MASTER THESIS

Modelling of a paludiculture system for filtering excess nutrients on farmlands in Dutch polder landscapes

August 2020

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ABSTRACT

Phytoremediation has been emerging as a cost efficient and an effective solution for filtering excess nutrients from agricultural run-off. The concept of phytoremediation was applied in this thesis to remove excess nutrients (N and P) from farmlands in the province of Friesland in the Netherlands. Paludiculture plants that have the potential to yield high biomass and ability to remove the excess nutrients were studied. A model was developed using STELLA architecture to understand and analyse the factors that influence the removal mechanisms in order to design an effective system for nutrient removal. Based on theoretical calculations, using *T. latifolia* as vegetation over approximately 3% of total land cover would result in the removal of 42% of N and 37% of P of the inflow concentrations with the biomass capacity in the range of 4-22 t/Ha/yr. Using *P. australis* over the same area would result in the removal of 39% of N and 33% of P of the inflow concentration with the biomass capacity in the range of 6-18 t/ha/yr. The most important factors that influence nutrient removal were found to be nutrient loading rates, type of vegetation used and hydraulic retention time. For vegetation growth, the factors that caused major influences were seasonal periodicity and harvesting period. The motivation of farmers and problems that need to be encountered while having the paludiculture crops on the farmlands are also discussed in this paper.

KEYWORDS: Phytoremediation, Paludiculture, Peatlands restoration, Nutrient removal.

ACKNOWLEDGMENTS

I am deeply grateful to Dr. Jasper Van Belle, my technical supervisor in this project for providing me with the opportunity to carry out the internship and giving me all the resources to investigate a topic that I had little prior knowledge. He understood my needs even before I asked and showed me the directions to find the answers to my questions. It was a wonderful experience working with him.

I am obliged to my supervisor Dr. Gül Özerol, who has been supportive and had constant faith in me which kept me positive throughout the thesis work. Her immediate feedback to my drafts and timely help has kept me progressing consistently working without stress.

Special thanks to Dr. Laura Franco-García for her kind words and encouragement from the day I spoke to her during my master course. Her constructive feedback has helped me structure my work and deliver the information of my research in a better way.

And on a personal note, I thank my parents for believing in me and being my pillar of strength. I also thank my aunt and her kids for providing me the emotional support during these uncertain times.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

CO_2	Carbon dioxide
N	Nitrogen
P	Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
WFD	Water Framework Directive
NH_4	Ammonium
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
O_2	Oxygen
FFP	Free Floating Plants
CW	Constructed Wetland
HSSF	Horizontal subsurface flow
VSSF	Vertical subsurface flow
FWS	Free Water Surface
VF	Vertical Flow
HF	Horizontal Flow
HRT	Hydraulic Retention Time
g/m2/year	Grams per metre square per year
g/m2/d	Grams per metre square per day
kg/ha/yr	Kilograms per hectare per year
TA	Total Area

Chapter 1 Introduction

1.1 Background

Peatlands are a type of wetlands, covering over 400 million hectares, which is almost 3% of the total surface on earth (Joosten, 2009). The term 'peatland' refers to the peat soil and the wetland habitat growing on its surface. But currently they are being drained in most places due to land clearance, drainage, fire and climate change. This reduces the direct benefits that people get from these natural ecosystems and causes other environmental problems. Though they cover only 3 percent of the world's land area they contain 30 % of the world's soil carbon (Vroom et al., 2018).

Centuries of peat cutting and drainage has resulted in the reduction of total peatland cover in the Netherlands from 40% of total land cover to 10% currently. This has resulted in the emission of 19 tonnes of carbon dioxide CO2 per hectare in a year which, leading to poor water quality at the surface level and causing rapid soil subsidence of 2cm/year. It has been estimated that the continuous soil subsidence will lead to 40-60 cm reduction in the soil level between 1999 and 2050 (Brouns et al., 2014). The government and the water authorities have realised the emergency of the situation and are working in finding solutions for restoring the peatlands and reducing the environmental harm to minimum.

Peatlands play a significant role in climate regulation. It is estimated that in the last 10,000 years, peatlands has absorbed over 1.2 trillion tons of CO_2 from the atmosphere, resulting a net cooling effect, but currently due to human activities the peatlands are being drained at a faster rate in the past 100 years, which result in the emission of absorbed carbon into the atmosphere becoming a net source of carbon emissions (Parish et al., 2008). Globally, the CO2 emissions from drained peatlands (including emissions from peat fires) amount to two gigatonnes per year (Joosten, 2009) and represent almost 25 percent of the CO_2 emissions from the entire land use, land use change and forestry sector (Canadell, 2011). Peatlands are now the world's largest terrestrial long-term sink of atmospheric carbon storing twice as much carbon as the biomass of the world's forests (Parish et al., 2008). This means that, if conserved, peatlands can play a vital role in climate mitigation. The conversation and rewetting of the peatlands are one of the cost effective ways to control emissions. Therefore, strategies should be developed where the peatlands need to be converted for productive use, land use options that are compatible with wet conditions. This practice of converting peatlands for productive use is called paludiculture. Paludiculture is the productive utilization of rewetted wetlands and wetlaculture, which is the changing of a wetland to an agricultural field after years of receiving nutrients from agricultural and urban runoff that is maintained without adding any fertilizers.

Besides being an effective carbon sink, the peatlands can store large amounts of nitrogen (N) and phosphorus (P) due to the slow turnover of organic matter under anoxic conditions (Reddy and De Laune, 2008). The rewetting of peatlands results in the movement of nutrients which accumulate in pore water and surface water to be absorbed by these plants preventing eutrophication of water systems (Vroom et al., 2018).

The use of plant species to clean polluted soils and waters is called “phytoremediation”. This process is much cheaper compared to other cleaning technologies and many studies have been conducted in this field since the last decade (Lone et al., 2008). This thesis will employ the concepts of phytoremediation in the removal of N and P nutrients from agricultural run-off wastewaters.

The rapid uptake of the nutrients by paludiculture crops provides better nutrient cycling and the option of removing nutrients by harvesting biomass. The utilization of the paludiculture plants for biogas generation is a promising and sustainable option, delivering energy and also a digestate that can be applied as a valuable organic soil fertilizer rich in C, N, and P. The organic fertiliser reduces the dependence on synthetic fertilisers resulting in less pollution from artificial fertilisers and improving the natural nutrient cycle on land (Banaszuk et al., 2020).

1.2 Problem Statement

Excess nutrients flow from agricultural run-off wastewaters from the farmlands has been a problem in the province of Friesland in the Netherlands. The excess nutrients especially N and P results in the pollution of surface water when this water mixes in the canals. The final report of the ex-ante evaluation of the Dutch plans was published in January 2016 for the Water Framework Directive (WFD) (Van Gaalen et al., 2016). The conclusion of the report was that the water quality in 2027 would not meet the WFD targets, and almost half of the regional waters would not meet the nutrient target and nutrient concentrations would become too high, a limiting factor for realizing the WFD goals. Following that report, Wageningen Environmental Research was commissioned by Wetterskip Fryslân, the regional water authority in Friesland. The commission carried out the project “Dust Flow Analysis” (Van Boekel et al., 2016). In this project, the origin of the current load of surface water with nitrogen (N) and phosphorus (P) for six polders in the province of Friesland was quantified. The emphasis was on unraveling the total nutrient load, so that it can be distinguished which part of the nutrient load can be influenced. Also is the effect of the proposed fertilizer policy on the N and P loads of the surface water mapped. The results show that, depending on the area, the current fertilization, the inlet water and subsequent delivery from agricultural soils are the most important sources of nitrogen and phosphorus load to surface water. Based on the calculations performed within the framework of the ex-ante evaluation WFD the effect of the proposed manure policy is relatively low in limiting the nutrient pollution. Therefore, additional measures are necessary to reduce the nitrogen and phosphorus load on surface water measures. The rural development subsidy program makes it possible grants are awarded to initiatives to improve water quality. Attributing this, Wetterskip Fryslân wants to develop various measures to improve effectiveness. One of them is increasing the peatlands on the polder landscape (Van Boekal et al., 2017).

1.3 Research Objective

The objectives of this thesis are to develop the knowledge for designing the paludiculture system that can effectively function in removing excess nutrients, i.e., N and P, produced on the farmlands and to quantify the potential for biomass production. In order to reach these objectives, a model will be developed, including all the factors that influence the nutrient dynamics of the wetland as presented in chapter 6.

1.4 Research Questions

Multiple research questions were formulated to achieve the research objectives. The main research question is as follows:

> How to design the paludiculture systems in such a way that they function effectively in filtering the excess nutrients from the farmlands?

Following sub-questions will be answered to be able to answer the main research question:

a) Which factors influence the effective functioning of the plants in nutrient intake?
b) What is the amount of nutrients absorbed and the biomass produced by the different types of plants that can be grown in the study area?
c) What is the ideal position on the farmland to grow the selected paludiculture plants?
d) What is the farmers' perspective on growing the paludiculture plants in their lands?

The main research question is directly related to the research objectives. The sub-questions a) and b) provide the answers for understanding the nutrient removal processes and the factors that need to be considered in order to improve the removal processes. The sub-questions c) and d) deal with the practical implications of implementing the paludiculture plant system in the farmland.

1.5 Thesis Outline

Chapter 2 presents the research design that is carried out for finding the answers to reach the research objective. Chapter 3 discusses the nutrient dynamics within the wetland ecosystem to understand the removal processes in the removal of nutrients from wastewater. Chapter 4 analyses the factors that affect the removal processes and how the factors are interlinked with each other. Chapter 5 describes the plant species that can be used as vegetation to remove the nutrients and also provide biomass. Chapter 6 discusses the developed paludiculture model and the data about nutrient removal. Chapter 7 discusses the results, and finally chapter 8 includes the conclusions leading up to answering the main research question.

Chapter 2 Research Design

This chapter presents the research design that was employed in the thesis. The research strategy and framework are described along with the methods of data collection and analysis.

2.1 Research Strategy and Framework

The foremost step carried out during the research design was defining the research objective and then the objectives were translated into a central research question and three different sub-questions. Research framework and methodology was developed to find answers for the chosen research questions. The strategy followed, and the analytical framework developed for the research is described in a step-by-step manner and visualized in Figure 1.

Step 1: Secondary data was collected in order to find answers for the sub-questions. The secondary data was sourced from review papers, scientific publications and grey literature.

Step 2: The research was primarily carried out as a desk research obtaining information about the nutrient dynamics in a wetland ecosystem and the various factors influencing the nutrient dynamics. The collected data was analysed with a combination of different research perspectives, Exploratory (How the nutrient dynamics in the wetland ecosystem works) and Evaluative (The effectiveness of the plant and microbial functioning to remove nutrients under these certain conditions).

Step 3: The studied information was employed in developing a model for effective designing for nutrient removal using paludiculture plants and the model was discussed with experts working with paludiculture plants. With the expert inputs, the changes in the model were carried out. The model was developed using the software STELLA to visualise the processes along with the various important factors that are influencing the nutrient removal dynamics in the wetland ecosystem.

Step 4: Interviews were conducted with farmers to get their perspective based on the calculations made with the developed model to check the effectiveness of nutrient removal with the paludiculture crops and choosing the apt position for having the paludiculture crops in the farmlands in the selected area of study.

Step 5: The results of the interviews were analysed. Based on the results, the conclusions and recommendations were made.

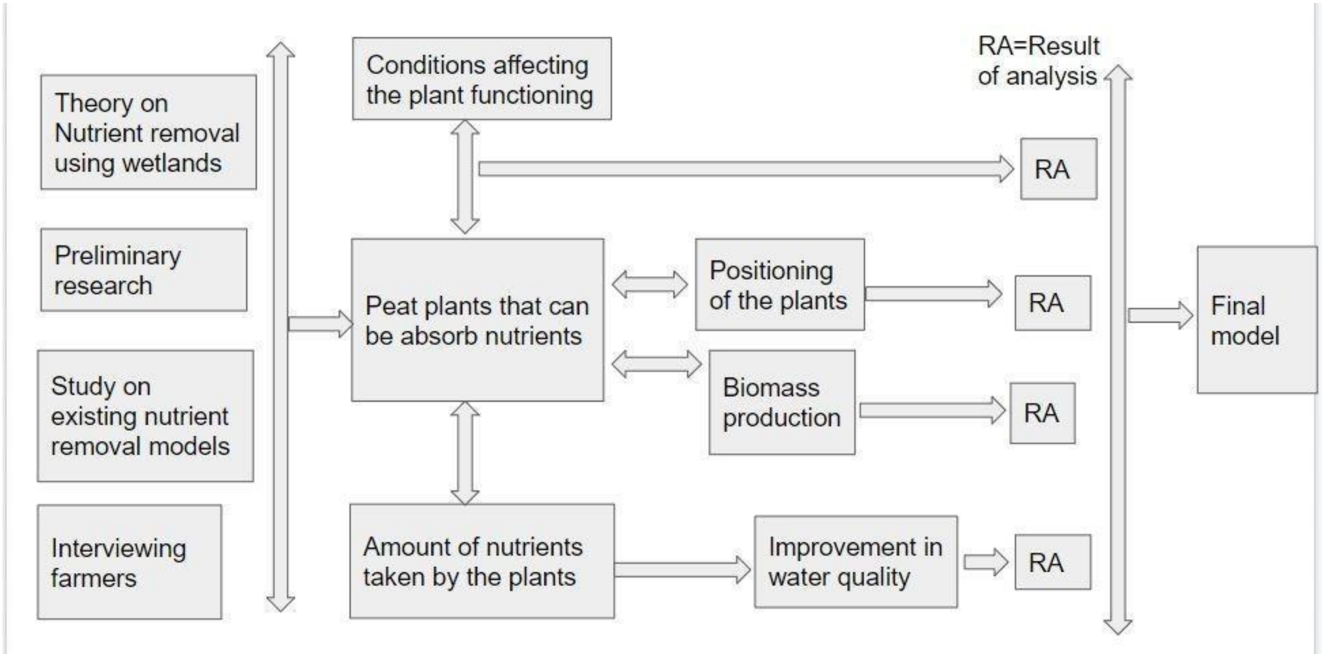

Figure 1 The schematic representation of the research framework

2.2 Research Unit

The research was conducted with the help of Van Hall Larenstein Applied Research Centre in Leeuwarden, the Netherlands. The knowledge provided by this research is to be used in the projects 'Carbon Connects' and 'Better Wetter'[1].

