Managing nutrients in Denmark's aquatic environment

A critique and a way forward for Danish management of re-created wetlands

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LUCSUS
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Abstract

Anthropogenic use of nitrogen and phosphorus causes a risk to aquatic ecosystems and hence the livelihood of humans. To tackle this issue, the European Union have imposed environmental obligations on its member states to higher the quality of the aquatic environment. As a member state, Denmark is partly fulfilling these objectives by re-creating wetlands in the landscape, which retain and remove nutrients from agricultural runoff. However, it has been identified that there is a risk of phosphorus leaking from the wetlands re-created on phosphorus rich soils. The biogeochemical processes regarding phosphorus mobilization in wetlands are of high complexity, making it hard to predict potential phosphorus leakage from a wetland. This makes management difficult as there is high uncertainty regarding the impact of decisions. This thesis maps and evaluates the management practice of the Danish government regarding re-creation of wetlands through interviews with governmental officials, conversations with experts and a literature review. Finally, it is discussed how an implementation of adaptive management could improve the long-term management of Danish wetlands regarding potential phosphorus leakage. The results show that the current management practice uses a phosphorus model to risk assess potential phosphorus leakage from re-created wetlands. This model has limitations regarding the variables used in the model and it is not dynamic over time. The model does currently not include aluminium, sulphur and calcium, which is shown to be important in assessing the risk of phosphorus leakage from re-created wetlands. Furthermore, the results suggest that the combination of high uncertainty in terms of low knowledge level on biogeochemical processes and high controllability in terms of carefully planned projects makes adaptive management a promising management option, which over time can reduce uncertainty and thereby make management more sustainable. The thesis concludes that management can be improved through an implementation of adaptive management in Denmark and that long-term monitoring of nutrient loads from wetlands are key to gain a better understanding, which can ensure a sustainable management of re-creation of wetlands in Denmark.

Keywords: re-created wetlands, phosphorus, Denmark, adaptive management, dealing with uncertainty, social-ecological systems

Word count: 13882

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List of abbreviations

AA	= Agricultural Agency [Landbrugsstyrelsen]
Al	= Aluminium
AM	= Adaptive management
Ca	= Calcium
DNA	= Danish Nature Agency [Naturstyrelsen]
DOI	= (United States) Department of Interior
EPA	= Environmental Protection Agency [Miljøstyrelsen]
EU	= European Union
Fe	= Iron
N	= Nitrogen
ND	= Nitrate Directive
P	= Phosphorus
RBMP	= River Basin Management Plans [Vandområdeplaner]
S	= Sulphur
US	= United States of America
WFD	= Water Framework Directive

1 Introduction

Anthropogenic nitrogen (N) and phosphorus (P) use have been identified by Steffen et al., (2015) to be one of the planetary boundaries that has exceeded the 'safe operating space' into 'beyond zone of uncertainty', causing a high risk of altering the natural system beyond a point of no return. Consequently, dealing with the pollution of N and P is an urgent problem. The human use of N and P is mainly agricultural and causes a risk for the aquatic environment as nutrients are carried from agricultural land via waterways, where they cause eutrophication, reduced water quality and loss of biodiversity (Steffen et al., 2015; van Dijk, Lesschen, & Oenema, 2016). The problem of nutrient runoff is socio-ecological, as it involves human actors and biogeochemical processes and it is a problem across scales, ranging from small ponds to oceans. These combined, make the long-term management wetlands to reduce N and P a sustainability science issue (Kates et al., 2001).

The European Union (EU) have addressed water pollution by N and P with two directives - the Water Framework Directive (WFD) and the Nitrate Directive (ND) - due to increasing demands from citizens and environmental organizations, who have demanded action to tackle this problem (European Community, 2000; European Union, 2016a). As Denmark is a part of the EU, the Danish government is obliged to implement various methods to reduce the aquatic pollution of N and P. One approach used by the Danish government, is re-creation of wetlands as a tool to reduce N and P in the aquatic environment in Denmark and its marine coastal waters (Miljøstyrelsen [Danish EPA], 2017b).

Re-creating wetlands in the landscape are a common tool to reduce N and P pollution in the aquatic environment (Mitsch & Gosselink, 2015). Wetlands have the ability to remove N through de-nitrification and to retain P through sedimentation, soil adsorption and plant uptake (Reddy & DeLaune, 2008; Verhoeven, Arheimer, Yin, & Hefting, 2006). However, it has been identified that there is a potential risk of releasing a surplus of P, when re-creating a wetland, especially on former agricultural land rich in P (Hoffmann, Kronvang, Andersen, & Kjærgaard, 2013; Land et al., 2016). This makes management of re-creating these wetlands difficult, as most re-created wetlands in Denmark are made on former agricultural land. In order to address this issue, the Danish government uses a P-model, which assesses the risk of P leakage from re-created wetlands (Hoffmann et al., 2013).

The issue of potential P leakage from re-created wetlands causes high uncertainty in management, which is typical of many social-ecological problems and it has been recognized that adaptive management (AM) can be helpful to deal with such uncertainty (Allen & Garmestani, 2015, p. 2). AM is a method that derives from the 1970's and has been implemented in several federal institutions in the United States to manage natural resources (Allen & Garmestani, 2015, pp. 182–185). AM is relevant to use in areas where both controllability and uncertainty is high (Allen, Fontaine, Pope, & Garmestani, 2011). In management of re-creating wetlands in Denmark, uncertainty is high as P is influenced by many factors, which are not fully understood. Controllability is also high, as every project is carefully planned, following official guidelines.

1.1 Thesis aim and research questions

This thesis takes a problem-solving approach and aims to improve the current management practice by the Danish government in terms of re-creating wetlands and assessing potential P leakage from them. Through this aim, the thesis contributes to an ongoing debate in Denmark regarding the management of the social-ecological water system. The social-ecological system is here defined as the country of Denmark and its marine coastal waters with the land use and hydrological processes occurring there. Key actors in this social-ecological system are the EU, the Danish government and their collaborating scientists, Danish municipalities, farmers and agricultural land owners.

This thesis is guided by the 3 research questions:

1. How is the Danish government managing re-creation of wetlands as a tool to mitigate aquatic nutrient pollution from Danish agriculture and what are the current limitations?
2. How can Denmark's current management approach be improved, drawing on knowledge from scientific and grey literature?
3. How would an adaptive management approach address the current limitations in management of wetlands as nutrient retainers in the Danish landscape?

This thesis has been written in collaboration with the Danish EPA. No contract has been formed and no funding has been given. The Danish EPA has provided me a working space in their office and has been helpful at clarifying questions regarding their management of wetland creation. As an author, I have been free to write what I wanted without any constraints from the Danish EPA.

2 Methodology

To collect the data necessary to answer the research questions I have used semi-structured interviews and literature reviewing as methods. In addition to this, conversations with several experts on the biogeochemistry of wetlands and the management of them in Denmark and Sweden have been used to guide to my research. These conversations were not conducted as formal interviews.

