *Hoofdstuk 2 - Gebiedsanalyse*. Retrieved from https://www.planviewer.nl/imro/files/NL.IMRO.0758.BP2011065001-0501/t_NL.IMRO.0758.BP2011065001-0501_0002Gebiedsanalyse.pdf

Planviewer. (n.d.). *Rijksinpassingsplan Waterberging Volkerak-Zoommeer*. Retrieved from https://www.planviewer.nl/imro/files/NL.IMRO.0000.IMip12BERGINGVZM-3000/t_NL.IMRO.0000.IMip12BERGINGVZM-3000_2.1.html

Rijkswaterstaat, Waterdienst, Deltares, Royal Haskoning, Arcadis. (2012). *Milieueffectrapportage Waterkwaliteit Volkerak-Zoommeer.* Retrieved from https://www.commissiemer.nl/projectdocumenten/00000502.pdf

Rios, S., & Bailey, R. (2006, January). Relationship between Riparian Vegetation and Stream Benthic Communities at Three Spatial Scales. *Hydrobiologica*, 153-160. Retrieved from https://www.researchgate.net/publication/226489964_Relationship_between_Riparian_Vegetation_and_Stream_Benthic_Communities_at_Three_Spatial_Scales

Schomaker, A., Otte, A., Blom, J., Claassen, T., & Kampf, R. (2005). *Waterharmonica - De Natuurlijke Schakel tussen Waterketen en Watersysteem.* Utrecht. Retrieved from https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202000-2010/Publicaties%202005-2009/STOWA%202005-18.pdf

Sentinel Hub. (2019, August 24). *Sentinel Hub EO Browser*. Retrieved from apps.sentinel-hub.com/eo-browser/

Syversen, N., & Bechmann, M. (2004). *Vegetative buffer zones as pesticide filters for simulated surface runoff.* Norwegian Centre for Soil and Environmental Research. Aas: Elsevier. Retrieved from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1043.7171&rep=rep1&type=pdf

The Task Force. (2002). *The Natural and Beneficial Functions of Floodplains.* The Task Force. Retrieved from https://www.hud.gov/sites/documents/DOC_14217.PDF

Thiere, G. (2009). *Biodiversity and ecosystem functioning in created agricultural wetlands.* Lund University, Department of Ecology, Limnology, Lund. Retrieved from http://www.diva-portal.org/smash/get/diva2:240186/FULLTEXT01

Ton, H. (2019, April). *Fort Sabina*. Retrieved from Google Maps: https://goo.gl/maps/34JbQQtvRegqywkx8

Tosserams, M., Lammens, E., & Platteeuw, M. (2000). *Het Volkerak-Zoommeer - De ecologische ontwikkeling van een afgesloten zeearm.* Rijkswaterstaat, Lelystad. Retrieved from https://www.deltaexpertise.nl/images/5/54/Tosserams_Volkerak-Zoommeer_afgesloten_zeearm_2000.pdf

Tosserams, M., Vulink, J., & Coops, H. (1999). *Tussen Water en Land, Perspectief voor oeverplanten in het Volkerak-Zoommeer.* RIZA, Lelystad.

Van Houdt, J. (2008). *Luchtfoto RWS Zuid Holland Volkeraksluizen.* RWS Beeldbank, Zuid-Holland. Retrieved from https://beeldbank.rws.nl/MediaObject/Details/318088

Van Houdt, J. (2008). *Volkerak schorren ter hoogte van Oude Tonge.* RWS Beeldbank, Oude-Tonge, Zeeland. Retrieved from https://beeldbank.rws.nl/MediaObject/Details/342405

Van Rooij, S., Groen, K., Röling, Y., Slager, H., & Stoffer, M. (1996). *De oevergebieden van het Volkerak-Zoommeer.* Ministerie van Verkeer en Waterstaat, Lelystad. Retrieved from https://edepot.wur.nl/257028

Vereniging Markdal. (n.d.). *Over het Markdal*. Retrieved from https://verenigingmarkdal.nl/het-markdal/over-het-markdal/

Vereniging Markdal. (sd). *Over het Markdal*. Opgehaald van https://verenigingmarkdal.nl/het-markdal/over-het-markdal/