Area of study

In the study by Van Boekel et al. (2016), the measures on the nitrogen and phosphorus load of the surface water are calculated for nitrogen and phosphorus load throughout the period 2011-2013 in the six polders using the substance flow analysis. Based on this data, the polder area Echten was chosen as the area of study out of the six polder areas mentioned in the report. The six polder areas are shown in Figure 2. Figure 3 shows the buffer strip alongside the farmlands in which the paludiculture plants are to be placed.

[1] **Carbon Connects** is an EU funded project that aims at restoring the peatlands in Europe by establishing a carbon credit system to encourage farmers to grow the peat plants on their farmland. The project **'Better Wetter'**, aims at improving the water quality in Friesland using the peat meadows.

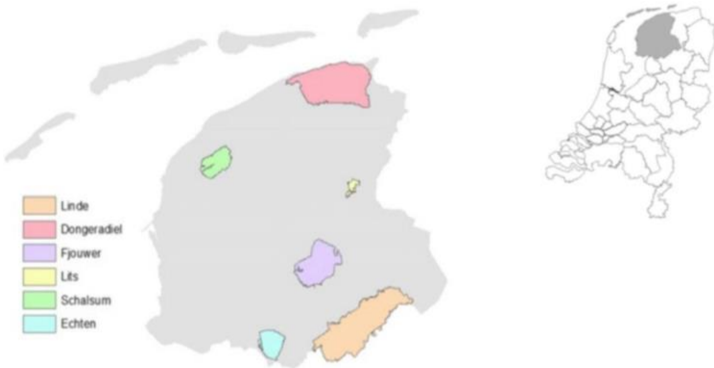

Figure 2 Map of the province of Friesland with chosen area of study

Figure 3 The buffer strip alongside the farmlands in which the paludiculture plants are to be placed

Source: Van Boekel et al. (2016)

The nutrient loading rates of the selected study area are shown in Table 1.

Details about the area of study	
Name of the chosen polder	Echten
Total area (Ha)	2858
Area with agriculture (Ha)	2326
Total N inflow (Kg/Ha/year)	11.4
Total P inflow (Kg/Ha/year)	1.5
Shallow water flow (%)	8
Percentage of flow in summer (%)	15
Percentage of flow in winter (%)	85

Table 1 Nutrient loading information about the polder area of study

Source: Van Boekel et al. (2016)

2.3 Data Collection

Primary and secondary data was used to answer the research questions. The sub-questions (a) and (b) were answered based on secondary data, while the answers for the sub-question (c) were based on primary data by collected interviewing stakeholders involved in the application of the project. The data collection is described in Table 2.

Research question	**Information/data needed to answer the question**	**Sources of the data**	**Method of accessing**
a) Which factors influence the effective functioning of the plants in nutrient intake?	Nutrient transformations happening that occur in the wetland ecosystem	Secondary data: Scientific publications	Content analysis
	Factors that affect the processes that help nutrient transformation in the wetland	Secondary data: Scientific publications	Content analysis
b) What is the amount of nutrients absorbed and the biomass produced by the different types of plants that can be grown in the study area?	Plants that can intake nutrients	Secondary data: Scientific publications	Content analysis
	Amount of nutrients the plants can intake	Secondary data: Scientific publications	Content analysis
	Total biomass provided by the plants	Secondary data: Scientific publications	Content analysis
c) What is the ideal position on the farmland to grow the selected paludiculture plants?	Information about the study area	Documents	Content analysis
	Criteria for choosing the ideal position	Primary data	Interview
d) What is the farmers' perspective on growing the paludiculture plants in their lands?	The motivation of farmers to grow paludiculture plants	Primary data	Interview

Table 2 Data collection for answering the research questions

2.4 Ethical Considerations

The research was conducted keeping the ethical principles, avoiding exploitation, distribution of benefits and burdens, respect for the person involved in the research, respect for human dignity, scientific validity, scientific and social relevance, upholding the rights of the research participant and safeguarding confidentiality and privacy. The participant taking part in the study was requested to sign a consent form declaring their willingness to take part in the research and the context of the study.

2.5 Limitations

The following limitations were considered in the conducted thesis:

i) Due to the uncertain situation of the coronavirus pandemic outbreak, the site visits were cancelled, and the research was carried out remotely with the available data about the area of study.
ii) The calculation carried out to estimate the amount of nutrient removal using plants is theoretical. The actual results can vary during the empirical implementation.
iii) Time was a restriction that led to only one interview conducted to obtain the stakeholders' perspective.

Chapter 3 Nutrient Dynamics

This chapter discusses how nutrients (Nitrogen and Phosphorous) are being cycled, transformed into different forms and are being transferred and taken up by the microbes and vegetation in the wetland ecosystem. The chapter explains the various processes that take place and the relationship between these processes and the flow of nutrients within the wetland environment.

Understanding the hydrology (balance of water rise and loss along with net water storage) lies the important basics for understanding about the wetlands and their management. The particular hydrology of the wetlands controls biogeochemical processes, the structure of the ecosystem and the storage of organic matter. The combination of the wetland hydrology along with the organic and non-organic compounds help in the environmental regulation. Like said, the mix of chemicals, particulate matter, organic matter, plant nutrients and the environment (patchy, dry, wet) determines the functioning of the ecosystem in this wetland environment. Wetlands are the conjunctions of not only land and water but only surface water, groundwater and the atmospheric moisture. These wetlands process the biologically available elements such as carbon (C), nitrogen (N) and Phosphorus (P), which play the main roles in the functioning of the ecosystem and also have a role to perform in the balance of these nutrients in the biosphere. The soil, the water levels, fungi, bacteria along with the vegetation in these wetlands constitute an efficient recycling of the nutrients and are capable of breaking down the incoming nutrients from external sources (organic plant waste, waste from human activities) by which they maintain the balance between the nutrients in the biosphere (Barker et al., 2009).

3.1 Nitrogen Transformation in Wetlands

Nitrogen has seven valence states (+5 to -3) making it a complex element having various biochemical cycles going through various biotic and abiotic transformations. The organic and the inorganic forms of Nitrogen are essential for various life forms. The inorganic forms of Nitrogen in the wetlands are Ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). Gaseous nitrogen may exist as dinitrogen (N_2), nitrous oxide (N_2O), nitric oxide (NO_2 and N_2O_4) and ammonia (NH_3) (Vymazal, 2007).

Nitrogen in the wetlands continuously goes through chemical transformation taking various forms from inorganic to organic compounds and then back from organic to inorganic compounds. Some of these processes require energy (mostly obtained from external carbon sources) while some of them release energy which is taken up by the organisms for their growth (Vymazal,2007).

Not all the process of Nitrogen transformation in wetlands removes Nitrogen from the wastewater. Some of the processes convert Nitrogen from one form to another. Ammonia volatilization, denitrification, plant uptake (with biomass harvesting), ammonia adsorption, ANAMMOX and organic nitrogen burial are the mechanisms that remove Nitrogen from the water while processes like ammonification and Nitrification only convert Nitrogen to various forms. The processes that affect the transformation of Nitrogen in the wetland are discussed in the following sections. All the mechanisms involved in the removal of nitrogen are shown in Figure 4.

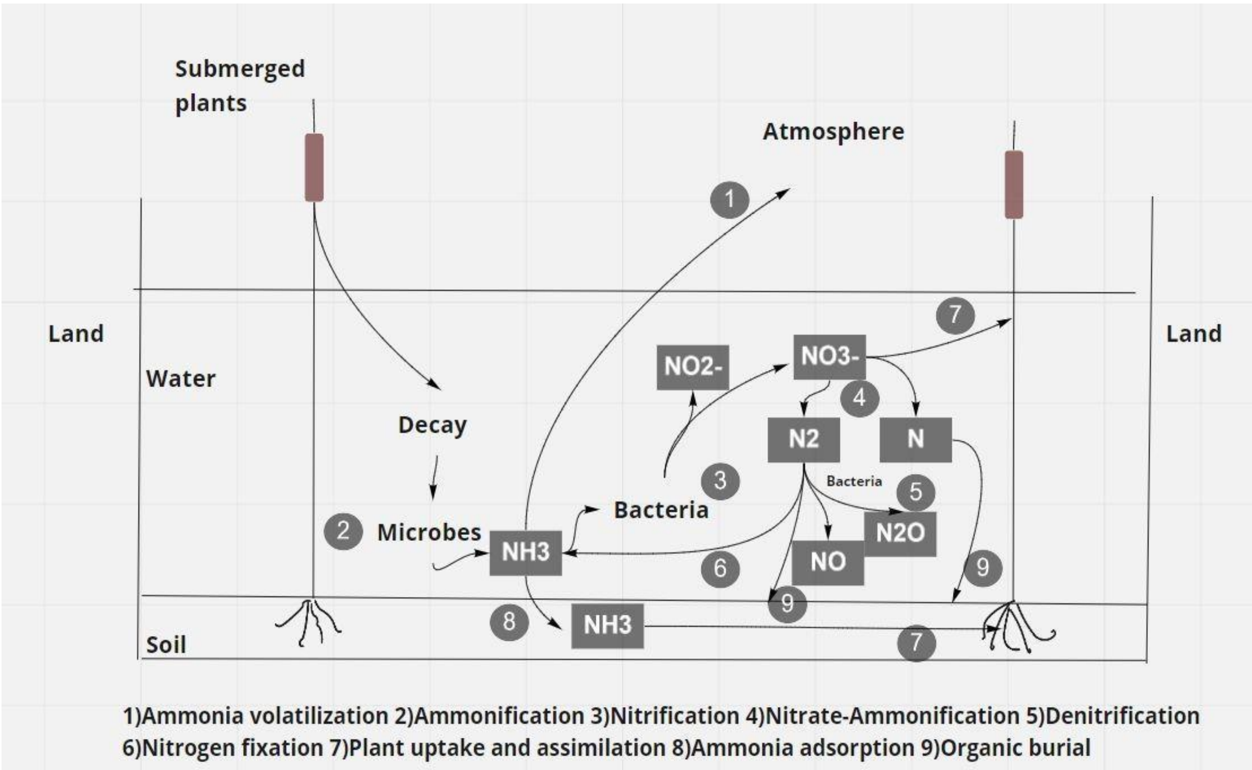

Figure 4 Nitrogen removal processes in the wetland ecosystem

Ammonia volatilization

Nitrogen can be changed into Ammonia gas (NH_3). Ammonia gas can be lost from the soil and return to the atmosphere. This is called Ammonia volatilization. The process of volatilization commonly takes place when nitrogen is in organic form known as urea. Urea may come from animal manure, urea fertilisers or from the decay of plant materials (Killpack and Buchholz,2020). Ammonia volatilization is a physicochemical process in which the ammonium-N is in equilibrium between gaseous and hydroxyl forms. According to Reddy and Patrick (1984), the losses of NH_3 is insignificant under a pH of <8, the ammonia and ammonium are to be in the ratio of 1:1 when the pH is above 9.3 and the losses through volatilization is significant. The photosynthesis of submerged macrophytes and that of algae often creates high pH values during the day. The pH of the water is greatly affected by the gross photosynthesis of all the species present in the water (Vymazal,2007).Though the process of Ammonia volatilization does not directly impact the water quality, it results in a net loss of Nitrogen from the soil system. The nutrient removal rate through ammonia volatilization was found to be as high as 2.2 gN/m/d Stowell et al. (1981)

Ammonification

Ammonification is a multi-step biochemical process that converts nitrogen from microbes, plants and macrophytes into Ammonia after their death. According to (Kadlec and Knight, 1996), a large fraction of organic Nitrogen (up to 100%) is converted into Ammonia. This process is mostly performed by the bacteria and fungi present in the water. The process of mineralisation happens both in aerobic and anaerobic zones, the rate of mineralization is much faster in aerobic zones and decreases as they move through anaerobic zones. Ammonification depends on factors like temperature, pH, C/N ratio, other available nutrients and soil conditions like texture and structure (Reddy and Patrick, 1984). The optimal pH for this process is between pH 6.5-8.5 and the temperature is 40-60 °C. A wide range of ammonification rates are reported in the literature, with values ranging between 0.004 and 0.53 gN/m2/d (Vymazal, 2007).

Nitrification

Nitrification is the biological oxidation process in which the ammonium is converted into Nitrate with Nitrite as an intermediate. Nitrification is a chemoautotrophic process done by bacteria, the process in which the bacteria carrying out obtains energy from the oxidation of ammonia or nitrate with CO_2 used as the carbon source. Paul and Clark (1996) point out that Nitrification is a two-stage process involving two groups of microbes, one group converts Ammonium-N into Nitrite-N and another oxidises Nitrite-N into Nitrate-N. The first stage is performed by aerobic bacteria which relies completely on the oxidation of Ammonium for its energy. The second stage of oxidation is carried out by chemolithotrophic bacteria which uses organic compounds and Nitrate for its growth. Temperature, alkalinity of the water, source of C, pH, amount of dissolved oxygen and concentration of ammonium are found to be some of the factors that influence the rate of nitrification. The optimum temperature for nitrification is found to be between 30 to 40 °C in the soil and pH between 6.6-8. The amount of N removal through nitrification was found to be in the range of 0.01–2.15 gN/m2/d with the mean value of 0.048 gN/m2/d (Tanner et al., 2002).