2.1 Semi-structured interviews

I conducted three semi-structured interviews with officials from the Danish EPA, mainly to answer research question 1. These three officials were chosen because they are officially tasked with implementing the Danish government's management practice of re-creating wetlands. I chose the semi-structured interview form to be able to ask follow-up questions when interesting matters came up, but still making sure to gather the information needed (Brinkmann, 2013, p. 21). Two of the interviews (Vang & Nielsen) were made with officials, with a general knowledge on the Danish governments effort to mitigate nutrient pollution, through the re-creation of wetlands. The last one, Thomsen, was made with the official responsible for an ongoing monitoring programme covering the effect of re-created wetlands. Two different interview guides were developed, tailored to get the relevant information. The first interview guide (appendix A) aimed to get a broad understanding on how the Danish government manages the re-creation of wetlands, in order to mitigate aquatic nutrient pollution and which challenges they face. The second interview guide (appendix B) was designed to learn about a monitoring programme currently running. All interview recordings and transcripts can be found in the accompanying zip file. All quotes used in the results have been translated from Danish to English. All interviews were conducted on March 8, 2018.

2.2 Literature review

A literature review was conducted to answer research question 2. The methodology for the literature review was guided by the six steps outlined by (Machi & McEvoy, 2016). The process is described in Table 1.

Table 1. An overview of the steps in the conducted literature review. (Own illustration, 2018).

Steps described in (Machi & McEvoy, 2016)	What was conducted
1: Select a topic	The topic was selected using results from research question 1, by the guiding question; how can management be improved drawing on knowledge from scientific and grey literature?

2: Develop the tools of argumentation	The current management practice uses instructions that guides the use of an excel spreadsheet P-model to assess the risk of P leakage for a wetland project. While searching for literature, the argumentation to include or exclude literature was guided by following the questions; does the literature support or conflict with the instructions and the P-model? Does it add new knowledge that could improve the instructions and the P-model?
3: Search the literature	Literature was continually searched for during the research. Inputs from experts were used to find new relevant literature. The gathered literature was collected digitally and organized by topics.
4: Survey the literature	The literature was surveyed for relevant information to answer research question 2. Relevant literature was extracted and read fully.
5: Critique the literature	The literature was critically read to remove studies, which would not be relevant to evaluate the Danish P-model.
6: Write the review	The review was written as a text explaining the key findings, with a supplementing table for overview.

2.3 Conversations with experts

The wetland experts in Denmark and Sweden who were consulted in this thesis were:

1- Lisa Heiberg, former postdoc at University of Copenhagen, who has published several articles on P mobilization. Now she owns the company DiaPure, which develops filters to remove P from water. She developed a model to risk-assess P mobilization in wetlands for the Swedish institution Länsstyrelsen.

2- Carl Christian Hoffmann, Senior Researcher in Department of Bioscience, Aarhus University. Co-developed the model, which the Danish government uses to risk-assess P mobilization in wetlands.

3- Charlotte Kjærgaard, Chief Scientist at SEGES (Danish research department of the Danish Agriculture & Food Council). Formerly senior researcher at Aarhus University where she co-developed the P-model, which the Danish government uses to risk-assess P mobilization in wetlands.

4- Tette Alström, Natural Geographer from Lund University, working at the consultancy 'Ekologgruppen' as a consultant specialized in risk assessment of P from wetlands.

3 Background

3.1 Nutrient pollution and eutrophication

P is a chemical element, which plays an increasingly important role in the aquatic environment in Denmark. Together with N, it is the main macro nutrient, which causes eutrophication in the aquatic environment in Denmark (Kronvang et al., 2001). Most often, P is the limit to algae growth in Danish surface freshwaters (i.e. lakes, streams and fresh fjords), whereas N is generally the limiting factor in the marine environment (Kronvang et al., 2001, p. 81; Wiggers, 2003). Eutrophication leads to an extensive growth of algae which blocks light from reaching the bottom of e.g. a lake. This causes a lack of vegetation on the bottom, which is important for biodiversity as they support the existence of other species (Wiggers, 2003). In addition, dead algae sediment and decompose, causing a risk of oxygen depletion in the water body (Reddy & DeLaune, 2008). Decomposing bacteria requires oxygen and hence an extensive amount of dead algae can drain the water from oxygen, which makes the bottom uninhabitable for species that require oxygen to live (Hansen, Balsby, & Jensen, 2017). These subsequent impacts of excess P and N in the aquatic environment have consequences for ecosystems and human water uses. To address this issue, the EU has implemented directives that regulate nutrient pollution in the aquatic environment (European Union, 2016a).

3.2 The Water Framework Directive and The Nitrate Directive

The WFD and the ND are both directives that apply for all member states of the EU. The WFD was passed in 2000 and the ND in 1991. The two directives are interlinked as they both regulate pollution of water in the EU.

The WFD prescribes that water bodies should be classified in five categories based on their ecological status; 'high', 'good', 'moderate', 'poor' and 'bad' (European Commission, 2000). 'High' ecological status is defined using a reference point of "no, or very minor disturbance from human activities" (European Union, 2016a). In Denmark, the reference year is chosen to be 1900 (Jensen, 2017). The

WFD sets a series of goals, including achieving 'good' ecological status of all waters by 2027 (European Union, 2016a). This thesis focuses mostly on the 'good' ecological status goal, which is recognized to be the biggest challenge to achieve for Denmark (Naturstyrelsen [Danish Nature Agency], 2014). In order to achieve 'good' ecological status the amount of N and P in Danish surface waters must be significantly reduced (Miljøstyrelsen [Danish EPA], 2017b). The WFD is broken into cycles with milestones, the current cycle is 2015-2021. The final cycle will run from 2021-2027 (European Union, 2016b).

3.2.1 Ecological status in Danish lakes and streams

In 2014, an analysis was conducted to assess the status of achieving 'good' ecological status in Danish water bodies by 2021 (Naturstyrelsen [Danish Nature Agency], 2014). The results showed that 93% of the assessed streams and 92% of the assessed lakes were in risk of not meeting these milestones (Naturstyrelsen [Danish Nature Agency], 2014, p. 33). As Danish freshwaters are generally P-limited, P must be reduced from streams and lakes to meet the WFD targets.

3.2.2 Implementation of the Water Framework Directive in Denmark

The Danish government are responsible for achieving the WFD goals with the Ministry of Food and Environment being the main actor. To fulfil the goals, a set of different measures have been implemented including reducing pollution from point sources and diffuse sources (mainly runoff from agriculture) (Miljøstyrelsen [Danish EPA], 2017b). This thesis focuses on the management of re-creating wetlands to mitigate pollution from diffuse sources (i.e. agriculture), which is needed to fulfil the WFD goals. The Environmental Protection Agency (EPA) [Miljøstyrelsen] and the Agricultural Agency (AA) [Landbrugsstyrelsen] are the two institutions within the Ministry of Food and Environment, who are carrying out the management effort of re-creating wetlands to achieve the WFD goals.