Verspagen, J., Boers, P., Laanbroek, H., & Huisman, J. (2005). *Doorspoelen of opzouten? Bestrijding van blauwalgen in het Volkerak-Zoommeer.* Retrieved from https://puc.overheid.nl/rijkswaterstaat/doc/PUC_121758_31/

Vymazal, J. (1995). *Algae and element cycling in wetlands.* Boca Raton, Florida, United States of America: Lewis Publishers Inc. Retrieved from https://www.cabdirect.org/cabdirect/abstract/19951906893

Vymazal, J. (2004). Removal of Phosphorus in Constructed Wetlands with Horizontal Sub-Surface Flow in the Czech Republic. In J. Vymazal, *Water, Air and Soil Pollution* (pp. 657-670). Retrieved from https://link.springer.com/article/10.1023/B:WAFO.0000028385.63075.51

Vymazal, J. (2007, October 31). Removal of nutrients in various types of constructed wetlands. In J. Vymazal, *Science of the Total Environment* (pp. 48-65). Prague, Czech Republic. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0048969706007212

Wallace, S., & Knight, R. (2006). *Small-Scale Constructed Wetland Treatment Systems - Feasability, Design Criteria, and O&M Requirements.* WERF, North American Wetland Engineering. London: IWA Publishing.

Waterschap Brabantse Delta. (n.d.). *Project Cruijslandse Kreken en Smalle Beek*. Retrieved April 21, 2021, from https://www.brabantsedelta.nl/project-cruijslandse-kreken-en-smalle-beek

Waterschap Brabantse Delta. (n.d.). *Vastgestelde legger Waterschap Brabantse Delta*. Retrieved from https://www.brabantsedelta.nl/legger

Waterschap Scheldestromen. (2016). *Waterakkoord Volkerak-Zoommeer.* Retrieved from https://scheldestromen.nl/sites/scheldestromen.nl/files/default_images/Waterakkoord%20Volkerak%20Zoommeer.pdf

Weeber, M., Troost, T., Kramer, L., Tiessen, M., Genseberger, M., Boderie, P., & Nolte, A. (2018, February 8). *Data-analyse Blauwalgen en Quagga mosselen*. (Deltares) Retrieved from https://docplayer.nl/114001322-Volkerak-zoommeer-data-analyse-blauwalgen-en-quagga-mosselen.html

Wikipedia, the Free Encyclopedia. (2013, December 7). *Kleine Aa (Wildertse Beek)*. Retrieved April 15, 2021, from https://nl.wikipedia.org/wiki/Kleine_Aa_(Wildertse_Beek)

Wolfstein, K. (2003). *Microcystines in het Volkerak-Zoommeer en hun mogelijke rol in de vogelsterfte.* Ministerie van Verkeer en Waterstaat - Rijkswaterstaat. Retrieved from https://www.deltaexpertise.nl/images/9/96/Microcystines_VZM_mogelijke_rol_vogelsterfte_2003.pdf

Xibao, X., Chen, M., Yang, G., Jiang, B., & Zhang, J. (2020). Wetland ecosystem services research: A critical review. In *Global Ecology and Conservation.* Retrieved from https://www.sciencedirect.com/science/article/pii/S2351989420300263

Ysebaert, T., & Walles, B. (2017). *Quaggamosselen (Dreissena rostriformis bugensis) in het Volkerak-Zoommeer.* Wageningen Marine Research. Retrieved from https://www.zwdelta.nl/sites/all/files/default/quagga_mosselen_volkerak-zoommeer.pdf

Zhang, Y., Liang, J., Zeng, G., Tang, W., Lu, Y., Luo, Y., . . . Huang, W. (2020). How climate change and eutrophication interact with microplastic pollution and sediment resuspension in shallow lakes: A review. In *Science of the Total Environment.* Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/S0048969719359741

Zuidwestelijke Delta. (2018, March 29). *Blauwalg in het Volkerak-Zoommeer*. Retrieved from https://www.zwdelta.nl/nieuws/blauwalg-in-het-volkerak-zoommeer