Nitrate-ammonification

The anoxic oxidation process that reduces nitrate into molecular nitrogen or ammonia. This reduction process is performed by two different groups of bacteria which produces N_2O and N_2 as the products of reduction. The nitrate-ammonifying bacteria produces NH_4 as the product of the reduction of nitrate (Vymazal,2007).

Denitrification

Nitrate is converted into dinitrogen with nitrite, nitric oxide and nitrous oxide as intermediate. This process is called denitrification. Denitrification is a biochemical process in which the electrons are carried from an electron-donating substrate, usually organic compounds, to a more oxidized N form. The resultant free energy is used by denitrifying organisms to support respiration. This reaction is irreversible and happens only in anaerobic conditions. Many organisms have been found to perform this process, most denitrifying bacteria are chemoheterotrophs (Paul and Clark, 1996). These bacteria obtain their energy mainly through the chemical reactions and use organic compounds as electron donors. Environmental factors known to influence denitrification rates include the absence of O_2, redox potential, soil moisture, temperature, pH value, presence of denitrifiers, soil type, organic matter, nitrate concentration and the presence of overlying water (Focht and Verstraete, 1977; Vymazal, 1995). Optimum pH range lies between 6 and 8 while the process slows down below 5 and does not take place below 4. The process is strongly temperature dependent and happens between 60 to 75 °C. The denitrification rates varies widely in between 0.003 and 1.02 gN/ m2/d (Reddy and D'Angelo, 1997).

Nitrogen Fixation

Nitrogen fixation is the process in which the gaseous Nitrogen (N_2) is converted into Ammonia. In wetland soils, the nitrogen fixation happens on the soil surface in aerobic and anaerobic flooded soils, in the root zone, on the stem and leaves of the plant. Numerous bacteria that attach themselves to host plants, some heterotrophic bacteria and green-blue algae help in nitrogen fixation in the wetland soil. Though the fixation is said to happen in aerobic and anaerobic conditions, most studies show that the fixation is found to be greater under the anaerobic conditions (Buresh et al., 1980). The range of Nitrogen fixation in wetlands are in the range between 0.03 and 46.2 gN/m2/yr (Buresh et al., 1980).

Plant uptake and assimilation

Nitrogen assimilation refers to numerous biological processes in which the inorganic forms of Nitrogen is converted into organic compounds that help in building the tissues and cells in plants. The two forms of Nitrogen (Ammonia and nitrate) are used by the plants for assimilation. As Ammonia requires less energy than Nitrate, the most preferred source for assimilation is Ammonia while in Nitrate rich water, Nitrate is the most preferred Nutrient for growth. Ammonia is the most preferred source for assimilation (Kadlec and Knight, 1996). In Nitrate-rich water, Nitrate is the most preferred source of Nutrient for growth. Nutrients are assimilated from the sediments by emergent and rooted floating leaved macrophytes, and from the water in the free-floating macrophytes (Wetzel, 2001). Various experiments show that the minerals can be taken up directly by the shoots of submerged plants which put into question the uptake capacity of the root system. The nutrient levels in the plant tend to higher during the growing season and gradually decrease as the plants mature. When the nutrient accumulation reduces, the translocation of nutrients and photo assimilation from leaves to rhizome occurs. When the biomass decomposes, the absorbed nitrogen is released back to the wetland waters. The potential rate of nutrient uptake by a plant is limited by its net productivity (growth rate) and the concentration of nutrients in the plant tissue. The Nutrient storage in the plant depends on the plant tissue nutrient concentration and also the total biomass accumulation. The traits like high tissue nutrient content, the capability to stock more nutrients in the standing crop and nutrient assimilation for rapid growth should be looked for when choosing the plants (Reddy and DeBusk, 1987).Various studies indicate that the Nitrogen stocking for emergent species are in the range of 14 to 156 g N/m2 and more than 50% of this is belowground biomass.

Ammonia adsorption

Ammonia adsorption happens by the exchange reaction between soil detritus and inorganic sediments. The absorbed ammonia is not tightly bound to the surface and is released easily when the soil chemistry changes. In the water at a given concentration level, a fixed amount of ammonia is absorbed and saturates the available sites. When the ammonia concentration in the water level is reduced (due to nitrification), some ammonia will be released from the surface to be in equilibrium with the new concentration. When the ammonia concentration increases, the absorption will also increase. Factors like presence of vegetation, amount of clay available, amount of organic matter present in the soil and duration of submergence influence the rate of ammonia adsorption (Savant and DeDatta, 1982).

Organic nitrogen burial

Some amount of organic nitrogen found in organic waste in the wetland may not be recycled as they are buried in the soil or formed as peat. This process mostly occurs in natural wetlands and no practical data has been found for constructed wetlands.

ANAMMOX

ANAMMOX is an anaerobic ammonium oxidation process of converting NO_2 and NH_4 into N_2. It is found in the experiments that Oxygen is required for the process, but it is much less than the oxygen needed for nitrification/denitrification.

3.2 Phosphorus transformations in wetlands

Phosphorus in wetlands occurs as phosphate in organic and inorganic forms. Free orthophosphate is the only form of phosphorus that is believed to be utilized directly by algae and macrophytes thus acting as a connecting link between the organic and inorganic forms of Phosphate (Vyzamal, 1995). The interconversion of Phosphorus happens in the wetland environment. Soluble Phosphorus is taken up by the plants or maybe taken by soil and sediments. Phosphorus transformations in wetlands are peat/soil accretion, adsorption/desorption, precipitation/ dissolution, plant/microbial uptake, fragmentation and leaching, mineralization and burial. In order to understand the phosphorus removal from wastewater in the wetlands we need to quantify all the processes that lead to removing the Phosphor in the first place. The various process that affect the transformation of Nitrogen in the wetland are discussed in the following section.

Peat/soil accretion

Most studies show that the soil/peat accumulation is the major long-term phosphorus sink and this process happens more in natural ecosystems. The sediments hold the major portion of P in natural wetlands, the cycling of the Phosphorus is done by the plants and microbes. The process of peat accumulation is found to be very slow, only 1 to 2mm per year.

Soil adsorption and precipitation

Soil adsorption means the movement of soluble inorganic P from soil pores to soil mineral surfaces where it accumulates without penetration the soil surface. The adsorption capacity of a soil increases with the mineral components and the clay content available in the soil. The balance between P adsorption and desorption maintains the equilibrium between solid phase and P in soil. This is called phosphate buffering capacity. The concentration of phosphate in soil pore water and the ability of solid phase to replenish phosphate into the soil are found to be the factors that control the sorption of P. The sorption of P in soil happens in a two-step process:1)The exchange of Phosphate between soil pore water and soil particles 2) Penetration of phosphate into solid phases. The movement of P happens until there is an equilibrium between soil pore water and the soil.

Microbial uptake

Though the uptake of P by microbes happens in a rapid rate the amount of removal through it is very low. The microbes play a significant role in the solubilization of P in the soil. Bacteria are generally considered to be the decomposers of organic P, they also regulate the P flux across soil and water interface and help in P soil burial. The role of algae in nutrient cycling the wetland environment is found to be significant and they also help greatly in the uptake of P either by direct uptake or indirectly be inducing changes in pH or dissolved oxygen through photosynthesis

Plant uptake

The uptake of P in plants happens mostly through the roots, absorption is found to be little through leaves and shoots in submerged species. The uptake of P in plants is maximum during their growing season (Vymazal, 1995). The storage of P in vegetation can vary from short to long term depending on the type of vegetation, litter decomposition rates, leaching of P from detrital tissues and translocation from above to belowground biomass. Phosphorus storage in aboveground biomass of emergent macrophytes is usually short-term, with a large amount of P being released during the decomposition of litter. After the plant decay, P is released to the wetland from the plant biomass, this growth and decay constantly happens annually. The concentration of accumulated in the plant tissue is found to be varying from plant to plant (Reddy and DeBusk, 1987)

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Chapter 4 Factors that Affect the Removal of Nutrients

In this chapter, we discuss the factors that influence the nutrient dynamics of the wetland ecosystem. The factors were distinguished into type of wetland used, hydrological conditions (HRT, water depth, fluctuation in water level, nutrient and hydraulic loading), soil related factors (soil type, soil pH, vegetation) and climate related factors (climatic conditions, seasonal variations, temperature). We analyse the factors that should be taken into consideration while designing a nutrient removal wetland, and how the factors are interlinked with each other directly or indirectly.

4.1 Type of the Wetland

According to (Vyzamal, 2007), the constructed wetlands can be distinguished based on three criteria: 1) presence/absence of free water surface, 2) use of rooted emergent aquatic plants or free-floating plants and, 3) direction of flow. Based on these criteria, we are going to discuss three types of constructed wetlands: 1) Horizontal free-water surface flow (HF) 2) Horizontal subsurface flow 3) Vertical flow (VF). The type of wetland with the direction of flow and the suitable vegetation type is mentioned in Table 3. The different constructed wetland types with different flow directions are shown in Figures 5, 6 and 7.

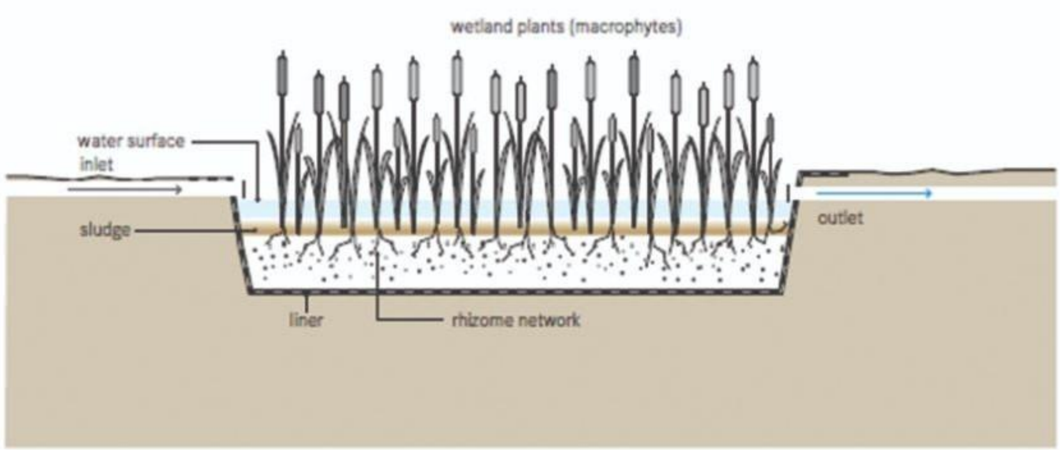

Figure 5 Constructed wetland with Free Floating Plants (FFP)
Source:(Maiga et al., 2017)

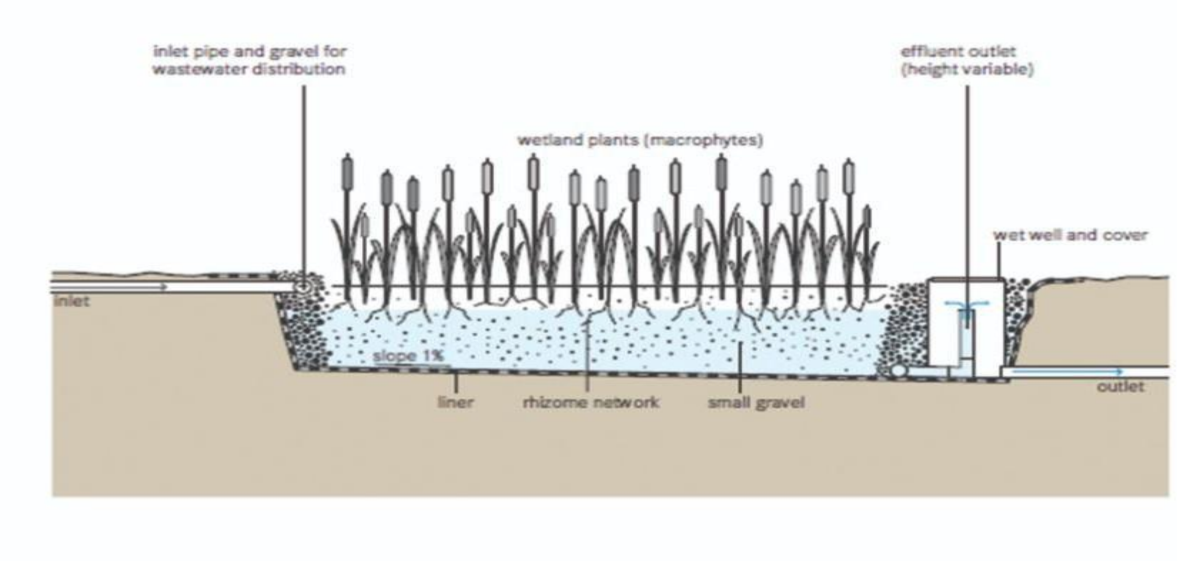

Figure 6 Constructed wetland with Horizontal subsurface flow (HSSF)

Source: (Maiga et al., 2017)

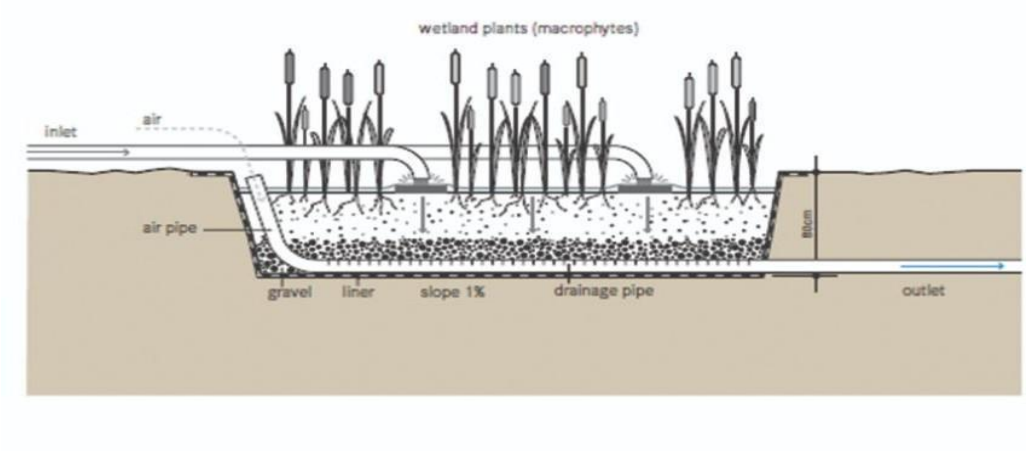

Figure 7 Constructed wetland with Vertical subsurface flow (VSSF)

Source: (Maiga et al., 2017)

Wetland type	**Free water surface**	**Sub-surface**
Vegetation type	Free-floating, floating-leafed, submerged, emergent	Emergent only
Direction of flow	Horizontal	Horizontal or vertical (vertical c be downflow or upflow)

Table 3 Description of wetland types

Source: (Maiga et al., 2017)

In subsurface flow, the water flows through the media and below the surface. The direction of water flow in a subsurface system can be either horizontal or vertical. In HSSF, the water flows in a direction horizontal and below the medium in which the vegetation is planted, while in VSSF, the water flows vertically from above the medium and is typically drained at the bottom as in Figure 7.