3.3 Wetlands

I define a wetland in line with the Ramsar convention on wetlands:

> "Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention Secretariat, 2013, p. 7)

Historically, Denmark had a lot of wetlands, which have changed drastically during the 20th century. Around the year 1900, Denmark had wetlands covering approximately 7.460 km^2 and in the 1990's there was only 569 km^2 left, representing a 92.4% reduction in approximately 90 years (Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016). This development reflects a historical period in Denmark where the agricultural sector was growing and became more efficient. As a part of this development, extensive drainage of the land happened (Jensen, 2017). This involved straightening and deepening streams, in order to move the water as fast as possible from the land to the ocean (Ovesen et al., 2000). This made more land available for agriculture and removed a lot of the naturally occurring wetlands, lakes and marsh (Ovesen et al., 2000). Since the 1980's there has been a focus on restoring these lost landscape features, through restorations of lakes, streams and wetlands to mitigate N and P pollution and to improve biodiversity and recreational activities (Jensen, 2017). Throughout this thesis, the term re-creation of wetlands is used to describe all wetland projects, also wetlands which are placed where there historically have not been one, as it is not always known if that is the case or not. When a wetland project is conducted, most often the drains are clogged or a pump is switched of, making wetlands re-occur where it used to occur naturally. An example of a Danish wetland is shown in Figure 1.

Figure 1. A photography of a wetland in Denmark. Source: (Naturstyrelsen [Danish Nature Agency], 2016)

3.3.1 Using wetlands as water cleaners

Re-creation of wetlands is a useful management strategy for improving water quality that has been employed in Denmark (Windolf, Tornbjerg, Hoffmann, Poulsen, et al., 2016). When a soil is covered with water, it slowly becomes waterlogged. Once saturated, oxygen disappears or is drastically reduced, which means anaerobic conditions occur in the soil (Reddy & DeLaune, 2008). This makes it possible for micro-organism to perform denitrification. Denitrification is a process that reduces nitrate to gaseous forms of N, mainly N_2, but also N_2O (Dotro et al., 2017). The denitrification combined with sedimentation of P in slow waters is what makes wetlands useful for mitigating aquatic pollution of nutrients (Reddy & DeLaune, 2008).

Utilizing this effect, the Danish government and the EU started to fund projects of re-creating wetlands in the landscape. However, the effectiveness of these wetlands as water cleaners varies substantially (Land et al., 2016). The denitrification is generally more effective the higher the load of N in the water is (Dotro et al., 2017; Land et al., 2016). For P, it is a lot more complicated, which is shown in the results of this thesis. Despite uncertainties and complexities there is agreement that broadly speaking and with a long-term perspective, re-created wetlands improve the water quality both in terms of N and P (Dotro et al., 2017; Reddy & DeLaune, 2008; Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016). In Denmark two catchments have been compared to assess the effect of re-created wetlands on mitigating N and P pollution (Windolf, Tornbjerg, Hoffmann, Poulsen, et al., 2016). One catchment had got re-created 1,8 ha of wetland pr. km^2 in the period 2000-2013. The control catchment had 0,5 ha pr. km^2 in the same period (Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016). The catchments are shown in Figure 2 and the trends in N and P that have occurred in both catchments since 2000 are shown in Figure 3 (Windolf, Tornbjerg, Hoffmann, Poulsen, et al., 2016). The comparison shows that both catchments have had a reduction in runoff of N and P, but the catchment with the most re-created wetlands have had a higher reduction (Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016).

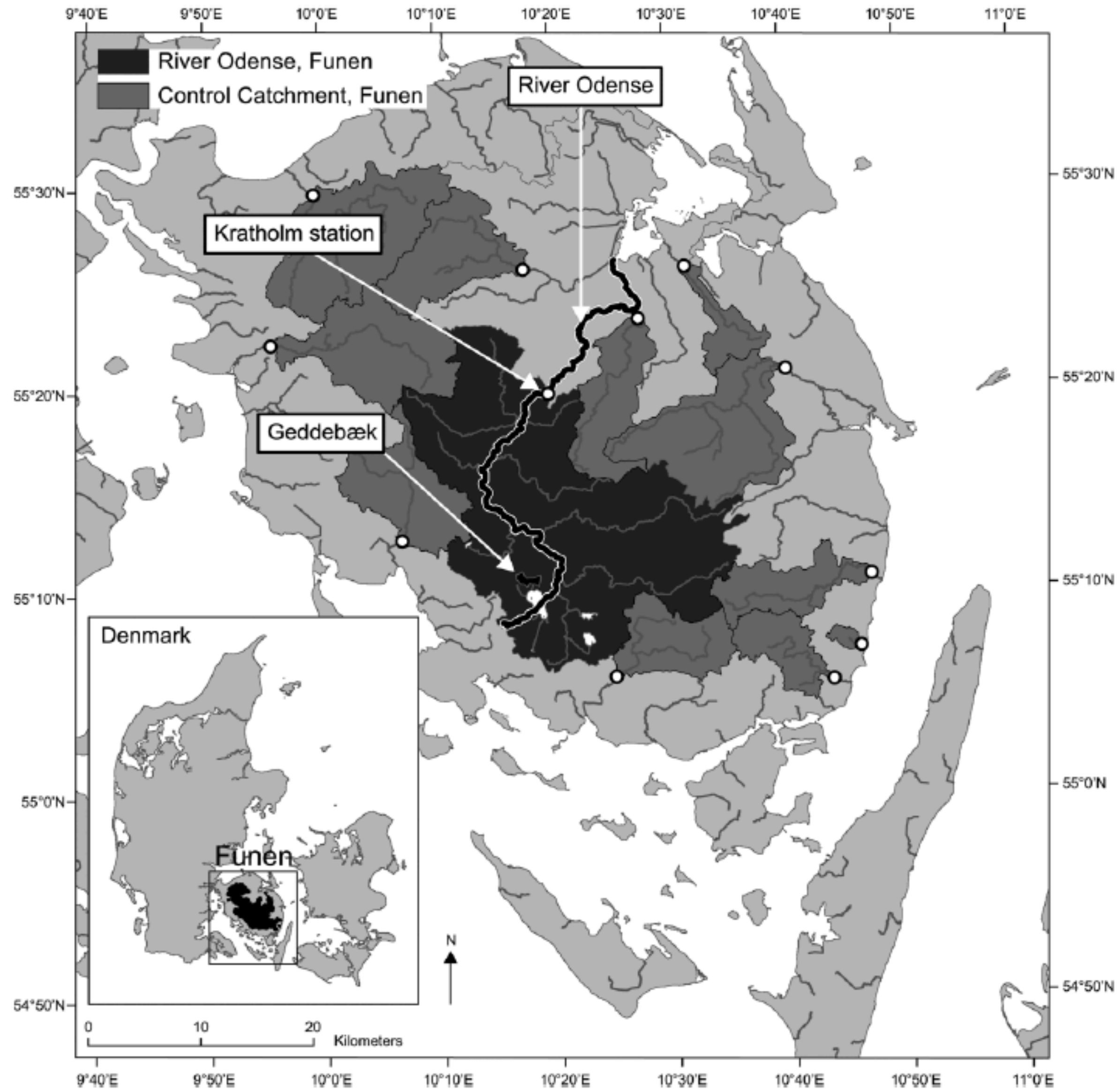

Figure 2. A map showing the location of the catchment with 1.8 ha of re-created wetlands per km^2 (black) and the control catchment with 0.5 ha of re-created wetlands per km^2 (grey) located at the Danish island Funen. Source: (Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016).

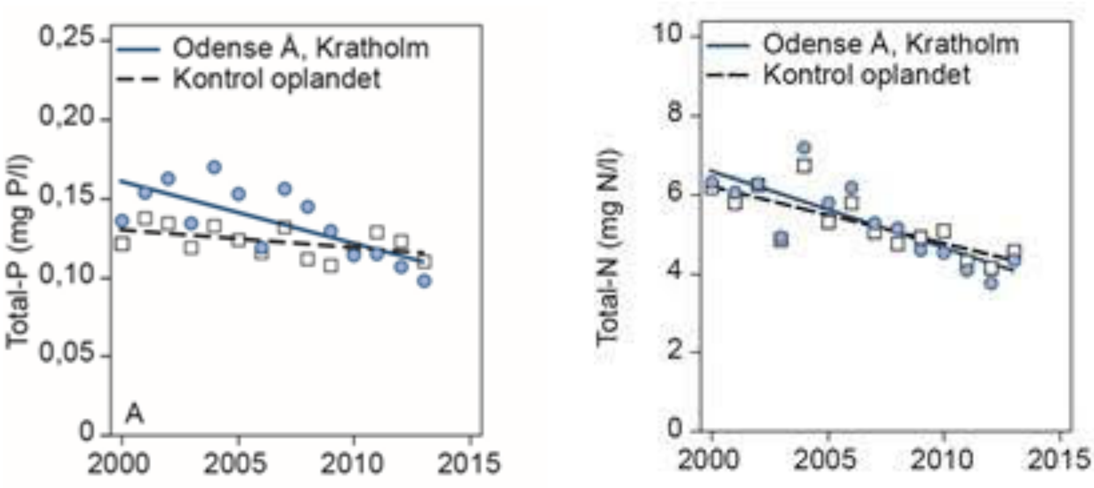

Figure 3. To the left it is shown that Odense Å, had a higher reduction of total P over the period, than the control catchment, which had less re-created wetlands in its catchment. To the right the same graph is shown for total N where the same statement is true. Source (Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016, pp. 92–93)

3.3.2 Unwanted side-effects of re-creating wetlands

While there are ecological benefits of re-created wetlands, unwanted side-effects can also occur. A systematic review of created and re-created wetlands, based on 93 articles, surveying 203 wetlands (most in temperate climates like Denmark) showed unwanted side-effects of re-created wetlands, as they do not always retain P immediately (Land et al., 2016). In particular, re-created wetlands on agricultural land retain less P than others, and in some cases release more P than they retain (Land et al., 2016, p. 13).

In Denmark, this effect has been observed in the case of Vilsted Sø [Vilsted Lake]. The lake was re-created in 2006 on an area of 450 ha (Aarhus University, 2015). Continuous measurements of P showed that there was a higher amount of P leaving the area shortly after the restoration, compared to prior to restoration see (Figure 4). This case is unique in Denmark as it is surprisingly rare to have continuous long-term measurements of P transportation before and after a restoration project. The case of Vilsted Sø has spurred the debate around possible P leakage from re-created wetlands.

Before the lake was restored, a stream was running through the land, where P was measured. Figure 4 shows the measurements of P from the stream prior to the lake restoration and after. The data shows an increase of P in the water shortly after the restoration project, which then levels out to approximately prior levels after a few years (see Figure 4). This suggests that a pool of P has been released because of the restoration (flooding of the area), but also that it is a short-term phenomenon. Despite indicating that the phenomenon is short term, the case of Vilsted Sø cannot be extrapolated to all restoration projects in Denmark, since it could be a unique case.