The most important aspect that needs to be considered as a result of the difference in the direction of water flow path between the HSSF and VSSF is the redox environment created by them in the wetland. The downflow in VSSF will increase the presence of aerobic conditions because the media stays unsaturated. This will increase the conversion of ammonia to nitrate. On the other hand, in the system of upward flow the media will remain saturated and this will result in anoxic conditions (Maiga et al., 2017).

Nitrogen removal based on Wetland type

Not all the processes occur in the constructed wetland, and there are various factors that stop these processes from taking place. These mechanisms vary mainly based on the type of wetland system chosen and the kind of plant species selected. Constructed wetlands with Free Floating plants (FFP) are floating on the surface of the water and they lack the processes that take place in the soil. Free Water Surface (FWS) have only limited soil processes, while subsurface wetlands lack the processes that take place in the FWS CWs.

Ammonification only converts the Nitrogen into Ammonia, increasing the level of total Ammonia in water. However, ammonification process helps in making nutrient available for other removal processes like adsorption, volatilization, nitrification and plant uptake. The plant decomposition also leads to Ammonification. Volatilization can be a significant way of removing Nitrogen with open surface water in constructed wetlands. Nitrification seems similar to ammonification but when it is coupled with Denitrification it can remove a significant amount of N. Nitrification process occurs in all types of CWs, the process is limited by the amount of oxygen available and the bacteria thrive based on the concentration of oxygen available. There are fewer studies on Nitrate-ammonification process of Nitrogen transformation in wetlands. Nitrate-ammonification happens under conditions of low redox potential where anaerobic conditions occur, however this process does not remove any Nitrogen from the wastewater. One of the major removals happens through the plant uptake in CW with free-floating macrophytes. Ammonium adsorption is limited in CW with sub-surface flow where the contact between substrate and wastewater is efficient. The clay soil is most effective in ammonia adsorption which can be used in CWs. Organic nitrogen burial is restricted to CWs with free water surface and emergent vegetation with peat layer playing an important role.

Though the removal efficiency is mostly similar to all the CW types. FFP CWs have higher removal rates than the rest because of multiple harvest. For secondary treatment, SSF are preferred because they can be effective with higher inflow concentration while FFP and FWS are mostly used for tertiary operation. Using emergent macrophytes in CWs, the amount of N removed is found to be only 10% by harvesting them. The nutrient standing stock in the plants are quite limited and that does not vary based on the inflow concentrations. VSSF CWs are found to remove more Nitrogen present in the form of Ammonia than FWS and HSSF, while the potential to remove nitrates are less in VSSF compared to FWS and HSSF. Vyzamal (2007) indicates that using single stage CWs to remove large amounts of TN is not possible unless achieved with a large treatment area. Therefore, using hybrid systems could help the cause if the objective is at removing TN as much as possible.

Removal of nitrogen in hybrid constructed wetlands

In order to effectively remove Nitrogen from the wastewater various types of CWs can be combined together to achieve a higher treatment effect. Most hybrid systems are arranged in a staged manner with VSSF and HSSF. HF cannot completely remove the nitrates because of their limited oxygen transfer capacity while VF systems provide the needed conditions for nitrification but no denitrification occurs in these systems. In the combined system the advantages of VF and HF can be combined together to effectively remove the Nitrogen from wastewater (Vymazal,2007).

Removal/retention of P based on different types of constructed wetlands

The extent of P removal depends on the type of CW employed for the removal. As mentioned, the P removal processes are accumulation of biomass by plants, sorption by soil, formation and sedimentation of new soil. First two processes are saturable and cannot contribute to long term P removal. Peat accretion process could result in sustainable long- term removal of P. This could be done in a CW with high production of biomass in FWS(Dunne and Reddy, 2005).. The same mechanism could be effectively used with sub-surface flow CWs. Horizontal flow systems can be much effective that vertical flow systems because of the oxygenation of the bed. Plant uptake is major P removal in systems with FFP. However, the efficiency relies majorly on the harvesting frequency of the plants.

4.2 Hydrological Conditions

Hydrology is a term in wetland engineering that covers all hydraulic and hydrologic processes. The hydraulic factors are critical to achieve the efficient functioning of the wetland. Important factors related to hydrology in wetland are hydraulic retention time (HRT), water depth, flooding duration and timing, flow speed, storage capacity, flow resistance, surface area and fetch (Hayes et al., 2000). Most of these factors are dependent on each other and are sometimes seen to be overlapping. The factors that are found to be largely affecting the nutrient removal in the wetlands are discussed below.

Hydraulic retention time

The total time the water stays in the wetland before leaving is called Hydraulic retention time. The wastewater needs to exist in the wetland system for a certain period of time for the biological, chemical and physical processes to take place in order to remove the amount of nutrients in the wastewater. For each of these processes to take place we need a minimum HRT. Among the various other factors that affect the nutrient removal rate in the wetland ecosystem, HRT plays a vital role. In the study (Jiang et al., 2017), the HRT was gradually varied when the denitrification became stable, the effects of HRT on removal efficiency was studied. It was found that the removal efficiency gradually increased with the increase in the HRT. Longer HRT leads to longer interaction of carbon in the system with the microbes, which helps the bacteria to have more energy and result in the conversion of N in the wastewater. Kang et al. (2017) observed that the removal rate of TN and TP decreased when the HRT was increased from 16 hour to 24 hours as the increased HRT results in trapped organic matter to be dissolved into wastewater again. The study also found out that the shorter HRT causes ammonia in the wastewater to be insufficient for contacting nitrifying bacteria due to the slow growth of autotrophic bacteria. The study shows that shorter HRT results in less TP removal while the longer HRT results in higher TP removal, TP is found to be not only dependent on the microorganisms present in the wastewater but also the removal of P through adsorption and sedimentation. Greater the retention time better the removal efficiency of the nutrients (Akratos et al., 2008). Also on the other hand, excessive HRT can cause emission of gases like sulfide and methane damaging the water quality. HRT is seen to be affected by factors like hydrologic setting, water depth, flow velocity, vegetation, and various other design factors (Hayes et al., 2000).

Water depth and water level

The depth of water in the wetland determines the cover and structure of the plants and the growth of microbes in the wetland. It is a key factor in determining the efficiency of the wetland, which is closely related to the hydraulic efficiency of the wetland and water depth can be a key factor in determining the hydraulic efficiency of the wetland (Kuo and Shih, 2013). Having deep water levels results in an increase of TN when compared to shallow waters. The increase in the depth of the water leads to higher retention time of water in the wetland which eventually results in the increase in the removal of TN from the wastewater (Song et al., 2019).

Fluctuation in water levels

A fluctuating water table can significantly affect the microbial activity in the wetland ecosystem. It is found that less nutrients are released when the water tables fluctuate. Further, the anaerobic bacteria become inactive and without the bacterial activity the nutrient cycling is largely affected. Less nutrients will be absorbed if the water levels fluctuate constantly. The variation in the water level means a variation in the amount of nutrients and oxygen levels in the water, which affects the plant growth and the microbial activity taking place in the uptake of nutrients in the wetland ecosystem. This means that a static water level condition is favourable for a high biomass yield in paludiculture (Lew et al.,2019).

Nutrient and hydraulic loading

The nutrient inflow significantly affects the removal efficiency of the wetland systems. The fluctuation in the flow of water into the wetland influences the amount of pollutants entering into the wetland treatment system and the volume of water flowing in. The capacity of the wetland to remove the nutrients strongly depends on these factors. Loading rates, the concentration of nutrients in the inlet along with the hydraulic loading rates need to be carefully assessed during the process of designing a wetland ecosystem. Low hydraulic loading rates may allow for greater opportunity of P uptake or adsorption, resulting in higher P retention. However, low loading rates result in the reduction of denitrification rates which leads to lesser removal of N due to insufficient anaerobic zones for the denitrification process to take place (Zigler, 2016). It is found that the high loading rates result in high removal rates. However, studies have also indicated that high hydraulic loading rates leading to high nutrient loading may result in reduced removal efficiency (Travaini-Lima et al., 2012).

4.3 Soil-related Factors

Soil plays a significant role in regulating the flow of nutrients within the wetland ecosystem. Therefore, it is important to understand the factors related to the soil that influence the nutrient removal process. The major soil-related factors are discussed in this section.

Vegetation

Vegetation helps in the uptake of N and P from water and soil during the plant growth season. Unless the plants are harvested, the removal of nutrients is not permanent, and they are only cycled into different forms (Verhoeven et al., 2006). However, the removal of nutrients by the plants depend on various factors including seasonal climatic patterns, nutrient inflow concentration, HRT, type of plant species, plant decay rates and translocation of nutrients (Reddy et al., 1999). The quantity of the nutrient removal depends on the type of plant used in the wetland and the factors that need to be considered for selecting the appropriate plant is being listed below. The rate of nutrient uptake and storage is found to be high during the season of spring when the growth of vegetation is substantial. The decay of plants at the end of the growing season may result in the release of nutrients into the wetland as well (Beutel et al., 2014). Richardson and Craft 1993, state that plants might release 35 to 75% of P into water columns as organic waste. Plant nutrient accumulation results for 16% to 75% of total nitrogen removal in wetlands (Reddy and D'angelo, 1994).

Soil pH

The pH of the soil in the wetland ecosystem influences the microbial action and the growth of vegetation. High pH might limit the growth of certain plant species while low pH might result in the reduction of microbial activities. Yin et al. (2016) investigated the effects of pH on nutrient removal and found that the increase in pH was caused by the intensive photosynthesis of plants and when the pH was increased from 7.5 to 10.5, the removal efficiency of TN was decreased from 76% to 52% which was mainly attributed to the decrease in microbial activity. (Garcia et al. (2019) also confirm that the difference in pH affects the nutrient removal efficiency, and the increase in pH above 8.5 decreases the total removal efficiency. The soil pH also influences the solubility of various other chemicals. The redox potential of these chemical compounds affect the chemical and biochemical interactions that occur in the wetland (Hayes et al., 2000). However, it is difficult to estimate the amount of all chemicals present in the wetland waters.

Soil type

Soil is a critical component of wetland ecosystems. Soil acts as the structural vessel in which the macrophytes, microbes interact and act as a medium for plant growth (Hayes et al., 2000).In order for the microbes to thrive in soils, there must be sufficient food available. In aerobic conditions, the organic matter gets accumulated over the soil surface and is consumed by the microbes but when the soil is saturated, the oxygen availability is reduced and the soil becomes anaerobic. This results in anaerobic microbe formation. Anaerobic microbes are found to be not as effective as the aerobic microbes in nutrient removal (Hayes et al., 2000). The P adsorption in soil through sedimentation is directly influenced by the mineral content of the soil. In acidic soils, P is absorbed to aluminium and Iron while it is attached to Calcium in alkaline soils.. A concrete understanding of the mineral content in soil in the selected site is needed to maximise the nutrient removal rates (Zigler, 2016).

4.4 Climate-related Factors

Climatic conditions

The climate of the place in which the wetland is set up is of foremost importance; because it largely influences the biological processes that result in nutrient removal. The rainfall patterns, the evaporation and precipitation rates and the variation in temperature directly influence the factors affecting the nutrient removal in wetlands (Tanner,1996).

Seasonal variations

When compared the seasonal variance in phosphorus removal is less than nitrogen (Picard et al., 2005) The Hydraulic loading is affected by the seasonal variation in precipitation, this also affects the detention time (Kuschk et al., 2003). The water runoff might increase in the months of spring and winter, in the month of spring there might be major runoff within a short period of time, which needs to be considered during the study (Graczyk et al., 2011). Due to this reason the wetland has the potential to remove maximum nutrients during this period. Also, during this time the vegetation is less and this might lead to more nutrients leaving the wetland. Beutel et al. (2014) found that the increase in sunlight during summer seasons after dormant winter periods increased the plant growth and rates of N and P removal by the plants.

Studies indicate that the high water inflow during the seasons of rain causes difficulty in the process of filtration and sedimentation of particles. The metabolism of the microbial community is also seen to be affected by it. All lead to decrease in the removal of nutrients (Travaini-Lima et al., 2012). In the study conducted by Boutilier et al. (2009), the total concentration of nutrient flow in the outlet was increased in the rainy season because of the higher concentration of nutrients entering the wetland system and the microbial activity being affected by the change in water flow pattern.

Temperature

The change in solar radiation and air temperature over daily and annual basis affects the plant and the microbial activity in the wetland ecosystem. The end result of the nutrient removed through the wetland ecosystem is due to the combined effect of temperature, seasonal variations and a combination of other parameters. From the studies it is found that the removal of Nitrogen is strongly influenced by the changes in the temperature and season when compared to Phosphorus. The N removal is strongly done by the microbial action and the microbial action is strongly influenced by temperature variation. Van de Moortel et al. (2010) conducted a small-scale experiment in which they investigated the effects of temperature on nutrient removal rates by plants. The microbial metabolism is found to be decreasing with the decrease in temperature (Allen et al., 2002).

For the purposes of the thesis, the factors that were discussed in this chapter were considered in designing the paludiculture model, which is described in chapter 6.

Chapter 5 Plant Species for Nutrient Removal

This chapter discusses the plant species that can be used for nutrient removal in wetlands. The plant species were chosen based on the selection criteria as described below. Then the chapter discusses for each selected plan the necessary conditions for the optimal plant growth, the nutrient removal capacity of the plants and the biomass production capability.

Several factors should be considered before choosing the plant for nutrient removal. According to Angela (2018), these factors include the ability of the plant to grow in the climatic conditions where the wetland is setup, the growth potential of their roots and oxygen carrying capacity, the high capacity of photosynthetic activity, the tolerance to high pollutant concentrations, disease resistance, and management requirements. These factors were considered before selecting the following plants.

5.1 Duckweed (*Lemna*)

Duckweed is a generic name that is often used for the small, floating water plants duckweed and duckweed fern. Duckweeds can be found in most parts of the world, often seen growing in thick blankets or mats on slow moving or still water that is fresh and nutrient rich. The leaves are flat and ovoid in shape. Many species have adventitious roots which function as a stability organ and tend to lengthen as it takes nutrients from the water.

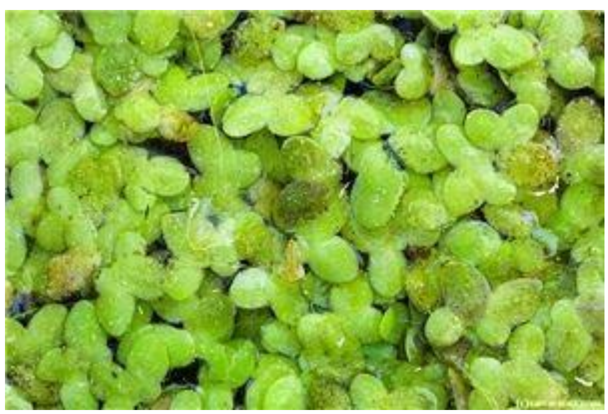

Figure 8 Duckweeds

Source: (CABI,2020a)

Growing conditions: Duckweeds need to be managed from the wind and have to be regularly harvested and fertilised to balance the nutrient concentrations in water to obtain optimal growth rates. Duckweeds have been seen to be growing in temperatures between 6 and 33°C. When the water becomes cold for the plant, it forms a turion and sinks to the bottom of the water surface where it remains dormant until the warm water brings the resumption in the plant growth. Duckweeds grow in the surface of fresh or brackish water which is well protected from wind and waves. Duckweeds can't sustain in fast moving waters (>0.3 m/second) or unsheltered from the wind. Ideal growing conditions for Duckweeds will be in the wears with constant supply of nutrients. Duckweeds can grow dense and might affect the growth of microbes threatening their supply of sunlight to produce energy. The plant growth could be affected by variety of pressures like toxins in water, scarcity of nutrients, Overcrowding, competition with other species for nutrients, extremes of pH, temperature. Duckweed survives pH 6.5 to 7.5 range, Ammonia in the ionised form is preferred N substrate for this plant. (CABI, 2020a).

Nutrient removal: The optimum level of Nitrogen in water seems to be around 30 mg N/l. But however maximum yield has also been obtained at levels of 72 mg N/l. The optimum level of nitrogen in water is influenced by species and the growing conditions also NH4-N content. (Timmerman and Hoving., 2016) Under these optimal growing conditions, the higher the Nitrogen in water, the higher level of protein content in the plant. The daily removal rate has seen to be varying from place to place. (Zimmo,2003) gives a table with N and P removal rates of Duckweeds.

Region	Species	Daily removal ($g/m^2.d$)	
		N	P
Louisiana	Duckweed	0.47	0.16
Italy	*L.gibba/L.minor*	0.42	0.01
USA	*Lemna*	1.67	0.22
India	*Lemna*	0.5-0.59	0.14-0.30
Minnesota	*Lemna*	0.27	0.04
Florida	*Spirodela polyrrhiza*	-	0.015
CSSR	Duckweed	0.2	-
Bangladesh	*Spirodela polyrrhiza*	0.26	0.05
Yamen	*Lemna*	0.05-0.2	0.01-0.05

Figure 9 Duckweeds nutrient removal data

Source: (Zimmo,2003)

Biomass: It is observed that the Duckweeds can double their mass in between 16 to 48 hours under optimal growing conditions. Under experimental conditions, the rate of production was found to be 183 metric tonnes/ha/year of dry matter although yields are closer to 10-20 tons of DM/ha/year under real-world conditions (FAO,2020).

5.2 Reed Canary Grass (*Phalaris Arundianacea*)

Reed canary grass is large, coarse grass with an erect, hairless stem and gradually tapering leaf blades. The panicles are compact, erect or slightly spreading at a range of 7 to 40 centimetres long and branches 5 to 30 centimetres in length. The flowers occur in clusters from May to Mid-June. Flowers are green to purplish in colour and it is one of the first grass to sprout in spring (WI DNR 2009). The reed canary grass has a running root system and creates an impenetrable ground cover. They should be mown 2-3 times in their first 2-3 years in order to encourage thick growth. They begin growing in early spring (April) and the growth declines in mid-August. The flowering is found to be occurring throughout the season with pollen produced for wind pollination. Reed canary grass grows back rapidly following manual removal with heavy equipment from rhizomes and seeds that remain in the soil. Combination of chemical and physical removal methods need repetition to effectively control the plant growth and prevent re- infestation (Kilbride and Paveglio 1999).The preferred spacing of growth is 60 cm. The plant is reported to tolerate an annual precipitation in the range of 30 to 260cm, an annual temperature in the range of 5 to 23°C and a pH of 4.5 to 8.2. It is found to be an invasive plant.

Figure 10 Reed Canary Grass (Phalaris Arundianacea)
Source: (CABI,2020b)

Size: Ranges from 0.6 to 2.8 meters in height. Leaf blades are 8 to 25 centimetres long and 65 to 190 mm in width.

Growing conditions: Reed canary grass grows in many wetland areas including wet meadows, prairie potholes, marshes, riparian areas and peatlands. The plant grows in sandy, loamy, clay and saturated soil but not in standing waters where the water is stagnant for a long period of time. Though the plant does not originally grow in the flooded areas, it can tolerate periods of inundation once established (Weinmann et al. 1984). The plant does not like saline soil.

Nutrient removal: In favourable conditions, Reed canary grass is a fast-growing plant that can take up large amounts of nutrients. Hurry and bellringer (1990) studied the potential yield of Reed Canary grass in an overflow wetland treatment system, they found out by harvesting the aerial biomass removed 494 kg/ha of Nitrogen and 109 kg/ha of Phosphorous with an annual removal of 11% Nitrogen and 7% Phosphorus loading.

Biomass: Phalaris arundinacea L is found to be one of the highest yielding fodder grasses with annual yields ranging from 8-20 tonnes per hectare and has a large potential as a source of biomass. In the experiments carried out by Dubois (1990), the plant production during the growing season reached 10.5 Kg/m2 of dry biomass of which 66% was in the aerial parts. Hurry and Bellringer (1990) found that Maximum shoot yield was very high at 25 tonnes ha-1. Vymazal and Lenka (2007) reveal that Phalaris usually reaches its maximum biomass as early as the second growing season (1900 g m−2 for Phalaris). Number of Phalaris shoots is the highest during the second season and then the shoot count remains about the same. Additionally, the shoot length remains steady over years of constructed wetland operation.

5.3 Common Reed (Phragmites australis)

Pharagmites Australis, the common reed is a robust erect perennial grass, aquatic or subaquatic that grows 4m tall (sometimes 6m). Stems are rigid, many-noded, leaves alternate (70 cm long), tapering to a spiny point. The Phragmites are strong competitors and are aggressive, fast growing species that require constant clearance measures or else completely block the vegetation area (CABI, 2020c).

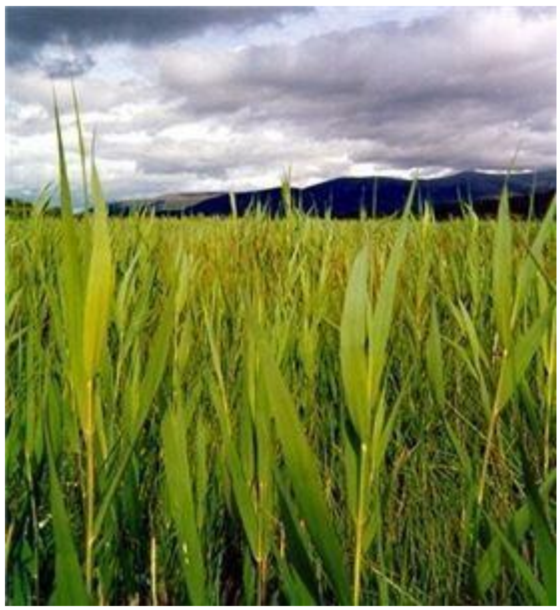

Figure 12 Common Reed (Phragmites Australis)
Source:(CABI,2020c)

Growing conditions: Phragmites is cosmopolitan and is highly adaptive emergent grass in fresh or brackish water. The plant prefers slow-moving waters and areas of land with high water tables that are seasonally inundated. They grow in heavy, light, medium soil and are even tolerant to saline soils (CABI, 2020).

Nutrient removal: Ying et al. (2013) performed a study with Phargmites in China into two different sites with different nutrient loading and different water levels varying between above and belowground of the plant system. The results show that the reed growth was influenced more by water levels than the nutrient loading in the water. It was found that the maximum Nitrogen intake happened with the terrestrial zone. In the paper (Reddy and Busk., 1987), it is described that Phragmites Australis is capable of removing up to 225 Kg.N/ha/yr and 35 Kg.P/ha/yr. It is also found that the removal rate of the plant varies largely depending on the season and the harvest time.

Biomass: Phragmites usually reaches its maximum only after three to four growing seasons. In the study which was carried out in Czech Republic, Phragmites provided the biomass of 5070 g/m2. The shoot count of Phragmites decreases after the second growing season while length and weight of individual shoots increases over time due to the self-thinning process (Vymazal and Lenka, 2007).

Seasonal variations: In the study done by (Mulkeen et al., 2017) in Ireland, the biomass harvest was found to be the maximum in the month of August (1636 ± 507 g m^{-2}).The nutrient accumulation was found to be occurring throughout the year, the biomass harvest is suggested to be performed in the period of late August or September to obtain the maximum yield. In the study by (Ying et al., 2013), it was found out the nutrient storage in Phragmites reached the maximum in late August or September.

5.4 Common Rush (*Juncus effusus*)

Juncus effusus grows in large clumps about 1.5 meters tall at the edge of waters along the waterways. It can be invasive anywhere with moist soil and can be commonly found growing in humus rich areas like marshes, ditches, fens and beaver dams. It is one of the most common grassy plants which does not belong to the grass family. The plant can be very hard to pull out due to its strong growth of Rhizome with the soil. The stems are smooth and cylindrical in shape, shiny and bright green in colour (CABI, 2020)

Figure 12 Common rush (Juncus Effusus)

Source: (CABI,2020d)

Growing conditions: The plant is more likely to grow in wet places but is also found to thrive in drier soils. The species is found on acidic, wet soil on waterfronts, in grasslands, in marshy places and in forests. The plant prefers light or medium soil to grow.

Nutrient removal: In the study done by Lauren et al. (2019), it was found that the peak N and P accumulation in J. effusus occurred in September within both root (50 g N and 4.8 g P) and shoot tissues (98 g N and 12.5 g P). It was found that the shoots accumulated more N and P than the roots. J.Effusus was found to remove 138.1 ± 8.45 g/m2 of N and 26.3 ± 1.72 g/m2 of P grown in a floating type of wetland (White et al.,2011).

Biomass: Limited data is available for the biomass capacity of J.effusus. In practical cases for J.effusus growth for biomass production in Japan, it is found that 10 t/ha/yr is possible as dry biomass from the plant. Production of 14 t/ha/yr has also been possible in the years of good production with the plant (PROSEA, 2020)

5.5 Broadleaf Cattail (*Typha Latifolia*)

Broadleaf cattail has an erect stem that is thick with flowers that consist of cylindrical spikes and stem grows up to 3 meters tall. Fibrous roots grow from rhizomes produced at the base of leaves. Rhizomes are as long as 70 cm, 0.5-3 cm in diameter. The seeds eventually break for the pollination by the wind

Figure 13 Broadleaf cattail (Typha latifolia)
Source: (CABI,2020e)

Growing conditions: Typha can be found in a wide variety of wetlands. Broadleaf cattail is seen to grow in wet meadows, marshes, ditches, pond margins, bogs and fens as well(Grace and Harrison, 1986).They prefer slow moving water with slightly brackish water and even grow in freshwater. The soil type for Typha to grow varies from sandy, slimy, loam or clay. The plant has been found to tolerate a pH of even 9.2 and has been observed to low pH as 3.5. Flooding and water depth are found to be the key factors in establishing the persistence of Typha latifolia, the plant can tolerate fluctuating water levels. It is an emergent plant species with water levels supposed to be high enough to keep the lower parts submerged. Experiments show that the rhizome production is decreased at water levels above 30cm (CABI, 2020e).