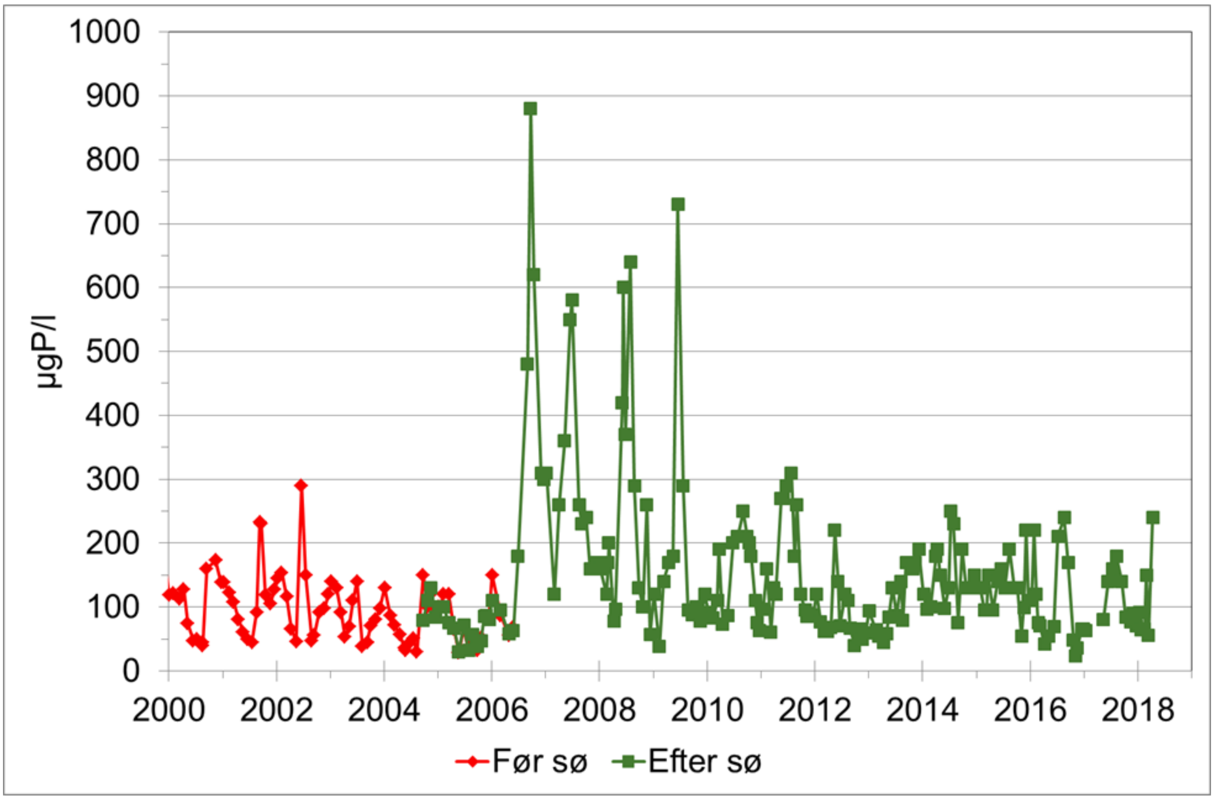

Figure 4. Concentration of Total P (TP), prior to restoration (in red) and after restoration (in green). The graph shows a high temporary increase of TP in the years following the restoration, which then seems to settle to around prior levels. Source: **(**Jørgen Bidstrup, personal communication, April 23, 2018).

3.3.3 Non-nutrient related benefits of wetlands

Besides the ability to remove N and retain P, wetlands are considered beneficial as they can store carbon, improve biodiversity, support re-creational activities and provide climate change adaptation due their ability to act as water buffers during storm water (Mitsch & Gosselink, 2015; Reddy & DeLaune, 2008).

Carbon is mainly stored in the soils in wetlands (Fennessy, Wardrop, Moon, Wilson, & Craft, 2018). Residue plants which are not fully degraded, due to the anaerobic conditions ends up as humus soil as shown in Figure 5 (Reddy & DeLaune, 2008).

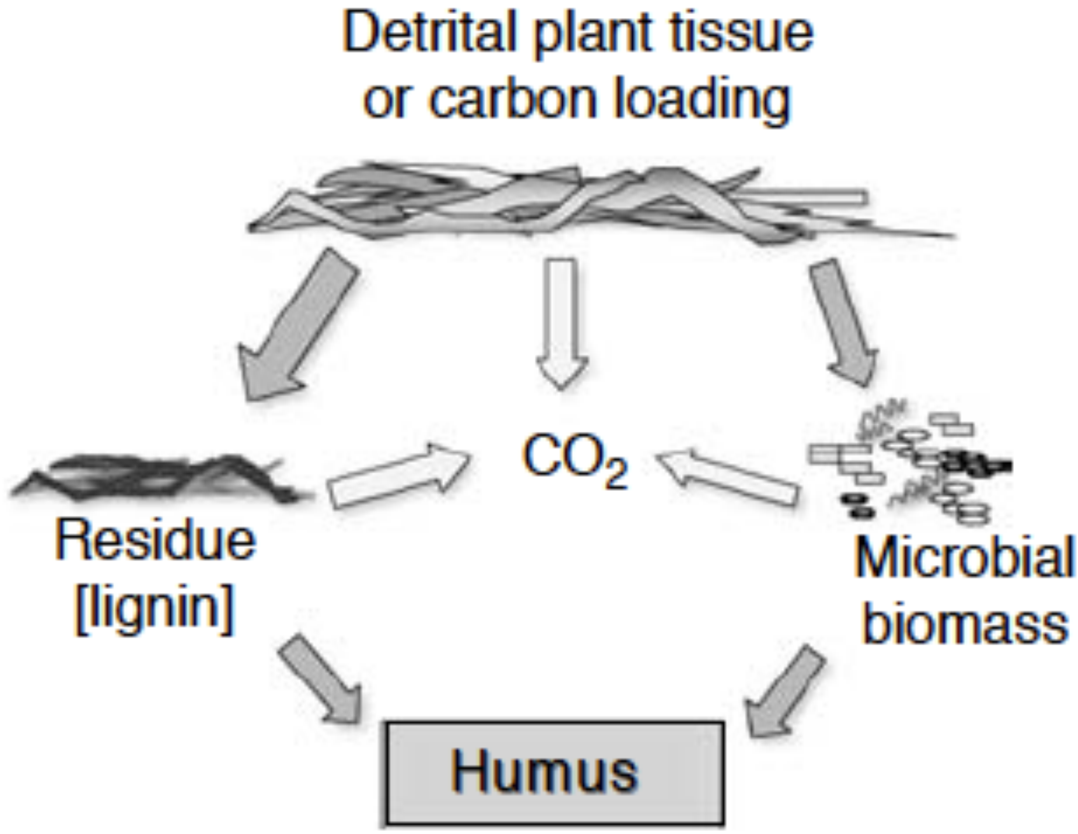

Figure 5. A conceptual drawing of how residual plant mass turns into CO2 and humus, respectively. The humus is rich of carbon and represents most of the long-term carbon storage in wetlands. Source: (Reddy & DeLaune, 2008, p. 179)

The effect of a specific wetland's capacity to store carbon is hard to assess, as there is high variability between wetlands capacity to sequester carbon (Fennessy et al., 2018), but average studies of freshwater temperate wetlands (e.g. Denmark) shows a sequestration rate of 278 ± 42 grams C m^{-2} yr^{-1} (Mitsch & Gosselink, 2015, p. 569).

Biodiversity is often improved when wetlands are re-created, especially in regards of birds, for which they provide habitats (Arheimer & Pers, 2017; Dotro et al., 2017; Thiere et al., 2009). The diversity of the fauna is dependent on the nutrient loading, where a high nutrient loading leads to less diversity in the fauna (Mitsch & Gosselink, 2015, p. 639). This means there is a trade-off between achieving biodiversity of fauna and removing N, as the most efficient N removing wetlands are those with the highest loading.

Recreational purposes includes bird watching, hunting and nonconsumptive use values, which essentially means appreciating the landscape in various ways (Arheimer & Pers, 2017; Mitsch & Gosselink, 2015, p. 545).

Re-creation of wetlands also functions as a climate change adaptation tool, as they are able to delay storm water, which is projected to become more frequent in Denmark due to climate change (Olesen et al., 2014). This concept is shown in Figure 6.