Nutrient removal: The phosphorus accumulation in cattails happens during the growing season with the plant taking more P in the belowground portion than the aboveground portion of the plant. Nutrients from the aboveground translocate during the autumn season with which the plant survives the season. Based on the lab tests performed by (Grosshans et al., 2011) the amount of P removed by cattails during the growing season ranged between 20 to 60 kg per Ha.This suggests that the cattails make a significant difference in the removal of P from the water. The results of the study indicate that the harvesting during the peak of the plant growth in the month of August would have the greatest nutrient removal potential, removing the maximum amount of Phosphorus from the water. In the study conducted by Yeke et al. (2018), on a 4-year period with the harvest of the plant being performed two times a year, they found that the plant was able to accumulate 36.7 g.N/m2 and g.P/m2. The annual N removal for T.latifolia ranges to 454 Kg.N/ha/yr and the P removal ranges to 62 Kg.P/ha/yr (Stefanakis et al., 2014).

Seasonal periodicity: The phosphorus removal by Typha was found to be highest during late summer harvests. The amount of nutrient (N and P) removed was found to be significant during the late summer harvest,30 kg of P per hectare during the pre-harvest and between 30 to 60 kg of P during the following harvest. The nutrient intake was found to be significantly less during the winter season only 5 kg of P per hectare. The cattails were found to emerge during the mid-May to early- June period depending on the spring weather conditions. The peak growth and accumulation in cattails happened during middle to late August, the cattails were found to contain the highest biomass (DM) per metre during the same period (Grosshans et al., 2011).

Harvest period: T. Latifolia can be harvested two times a year to obtain the biomass. Harvesting Typha once a year is found to be removing more nutrients from the wastewater when compared to harvesting the plant twice a year.(Yeke et al., 2018).

5.6 Water Hyacinth (Eichhornia crassipes)

The plant is variable in size, the leaves are elongated and strap-like, the seedlings once dislodged will float from the mud into open water. The seedlings have leaves and can grow up to 1m. Roots develop from the base and are usually 20-60 cm long. The ratio of root and shoot depends on the nutrient conditions.

Figure 14 Water Hyacinth

Source:(CABI,2020)

Growing conditions: The optimum temperature for growth for E. crassipes is 25-30 degrees celsius. The growth stops if the water temperature is above 40 degrees or below 10 degrees but for a short period it can tolerate freezing temperatures. High growth is seen in nutrient rich waters. The percentage of nitrogen varies between the plant parts. Optimum pH is between 6 and 8. The growth of the plant ceases if the level of calcium concentration is below 5 mg/l (CABI, 2020).

Nutrient removal: The amount of Nitrogen stocked up in a standing crop may amount close to 250 g N m-2. The plant is seen to be highly productive in the removal of nutrients, the annual amount of Nitrogen removed may amount to 600 g N m-2 yr-1(Vyzamal,1995). In the study conducted by (Reddy et al.,1985) they conclude that the water hyacinth is capable of removing 1176 to 1193 kg N/ha/ yr and 321 to 387 kg P /ha/ yr, respectively.

Biomass: Water hyacinth being a floating macrophyte and given its fast growing rate in nutrient rich water. The plant can produce a high amount of biomass with multiple harvest periods throughout the year. Depending on the amount of nutrients available in the water, the amount of biomass production of W. Hyacinth can range between 1500-5000 dry weight g/m2/yr.

As discussed under section 4.3, the vegetation plays an important role in the nutrient removal. The kind of plant species chosen as vegetation determines the amount of nutrients that can be removed and the biomass yield that is possible to be obtained with the plant biomass. Thus, it is vital to select the appropriate plant species that will select in effective nutrient removal and provide ample biomass along with it. The Table 4 compares the important characteristics of the plant species in the context of local environment.

Plant species	**Important nutrient removal trait**	**Advantages**	**Disadvantages**
Typha Latifolia	High Phyto remedial capacity	Can withstand fluctuating water levels	Dominant other plant species
Phragmites Australis	High Phyto remedial capacity	Highly adaptive to the local environment	Aggressive invader to the new environment
Duckweeds	Can grow faster within less time up taking more nutrients	Can be used as feed for cattle	Needs protection for wind and moving water
Water Hyacinth	High nutrient stocking ability	Faster growth and with frequent harvest provide high biomass	Needs tropical climate for growth
Phalaris Arundinacea	High productivity even in cooler seasons	Reduces soil acidity	Requires proper management
Juncus Effusus	Adapt to high nutrient loading rates	Ideal for bioenergy production	Needs constant wet soil

Table 4 Comparison of nutrient removal characteristics of the plant species

The nutrient removal rates and the biomass capacity of the plants are discussed in detail in the following chapter.

Chapter 6 Results

This chapter discusses the developed Paludiculture model and the information needed for the interpretation of the model. In this chapter we also analyse the data for nutrient removal processes and discussion with the farmers to incorporate their perspectives into the model implementation.

6.1 Model Design

The model was developed based on the factors that influence nutrient cycling in a wetland ecosystem as described in Chapter 4. The Figure 15 visualizes the resulting model. The arrows in the figure represent which factors are connected to each other and have a direct influence over one another.

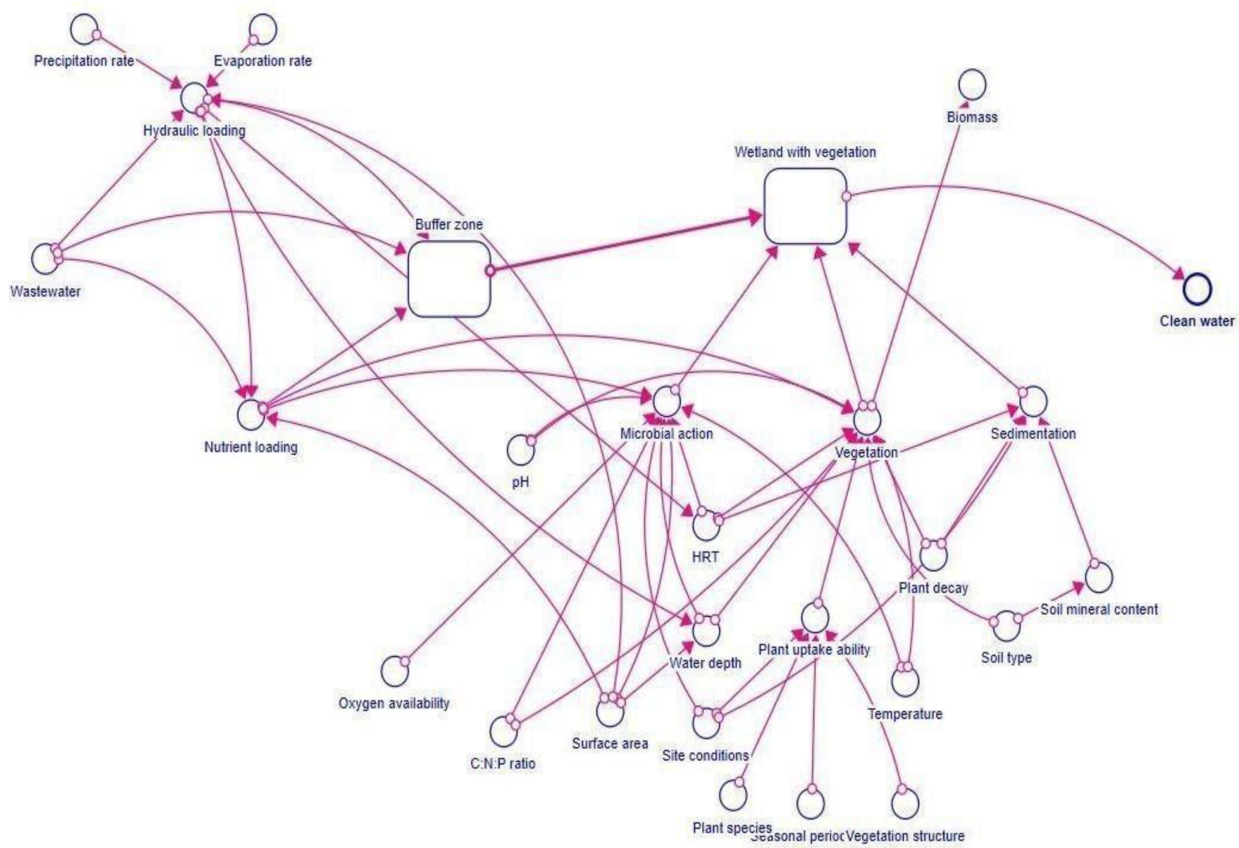

Figure 15 System dynamic model for an effective paludiculture system to remove excess nutrients

The process of water flow is as such the wastewater with excess nutrients (N and P) flow into the buffer area. The water from the buffer area enters into the wetland area with plant vegetation. The processes by which the nutrients are removed can be distinguished into three different ways: microbial action, plant uptake (vegetation) and sedimentation. Additionally, some amount of nutrients, especially N is lost into the atmosphere in the form of gas. However, such amounts are difficult to quantify. The factors affecting these processes of nutrient removal in the wetland ecosystem has been elaborated in Chapter 4. The model connects together all these factors and represents the same. The various processes happening in the wetland ecosystem result in the removal of the excess nutrients (N and P) and the cleaned water is let out into the canals(Final outlet). The elements are summarized in table 5.

Element	**Unit**	**Type**	**Description**
Wastewater	m3/ha	Input	The wastewater with nutrients (N and P) that need to be removed
Clean water	Not applicable	Output	The clean water flowing out from the wetland area into the canals
Biomass	Kg/ha	Output	The biomass that can be obtained from the plants grown
Wetland with vegetation	Not applicable	Area	The wetland with paludiculture plant vegetation
Buffer zone	Not applicable	Area	The buffer area for storing water
Microbial action	g/m2 or Kg/ha	Process	The microbial action that results in N and P removal
Vegetation	g/m2 or Kg/ha	Process	The paludiculture plants growth that remove the N and P from the wastewater
Sedimentation	Kg/year	Process	Sedimentation in the soil that permanently remove N and P from the inflow wastewater
Precipitation rate	Mm	Factor	The total amount of rainfall in the chosen area of study
Evaporation rate	Mm	Factor	The total amount of water evaporated in the chosen area of study
Hydraulic loading	m2/day	Factor	The rate of water flow from the farmlands.
Nutrient loading	g/m2 or Kg/ha	Factor	The total flow of N and P from the farmlands.
pH	Numerical	Factor	pH of the water in the wetland
HRT	Hours or days	Factor	Total HRT of the wastewater in the wetland from the removal process
Oxygen availability	g/L	Factor	Amount of O2 available for microbes and plants
C:N:P ratio	Numerical	Factor	Ratio of C, N and P in the wastewater in wetland
Soil type	Not applicable	Factor	The type of soil used is peat soil
Plant species	Not applicable	Factor	The six plant species chosen for the study
Plant decay	g/m2	Factor	The plant decay in the wetlands
Site conditions	Not applicable	Factor	Land slope, climatic variations, weather patterns
Seasonal periodicity	g/m2/year or Kg/ha/year	Factor	The change in nutrient uptake of plants based on seasonal variations and harvest periods
Vegetation structure	cm or m	Factor	The structure of plant vegetation (distance between plants)
Soil mineral content	g/m2	Factor	The mineral availability in the chosen soil type
Plant uptake ability	g/m2 or kg/ha	Factor	The nutrient stocking ability of the plant species
Water depth	M	Factor	The total water depth of the wetland area
Surface area	M or m2 or ha	Factor	The total surface area of the wetland

Table 5 Overview of the elements of the model

Process: The processes that result in the removal of nutrients
Factor: The factor that affects or influences the removal of nutrients directly or indirectly
Area: The area in which the removal action is performed, or the process flow is controlled

Factors that affect nutrient removal

The factors that are found influence the removal action in the wetland ecosystem are briefly represented in the model (Figure 15). The model shows that all the factors are related in such a way that change in one factor will have an influence on various other factors as well. The most important driving factors that need to be considered in designing an effective paludiculture system can be said to the nutrient loading rate, the hydraulic retention time, the type of plant species used as vegetation along with the seasonal changes in the area of the wetland. Distinguishing these factors are the most important helps in finding the removal efficiency of the wetland. These factors also play an important role in improving the accumulation of biomass in the plant species. However, factors like seasonal periodicity, the time of harvest and water fluctuation are other important factors that need to be considered with the biomass accumulation. The plants use the nutrients (N and P) for their growth, the growth of the plant is not the same throughout the year and hence the uptake of the nutrients also varies throughout the season.

6.2 Nutrient Removal Processes

The removal rates of the Nitrogen and Phosphor through the removal processes are described in the table. The removal rates help in the estimation of nutrient removal possible with the paludiculture plants.

Nitrogen removal

It is evident from the removal rates described in the table 5 that microbial action plays a significant role in the removal of N, with about 10-15% of removal done by vegetation and less removal happening through sedimentation when compared to the other two forms of removal. However, we also do find that a fair amount of N is dissipated to the atmosphere in the form of gas. The removal rates along with the removal action is represented in Table 6.