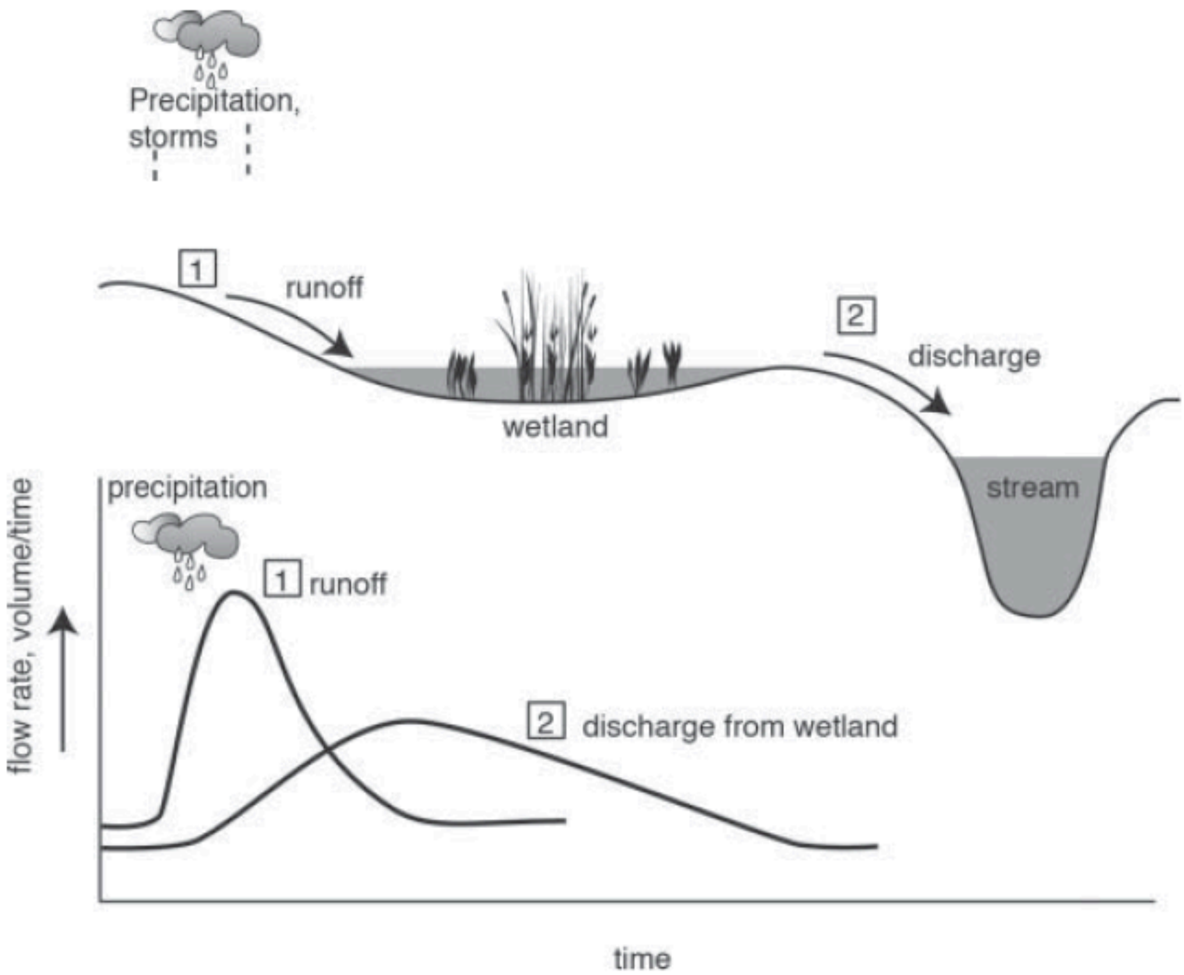

Figure 6. A conceptual sketch of how wetlands can delay the water flow from short term intense precipitation, to ease the pressure on downstream flows. Source: (Mitsch & Gosselink, 2015, p. 539).

3.4 Phosphorus in the Danish aquatic environment

In Denmark, P is currently introduced to the aquatic environment in several ways listed here in prioritized order, with the largest contributor first; diffuse leaching from agricultural lands, wastewater from point sources, natural erosion and atmospheric sedimentation (Ellermann et al., 2015; Kronvang et al., 2001; Wiggers, 2003). From the 1970's and onwards there was a reduction in the P leaching from point sources (wastewater treatment plants, industries, fish farms, scattered settlements) (Kronvang et al., 2001). From 1989-1999 effluent treatment methods was noticeably improved and there was an 85% reduction of P leaching to the aquatic environment from wastewater treatment plants over those 10 years (Kronvang et al., 2001, p. 38). Conversely, the leaching of P from agricultural land was historically not a big contributor, but due to the good results in reducing P leakage from point sources, agriculture has now become the biggest aquatic P polluter in Denmark (Wiggers, 2003). In Denmark, the agricultural pollution of P increased in the mid 1990's, due to an increase in pig production which produces P-rich manure that is used for fertilization of the fields and hence leading to higher runoff (Kronvang et al., 2001, p. 45).

P is transported in the aquatic environment either dissolved in the water or bound to particles that are moved by the water (Kronvang et al., 2001). P can bind to various minerals and metals, which will be shown in the results of research question 1. One common metal which binds P in soils are iron (Fe) (Laakso, Uusitalo, & Yli-Halla, 2016). Fe binds P strongly, when oxygen is present, which is common in topsoil (Reddy & DeLaune, 2008). If the soil is flooded, e.g. in a wetland, conditions can change to anaerobic and Fe will release the P to the water column. However, often the P is transported to an aerobic part of the water, where it again will be bound to available minerals and metals and become sediment, when it is Fe particles which releases and re-captures P due to change in the presence of oxygen it is referred to as the 'Fe(III) – Fe (II) redox wheel' (Li, Yu, Strong, & Wang, 2012). The likelihood of newly released P to sediment again is very place specific, as the structure of the soil, soil type, pH, hydrologic regime and the amount of available metals and minerals has an influence (Reddy & DeLaune, 2008).

Big amounts of P is often moved around in the environment when there is a high velocity of either wind or water (wind representing atmospheric deposition) (Ellermann et al., 2015; Reddy & DeLaune, 2008). The most common is that water will carry the P, as a result of high water flow following intense precipitation (Kronvang et al., 2001). The P is often carried by water from e.g. fields into streams and will then sediment in places where the water is slowed down (Kronvang et al., 2001). This is often in lakes, wetlands or when flooding vegetation like grass (Wiggers, 2003). Prior to human interventions in the Danish landscape, naturally many streams would temporarily flood the surrounding meadows, which would sediment a significant amount of the P in the grasses (Wiggers, 2003). Human interventions of straightening and deepening rivers, and draining soils have largely removed this mitigating effect (Kronvang et al., 2001).

4 Theory - Adaptive management

AM is an approach to natural resource management which acknowledges that management decisions have to be made, despite the fact that the knowledge base for decision-making is usually inadequate (Allen, Fontaine, et al., 2011; Benson & Garmestani, 2010). When the knowledge level is inadequate, e.g. regarding complex P-dynamics in wetlands, uncertainty is high in management decisions (Walters, 1986). In other words, it is uncertain what the outcome of a particular management decision will be. AM provides a way forward for management in these situations by using a transparent framework built on structured decision-making, which aims to reduce this uncertainty over time by 'learning while doing' (Allen, Fontaine, et al., 2011).