MICROBIAL ACTION	**Percentage of total removal: 60-85%**				**References**
Name of the process	**Type of action**	**pH**	**Soil temperature**	**Nitrogen loss**	
Ammonia volatilization	Permanent loss	> (8.5-9)	NA (Not applicable)	2.2 g N m − 2 d − 1	Stowell et al. (1981)
Ammonification	Conversion	6.5-8.5	40-60 °C	0.004 to 0.53 g N m − 2 d − 1	Vyzamal (2007)
Nitrification	Conversion	6.5-8	30 to 40 °C	0.048 g N m − 2 d − 1	Tanner et al. (2002)
Nitrate-Ammonification	Conversion	NA	NA	Insignificant	Vyzamal (2007)
Denitrification	Conversion	6-8	60 to 75 °C	0.003 to1.02 g N m − 2 d − 1	Reddy and D'Angelo (1997)
Nitrogen fixation	Permanent loss	NA	NA	0.03 to 46.2 g N m − 2 yr − 1	Buresh (1980)

VEGETATION UPTAKE	**Percentage of total removal: 10-15%**			
Plant species	**Type of plant**	**N uptake**		
Typha latifolia	Submerged	600-2630 kg/Ha/yr	0.16-0.72 g/m2/d	Reddy and De Busk (1987)
Juncus Effusus	Grass	800 kg/Ha/yr	0.21 g/m2/d	PROSEA (2020)
Phalaris Arundiacea	Grass	150-500 kg/Ha/yr	0.04-0,13 g/m2/d	Reddy and De Busk (1987)
Phragmites Australis	Submerged	456-3800 kg/Ha/yr	0.12-1.04 g/m2/d.	Reddy and De Busk (1987)
Duckweeds	Floating	350-1200 kg/Ha/yr	0.09-0.33 g/m2/d	Reddy and De Busk (1987)
Water hyacinth	Floating	1950-5890 kg/Ha/yr	0.53-1.61 g/m2/d	Reddy and De Busk (1987)
SEDIMENTATION	**Percentage of total removal: 10-15%**			
Name of the process	**Type of action**	**Nitrogen loss**		
Nitrogen adsorption	Permanent loss	No data available		
Nitrogen burial	Permanent loss	No data available		

Table 6 Removal rates of Nitrogen

Phosphorus removal

In the removal of Phosphorus, the microbial action is less significant while the vegetation uptake plays a major role contributing almost 30-35% of removal of TP and sedimentation is the most significant remover of TP in the wetland nutrient removal

MICROBIAL ACTION	**Percentage of total removal: 0-5%**		**References**
VEGETATION UPTAKE	**Percentage of total removal: 30-35%**		
Plant species	**P uptake**		
Typha latifolia	75-400 Kg/Ha/yr	0.02-0.1 g/m2/d	Reddy and DeBusk (1987)
Juncus Effusus	110 Kg/Ha/yr	0.03 g/m2/d	Reddy and DeBusk (1987)
Phalaris Arundiacea	30 Kg/Ha/yr	0.008 g/m2/d	Reddy and DeBusk (1987)
Phragmites Australis	35 Kg/Ha/yr	0.009 g/m2/d	Reddy and DeBusk (1987)
Duckweeds	116-400 Kg/ha/yr	0.03-0.1 g/m2/d	Reddy and DeBusk (1987)
Water hyacinth	350-1125 Kg/Ha/yr	0.09-0.3 g/m2/d	Reddy and DeBusk (1987)
SEDIMENTATION	**Percentage of total removal: 60-65%**		
Name of the process	**Type of action**	**P loss**	
Peat accretion	Permanent loss	NA	
Soil adsorption	Permanent loss	NA	

Table 7 Phosphorous Removal rates

In order to select the plant species, we also need to analyse the biomass production capacity of the certain plant species. The biomass capacity of the selected plant species obtained from literature studies are represented under table 8.

Plant species	Biomass capacity	References
Typha Latifolia	4-22 t/Ha/yr	FAO (2020)
Phragmites Australis	6-18 t/ha/yr	FAO (2020)
Duckweeds	40-100 t/Ha/Yr	FAO (2020)
Water Hyacinth	60-70 t/Ha/yr	Lake restoration (1979)
Phalaris Arundinacea	2-15 t/Ha/yr	FAO (2020)
Juncus Effusus	10-14 t/Ha/yr	PROSEA (2020)

Table 8 Plant species and their biomass capacity

Positions for growing paludiculture plants on farmland

Two possible positions were chosen to grow the paludiculture crops on the farmland. The positioning of the plants has to be in such a way that the plants are exposed to the maximum nutrient flow and also able to stop the nutrient from flowing into the main canal. The positioning of the plants should also not hinder the farming practices that are happening on the main area of the farm. Considering these factors, the following positions were chosen for the plants' growth:

i) Field margins

The margin of land around the farmland. There is no productive farming being carried out in this area of the farmland. These are areas around the land before the water is getting mixed with the ditches and could be an ideal position for having the paludiculture plants.

ii) Ditches

The plants could be directly grown in the ditches alongside the farmland. The ditches are separated from the main farm area and could be a position for the plants as the plants grow high up to 1.5 metres, the low area of the ditches could help the plants with constant water depth. Calculations for the removal of nutrients with the paludiculture plants is described in table 7.

Selection of plant species

Out of the six plant species that were studied, T. latifolia (Broadleaf cattail) and Phragmites Australis (Common Reed) are selected as the paludiculture plants that can be used in the chosen area of study. These two-plant species were selected over the other species because it is easier to inundate them in farmland and maintain them compared to the other species used in the study. Though floating plants are having much higher nutrient removal rates and capacity to produce more biomass than the chosen plant species, they are not suitable for the chosen area of study. Duckweeds need sheltering for the wind and Water hyacinth will not be grown on the buffer strips, the possibility could have them in the canal ditches directly which again comes with a problem of taking them out on a regular basis which is practically difficult for the farmer. The grass type plant species (Juncus effusus and Phalaris Arundianacea) are also good choices, but they weren't considered for further study because of the time restrictions and the less economic value that they possess when compared to the chosen two plant species.

Calculations for nutrient removal

The calculations were performed to estimate the amount of nutrient removal that is possible in the area of study with the data obtained from the literature. This is performed to determine the feasibility of using paludiculture plants for nutrient removal. The calculations were performed and stimulated for finding answers to the following questions:

1. year-round input of nutrients: is removal sufficient/feasible?
2. How does this differ between summer/winter?
3. Is removal sufficient/feasible for total (shallow + deep) nutrient outflow? (simulated with 2 m wide strip and all input nutrients)

The total nutrient removal happening in the wetland was distinguished into three types of removal action i) Microbial action ii) Vegetation uptake iii) Sedimentation as described in the model. The lowest value in the removal range was taken in the calculation to quantify the minimum amount of removal. In real time scenarios, these values might vary depending on the factors influenced by the environment in the area of operation.

Total area (TA) = Open space + Agricultural area + Buffer zone + Paludiculture plants

TA=2,858 Ha

Agricultural area= 2,326 Ha

Area possible for buffer strips (Field margins) = 99 Ha

Total amount of nutrients= Nutrient flow from total area

Total nitrogen (TN) = TA * N inflow per Ha

TN=2,858*11.4

TN=32,581 KgN/yr

Total Phosphor (TP)=TA * P inflow per Ha

TP=2,858*1.5

TP=4,287 KgP/yr

The inflow of nutrients was given only for the surface flow which is only 8-10% of the total nutrient inflows. The other inflows include groundwater inflows and nutrient flow into the water canal through the soil layers. Thus, the total nutrient inflow was multiplied by 10 for finding nutrient removal including all the interflows.

Nutrient removal rate = Microbial action + Vegetation + Sedimentation

Removal efficiency = ((Total inflow - Total outflow) / Total inflow) * 100

Nutrient removal	Plant species	Microbial action (g/m2/d)	Vegetation uptake (g/m2/d)	Sedimentation (Kg/yr)	Total nutrient inflow (Kg/yr)	Average removal (Kg/yr)	Removal efficiency
N removal	Typha	0.52	0.16	NA	325,810	131,902	42
	Phragmites	0.52	0.12	NA	325,810	125,187	39
P removal	Typha	NA	0.02	12,861	42,870	16,233	37
	Phragmites	NA	0.009	12,861	42,870	14378	33

Table 9 Nutrient removal calculation for year-round nutrient flow

The implications of the results from the nutrient removal calculations are discussed in detail in the next chapter.

6.3 Farmers' Perspective on Paludiculture

The model developed and the calculations carried out for effective removal of nutrients from wastewater was discussed with a representative from the farmers' association in the Friesland region to get their perspective on the farm area utilisation for having paludiculture plants on their farmlands. This section discusses the results of the interviews carried out with the farmers. Other practical problems that the farmers might encounter while growing paludiculture plants on their farmlands was also discussed.

Position of paludiculture in the farmland

The representative said that it is a good idea to have the paludiculture crops on the field margins. Currently experiments are being carried out by researchers having paludiculture on the field margins in the farm areas in Friesland. The idea of having the paludiculture plants in the area of land around the farmland which is of little productive use to the farmer seems viable. The idea of having the paludiculture crops directly in the ditches is also practically possible. The one problem will be that the ditches are located in the middle of the field and it will be easier to harvest if it was on a farm than having them in the ditches.

Motivation for farmers for growing paludiculture crops

Growing paludiculture crops can provide alternative business models for the farmers apart from conventional farming which is currently about dairy farming though it varies from farmer to farmer about the product they sell either cheese, milk or eggs. But it comes with its own implications, land has a value, a farmer will be motivated to have the paludiculture crops only if he sees enough revenue provided by these paludiculture crops to the land he is using for growing these crops. Another important factor to be considered is that if the farmer is ground bound. The term 'ground bound' is used in the Netherlands to mean that the farmer can use the manure of cows on his own grasslands. When a farmer has many cows and thereby too much manure and he is bound to transport them to another farmer. There are limitations for the N/P use from manure on soils. Therefore, in order to implement paludiculture, it is desirable for a farmer to have enough land to do so. The same for silage/fodder, a farmer needs to feed its cows. So if he doesn't have enough land for it he has to buy the fodder. In this research area, there is a possibility of using the land for growing paludiculture crops as an agricultural nature management area. In that way it provides the farmer with a different revenue model as well. Also having paludiculture crops can provide farmers the opportunity to sell the biomass of these plants commercially as these plants are used as raw materials in construction and insulation purposes. The biomass of the plants can also be used for the bio-energy production, the residue produced after the energy production is rich in P content and could be used as a fertiliser for the farming purpose.

Practical problems of having paludiculture crops on farmlands:

One of the problems that might occur is that Typha and Phragmites grow up to 1.5-2 meters. The problem is that some predators, like the Marsh harrier, like those high and dense paludiculture crops. Therefore, these predators are a problem for the meadow birds that breed in the same area. The second problem is that, for farmers it is important the soil is not damaged. It is the reason why the farmers mow in dry conditions with high temperatures so that the soil is dry. Mowing in the wet soil can cause damage to the soil surface. For Typha and especially Phragmites, it is hard to harvest in dry conditions because these crops thrive in open water. Therefore, in the Netherlands, Phragmites are mostly harvested when the water is frozen solid, thereby it can be harvested with special, hand pushed machines. So technically some developments are needed in order to harvest these crops on a large scale. Thirdly, if farmland (grassland) is inundated for more than 90 days a year it is not considered as agricultural use. The subsidy that the farmers receive from the government will be affected by this. This is a barrier in having the paludiculture crops. This will have to change to motivate the farmers in having the paludiculture crops without any financial constraints. These crops are not very valuable for the farmers. Typha could be used as feed for cows, but it is not very protein rich. There have been tests with feeding Typha to cows. A possibility is using the plants for insulation materials for the construction industry. This industry is looking for better biodegradable products. For Phragmites the market is not stable, Phragmites are used for roof sealing on farms. But here the quality matters a lot. The unstable market and demand for the paludiculture plants make it difficult for farmers to make consistent revenue with the paludiculture crops.

Based on the interview with the representative from the farmers' association, the positioning of the paludiculture crops along the field margins of the farmland seems to be the ideal position as it does not hinder the farm practice and is easier to harvest than placing them directly in the canals. The farmers are open to finding new business models. The growth of Paludiculture can provide the opportunity for such business models with efficient land management. The most important consideration is that the farmers do not face any form of financial constraints because of having the paludiculture plants on their farmland. We also find that number of problems need to be addressed in order to keep the farmers motivated to having the paludiculture crops on their farmlands.

Chapter 7 Discussion

This chapter presents the analysis of the results and then discusses the outcomes of the results in detail. We also look at the results from a critical point of view addressing the gaps in the research carried out.

The study began with the assumption that vegetation uptake plays a large factor in the removal of excess nutrients from the wastewater and increasing the plant biomass accumulation will result in increased nutrient removal. From the data represented in table 5 and 6 it is verified that vegetation uptake plays a major role in the removal of nutrients but is not the most significant nutrient removal action. For Nitrogen removal, microbial action plays a significant role and similarly for Phosphorus sedimentation plays a significant role. Understanding these removal actions and their significance in the removal provides the knowledge base in establishing an effective paludiculture system that can remove the excess nutrients from the wastewater. This finding is in accordance to previous research conducted in understanding the nutrient removal processes in the wetland ecosystem. This does not mean that the nutrient removal could be significant even without the vegetation. The vegetation provides the environment from the microbes to thrive and the plants constantly convert the nutrient from one form to another. It is vital to have the vegetation in order to have the nutrient removal processes to take place effectively.

Table 7 shows the TN and TP removal possibility using the selected two plant species. From the data, it is evident that almost all the removal of nutrient waste from surface water flow is possible to be removed using the buffer strips of two metres width along the field of the farmlands. From the nutrient removal calculations, we can infer that the nutrient removal is possible with the selected plant species and by increasing the area cover of the paludiculture plants more nutrients can be removed from the wastewater. However, the input loading rate that was used in the calculation can largely vary in the real-time scenario. The calculations prove as an indication showing the possible amount of nutrient removal that can happen with the selected plant species. However, factors like HRT, water depth are not considered during the estimation.

The paludiculture crops help in the improvement of water quality by removing the excess nutrient present in the water. In order to improve the quality of water, it is necessary to improve the removal efficiency of the nutrient removal processes. The factors that affect the removal efficiency of nutrients have been described in the developed paludiculture model (Figure 15). The model provides the understanding of different factors that affect the nutrient removal process and it can be used as a knowledge base in further research projects that are being carried out with the similar aim. The model has taken into account three major actions that influence the nutrient removal efficiency and distinguished these clearly with different factors that are interrelated. This makes it possible to be applied to similar research projects that can be carried out in a different area of study. Taking these factors into account helps hugely in designing and implementing an effective paludiculture plant system for the removal of excess nutrients.

The higher the biomass yield, the higher the commercial value of the harvest from the paludiculture plants. In order to increase the yield of the plant it is necessary to understand the growth patterns of the plants. For both Typha and Phragmites, the growth and nutrient uptake is maximum during the summer season in the months of August and September. After the plant growth is maximum it is ideal to harvest them as they provide the maximum biomass. During the months of winter, translocation of nutrients takes place and the plant also starts to lose some of its obtained nutrients in the form of plant decay. It is important to understand this and plan the harvest time accordingly. Significant uptake of nutrients also happens during the maximum growth period of the plant. We can say the maximum nutrient uptake also happens during this period of the year. The harvest frequency also affects the growth patterns and nutrient removal. Determining the number of times, the harvest of these plants over a year (one or two times in a year) is important as this directly affects the nutrient uptake and the biomass yield of the plant. Based on the interview with the farmers representative, the farmers find it easier to harvest in the summer period than winter as the land is dry and better to mown. So that makes it an ideal period both practically and technically to harvest the plants at the end of the summer season. Most of the scientific papers that were used in the study also recommend the summer period as the ideal harvest period for the paludiculture plants resulting in the maximum biomass yield and also for better improvement of the water quality. The input loading rates are highly variable throughout the year and so is the nutrient uptake rates of the plants. The input loading rates are only 15% in the summer period while the plant uptake is maximum during their period of the year. While the loading rates during the winter is 85% and if the plant are harvested for the biomass at the end of summer, the uptake will be very less during the winter. However, there is no certain clarity to say that the uptake is relatively less in the winter though the biomass is harvested there have been studies showing that the nutrient uptake is still been carried out by the roots of the plant during the winter period. It is difficult to conclude on the nutrient removal aspect of the plants during summer and winter period.

Most of the studies conducted to understand the nutrient removal processes have been lab experiments, pilot experiments, direct observation on site operations. The approach taken in this thesis for the estimation of nutrient removal is theoretical calculations based on data obtained from scientific publications. The data estimated used in this thesis are not from practical on site operation or experiments so it is bound to be varying on the real case scenario when the paludiculture plants are grown on the farmlands. This limitation should be kept in mind while considering this study but however the thesis clearly provides the recommendations and throws light on the practical difficulties that need to be addressed to make the nutrient removal process effective in removing the excess nutrients from the farmlands. Additionally, the calculations were carried out taking the lowest value of the available range of the data as it was done as a feasibility study. The results indicate that usage of paludiculture plants are feasible for removing excess nutrients from wastewater, but this gives only the minimum potential of the plants and not the maximum potential.

Chapter 8 Conclusions

This chapter presents the answers to the research questions of the thesis and their implication of the results and future research directions. The feasibility of having paludiculture plants on farming areas for effective nutrient removal from wastewater along with the effective management practices of the paludiculture system is discussed in detail.

Which factors influence the effective functioning of the plants in nutrient intake?

There are various factors that influence the nutrient removal action in the wetland ecosystem. It is difficult to pinpoint at certain factors and leaving out the rest as one factor can have an effect on another and in the end result in affecting the efficiency of the removal action to remove excess nutrients from the wastewater. However, it is possible to keep all the factors in mind and focus on some of the important factors that act as the driving forces for the removal action to be performed. By considering the rate of action and proportional change in these factors we can quantify the removal efficiency, this approach is seen to be performed in several research papers related to wetland nutrient removal studies. The important driving factors that need to be considered are HRT, loading rate of the nutrients, type of plant species used as vegetation. While the factors such as seasonal periodicity, frequency and time of harvest and fluctuation in water seem to be the most important factors that should be taken into account for plant growth and biomass accumulation.

What is the amount of nutrients absorbed and the biomass produced by the different types of plants that can be grown in the study area?

Based on the calculations performed in finding the possible removal rate of nutrients by the chosen plant species, having Typha for an area of 99 Ha would result in the removal of 42% of N and 37% of P of the inflow concentrations with the biomass capacity in the range of 4-22 t/Ha/yr. Using Phragmites over the same area would result in the removal of 39% of N and 33% of P of the inflow concentration with the biomass capacity in the range of 6-18 t/Ha/yr. These calculations are just basic estimations to see the feasibility of using these plant species for nutrient removal. The estimation might vary largely in real time scenarios. From these calculations we can see that using paludiculture plants over an area of 99 Ha in the total area of 2859 results in almost one third of the nutrient removal having the paludiculture crops only over an area of 3-4% of total land area. Using a paludiculture plant system to remove nutrient waste is designed keeping the factors that influence the removal action in consideration.

What is the ideal position on the farmland to grow the selected paludiculture plants?

The calculations for nutrient removal were carried out considering two positions, one being the field margins (the area of land around the polder where productive activities are not done mostly) and second position was directly having them in the ditches. Having the paludiculture culture over a 2m width along the field margins, seems to be a feasible option as this area of the farmland is not used for farming practices and also the paludiculture crops grown in this space will not hinder the farming activity in the main land. When considering having the paludiculture crops directly in the ditches between the farmland, the area possible is equal to the field margins and hence almost the same removal rate could be expected, However, one problem for the farmer will be harvesting the paludiculture crops from the low area of the ditches. It is easier to harvest on farmland than to harvest from the ditches directly.

What is the farmers' perspective on growing the paludiculture plants in their lands?
The farmers are looking for different business models other than conventional ways of farming. Growing of paludiculture crops provides them with the opportunity to generate value without reducing the level of income that they already acquire with their land. The biomass of the paludiculture crops harvested could be sold commercially, the biomass could also be used to generate bio-energy and the residue could be used as fertilizers to the land again. The land with paludiculture crops could be used as natural land management and that will provide a substantial amount of income as well. Some of the problems that farmers encounter with the paludiculture crops are that it is home for predators, harvesting the crops manually is difficult and there is a need for specific equipment, the market for selling the plants as raw materials is unstable and cannot be considered a reliable revenue solution. Also, the subsidy that the farmers receive from the government will be affected if they have crops on their farmland over 90 days. These issues need to be addressed so the farmer is able to grow paludiculture crops efficiently.

The sub-questions have been leading up to the finding the answer for the main research question. The main research question of the thesis is how to design the paludiculture systems in such a way that they function effectively in filtering the excess nutrients from the farmlands?

In order to design an effective paludiculture system that filters excess nutrients, the first step to take into consideration are the important factors that influence the nutrient removal rates of plant species and other removal actions. Secondly, understand how these factors affect the removal actions and create an ecosystem that provides the environment for the nutrient removal action to be performed efficiently. The local environment plays a major role is creating the ecosystem. So, it is vital to understand the local environment in which the paludiculture is to be setup and tailor the system by choosing plants species that are native to the environment. Thirdly, control the factors that are controllable like HRT, plant harvesting frequency in such a way that the nutrient removal is taking place with the maximum efficiency. The positioning of the plant on the farmland is also important factor when it comes to removing the maximum nutrients from the wastewater. Proper assessing of the farm area should be performed with the wastewater inlet and outlet of the paludiculture crop system and the plants must be placed in a position in the farmland that is ideal for receiving the maximum wastewater nutrient flow. The last and the most step is to obtain the farmers and other stakeholders' perspective in order to have the paludiculture crops on the farmlands. Study about the agricultural policy of the region, the commercial value of the chosen crop and create economic value for the farmer through paludiculture plantation.
From the results of this thesis we can conclude that when the paludiculture crops are grown effectively they can act as a natural filter for removing nutrient waste from the farmlands. Not

only help in the removal of excess nutrients but also provide an economic value to the farmers with the biomass obtained from the plant growth.

Future research possibilities and directions

Three possibilities and directions for research were identified to build on the findings of this thesis. Firstly, the developed model could be fed with data establishing the relationships between the various factors with numerical and the model simulation could be run to simulate the amount of nutrient removal possibility with the selected plant species. Secondly, only six plant species were considered in this thesis study. There is a plethora of plants that have the ability to remove nutrients which could be studied. And thirdly, different stakeholders' perspective, for example from the policy makers, water directory board and other farmers should be obtained to provide a more comprehensive view of the problem and bridging the gap between the stakeholders in finding the solution for overcoming the problems related to growing the paludiculture crops.

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APPENDICES

Appendix A. Consent form for the interview conducted with farmers' representative

Informed consent form

I declare to be informed about the nature,method and purpose of the study. I voluntarily agree to take part in this study.I keep the right to terminate my participation in this study without giving a reason at any time. My responses should be solely used for the purpose of this study.
(Please tick one of the boxes)

O be cited with my name or function revealed
O be cited anonymously, thus without identifying context
O only used as information source

During the course of the interview I keep the right to restrict the use of (some of) my answers further than indicated above.

Name of the participant:
Date:
Signature of the participant:

I declare to fully adhere to the above.
Name of the researcher:
Date:

Signature of the researcher:

Appendix B. Transcript of the Questions and Answers from the interview

1) What is the motivation for farmers to have the paludiculture crops on their farming land?
   It is about generating alternative business models, different from the current way. So now the business is about milk, meat, cheese, eggs and others (depends on the farmers). Most farmers have dairy farms in this part of The Netherlands.

2) What financial losses would the farmers incur because of having these paludiculture crops on your farmlands?
   a) Farmers need land to produce a certain amount of milk. The more land, the more cows you can maintain and thereby you can produce more milk. Selling milk is the main business case. Of course, there is a difference between individual farmers, some gain other incomes by applying agricultural nature management or gain income by producing biological. In your research area there's a possibility agricultural nature management is applied, most likely for meadow birds. Maybe also biological farmers.
   b) Also, it depends if the farmer is 'ground bound', it is a term used in Holland and it means in short; When you can use the manure of cows on your own grasslands. If you have too many cows and thereby manure, you have to transport the manure to another farmer. There are limitations for the N/P use from manure on soils. So, if you want to implement paludiculture, it is desirable for a farmer to have enough land to do so. The same for silage/fodder, a farmer needs to feed its cows. So, if he doesn't have enough land for it he has to buy it.
   c) Land has a value, if you downgrade it by producing paludiculture crops. The crops should represent a good business model for farmers to cooperate.

3) In what way do you think these paludiculture crops might hinder your farming practices?
   As described above at 2. A second problem that might occur is that Typha and Phragmites grow up to 1,5-2 meters. The problem is that some predators, like the Marsh harrier, like those high and dense paludiculture crops. So, these predators are a problem for the meadow birds that breed in the same area.

4) Do you think field margins are an ideal position for having the paludiculture plants?
   That is a good idea to have the paludiculture crops on the field margins. We are currently experimenting with having paludiculture plants in the field margins so if you are talking about the low areas of 100 of acres, those are the areas that are not very productive from the farmers and it is useful to have paludiculture crops in those areas such that they also don't hinder in the farming area.

5) Do you have sufficient knowledge already about the paludiculture crops, their economic and ecological benefits as a farmer?
   In the project Better Wetter, we are experimenting with growth and nutrient removal. But there is not a lot of knowledge about producing paludiculture crops on a big scale. Only laboratorial or small-scale experiments.

6) What width of buffer strips would be practically convenient for the farmers?
   It depends on the grasslands. It is practical if a farmer can mow the grasslands without having to turn or move around the paludiculture strips. So if there are ditches in the field, it is practical to have a strip up to the ditch.

7) What frequency of harvesting and replanting would be convenient for the farmers?
   Depends on the paludiculture, for farmers it is important the soil is not damaged. That is why farmers mow in dry conditions with high temperatures. For Typha and especially Phragmites it is hard to harvest in dry conditions because these crops thrive in open water. So, in Holland we see that Phragmites are harvested when the water is frozen solid, thereby it can be harvested with special, hand pushed machines. So, we need some developments if we want to produce on a higher scale.

8) What use do the farmers see from the obtained biomass from the paludiculture plants?
   These crops are not very valuable for the farmers. Typha could be used as feed for cows, but it is not very protein rich. There have been tests with feeding Typha to cows. A possibility is using the plants for insulation materials for the construction industry. This industry is looking for better biodegradable products. For Phragmites the market is not stable, Phragmites are used for roof sealing on farms. But here the quality matters a lot.

9) Based on the calculations, what problem do the farmers see if the ditch itself is being used to filter the wastewater?
   This is also practically possible to have the paludiculture crops in the ditches directly. We have a project in which we are discussing this solution and this is also quite convenient. The one problem will be that the ditches are located in the middle of the field and it will be easier to harvest if it was on a farm than having them in the ditches.

10) Will the subsidies provided by the government for having crops on farmlands be affected by growing the paludiculture crops?
    If farmland (grassland) is inundated for more than 90 days a year it is not considered as agricultural use. So that has to change if you want to produce paludiculture crops.