4.1 Structure of adaptive management

AM follows the process visualized in Figure 7. The grey circles indicate what is referred to as 'structured decision-making', which is an important element of AM, but should not be confused with AM itself (Allen, Fontaine, et al., 2011).

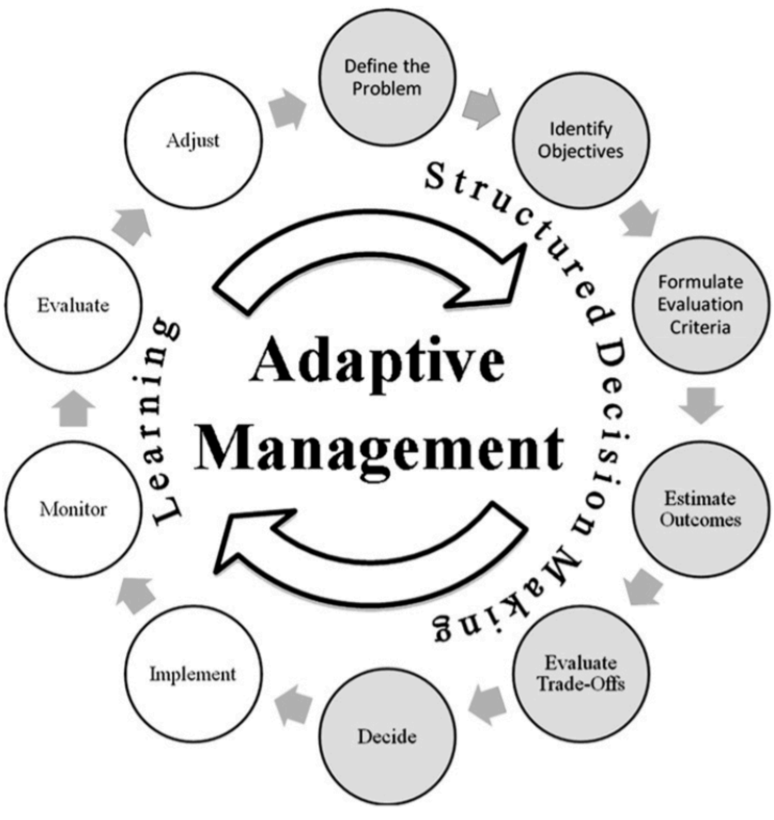

Figure 7. An outline of the steps in a successful implementation of AM. Grey circles represent the structured decision-making steps. Source: (Allen, Fontaine, et al., 2011).

Structured decision-making is a problem-solving method derived from sociology that can be used to identify and transparently weigh different options against each other through engagement of stakeholders (Allen & Garmestani, 2015). A key point of structured decision-making is to set clear measureable goals for the outcome of the decisions, which ensures that the goals are not altered during the project (Allen & Garmestani, 2015). The clear goals from structured decision-making will help to find the best future management practice, as exemplified in Figure 8. The example in Figure 8, shows a scenario where several options are implemented simultaneously and then compared against each other in how successful they were, to find the best option (Allen, Fontaine, et al., 2011). The key point here is that the successfulness is measured according to the pre-defined goals (Allen, Fontaine, et al., 2011). To compare the outcomes monitoring is key, as it is used to evaluate outcomes and hence achieve new knowledge and adjust management accordingly (Benson & Garmestani, 2010).

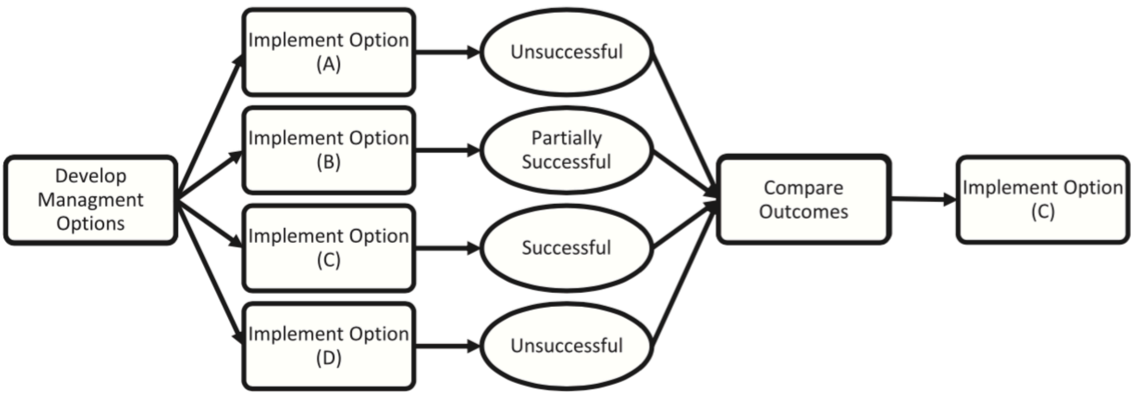

Figure 8. A visualisation of how AM aims to develop different management option (A, B, C & D) which then are implemented and compared to find the best option. Source: (Allen, Fontaine, et al., 2011).

4.2 When is adaptive management appropriate?

AM is appropriate when both uncertainty and controllability are high, as shown in Figure 9 (Allen, Fontaine, et al., 2011). High uncertainty in AM is defined as a situation where it is a gamble what the outcome of a management decision will be, despite efforts of modelling and reasoning (Walters, 1986, p. 159). High controllability means that the system can be manipulated precisely (Allen, Fontaine, et al., 2011; Peterson, Cumming, & Carpenter, 2003). AM builds on a structured design, where different options will be tested and the most successful chosen. To do this, high controllability is needed. If controllability is low, then it is difficult to carry out different management options, making it hard to compare them afterwards. Low controllability are scenarios where planning or interventions are not possible (Walters, 1986). An example where AM is not appropriate is climate change, because it ranges across so many scales and is influenced by so many entities it is virtually impossible to carry out a management option and monitor the outcome of it (Allen & Garmestani, 2015).

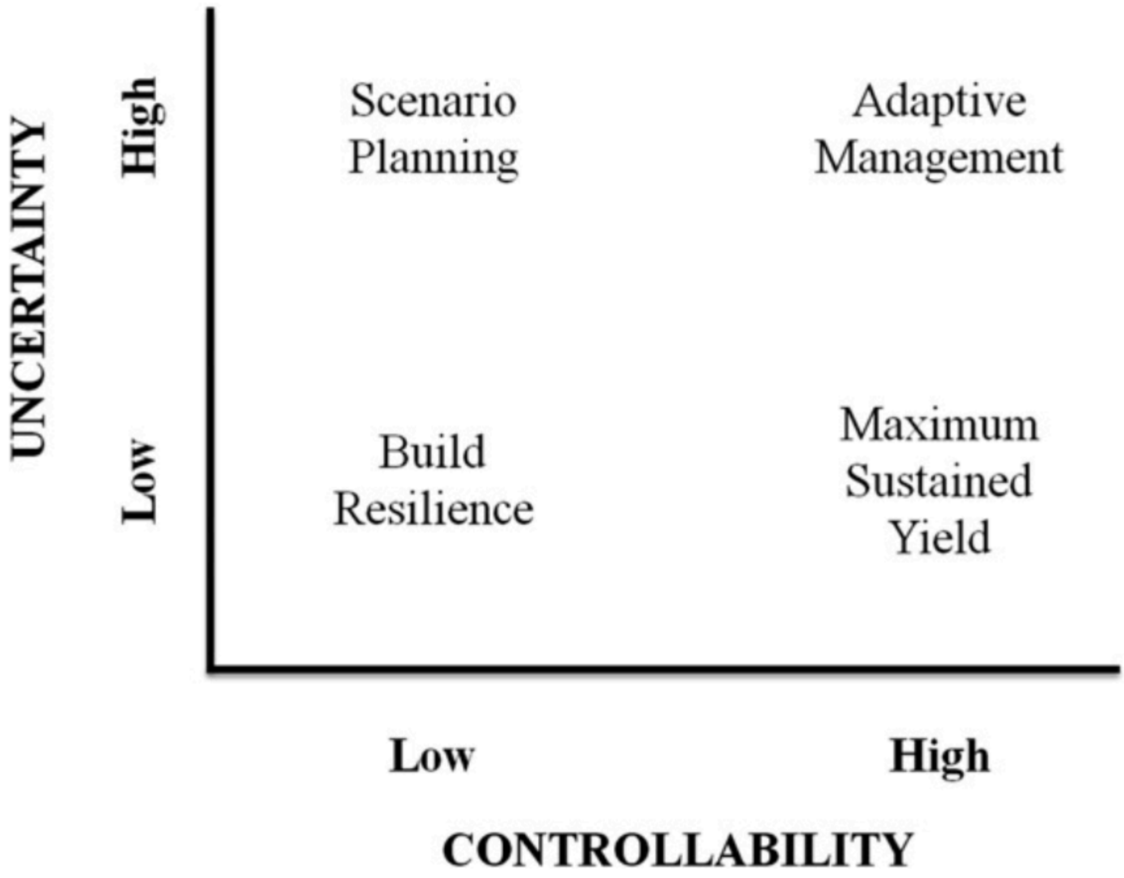

Figure 9. The figure shows in which cases AM is appropriate to use, which is when both controllability and uncertainty is high. It also shows which alternatives to AM is appropriate in other situations. Source: (Allen, Fontaine, et al., 2011).

4.3 Where adaptive management is used in natural resource management

AM has most successfully been implemented in the US by the Department of Interior (DOI), to improve the long-term management of natural resources (Williams, Szaro, & Shapiro, 2009). The DOI, uses AM to deal with a variety of challenges often including prescribed interventions in ecosystems (e.g. controlled burns, water level control, relocation of animals etc.) (Williams et al., 2009). Using AM in cases like this is appropriate, because uncertainty is high (regarding the effects of an intervention) and controllability is high, as interventions can be designed as pleased (Williams & Brown, 2012). Not all management in the DOI follows AM principles, as it is not always appropriate. A US governmental working group published two reports for practitioners to better understand when AM is appropriate and how it is implemented (Williams & Brown, 2012; Williams et al., 2009).

AM has successfully been used to re-create wetlands in the Delaware Bay (US) (Teal & Weishar, 2005). AM was used to test different management options regarding how to re-create ditches and channels to restore the natural vegetation and function of the wetlands. Before the project was carried out, clear goals were set to which functions the wetlands should have to be considered successful. The AM was implemented by having three different sites, where different management options were carried out in order to find the best management practice to achieve the goals (Teal & Weishar, 2005). Restoring wetlands can be planned carefully (high controllability), but with high uncertainty regarding e.g. flooding events, and the authors concluded that applying AM to such an intervention was successful (Teal & Weishar, 2005).

4.4 adaptive management and legislation

Implementing AM in large organizations that are working with environmental protection has proven difficult due to legal barriers, which have been shown e.g. in the US (Allen & Garmestani, 2015, p. 39). One reason for this is that AM often involves taking risky decisions to learn from the success or failure of those decisions, but that is not always allowed for by legislation (Benson & Garmestani, 2010, p. 1422). In 2013, a survey was conducted among US practitioners of AM, which showed that more than 70% of the respondents felt constrained by legislation and could name specific legal constraints that hindered them in implementing AM (Benson & Stone, 2013). The legislations which was noted to constrain implementation of AM were: Endangered Species Act, National Environmental Policy Act, Sustainable Fisheries Act and various water supply and management statutes (Benson & Stone, 2013). An example of a constraint was the lack of flexibility in management options for conservation of endangered species, due to the Endangered Species Act. The practitioner notes that this is not necessarily a bad thing, but it impedes the implementation of AM (Benson & Stone, 2013). This emphasises that legislative authorities must be on board to ensure a proper implementation of AM.

5 Results

5.1 Research question 1 – Danish management of re-creating wetlands

Research question 1: How is the Danish government managing re-creation of wetlands as a tool to mitigate aquatic nutrient pollution from Danish agriculture and what are the current limitations?

5.1.1 Overview

In this section I will show how the current management of re-creating wetlands is planned and funded by the Danish government. I do this by using information available from the Danish government and the interviews I conducted with officials from the Danish EPA. First I outline how the current management works and then I show the limitations to the current practice.

5.1.2 State institutions managing wetland creation

The Danish EPA and AA are in charge of planning what methods to use to fulfil the EU environmental goals. This includes deciding which kind of wetlands and how many should be restored with state funding (Miljøstyrelsen [Danish EPA], 2018a). Privately initiated re-created wetlands also exist, e.g. foundations who buys lands and creates wetlands, but the majority of wetlands are state funded and hence planned by the Danish government and the EU (Miljø- og Fødevareministeriet [Ministry of Food and Environment], 2017).

The Danish government have developed River Basin Management Plans (RBMP) [Vandområdeplaner], which specify how the goals set by the EU directives should be met (Naturstyrelsen [Danish Nature Agency], 2014). The RBMP functions as a management plan for, among others, re-creation of wetlands (M.S. Nielsen, personal communication, March 8, 2018).

5.1.3 Initiating a wetland project

In the current practice, it is most often one of the 98 Danish municipalities who initiates a new wetland project (Miljøstyrelsen [Danish EPA], 2018a). Together with landowners and consultants, municipalities send applications to the AA to achieve funding to re-create a wetland. This can only be done if the project fits with the RBMP (i.e. the RBMP should specify a need for a project in that area) (M. S. Nielsen, personal communication, March 8, 2018). Within the last year, it has also become a possibility for the Danish Nature Agency (DNA) [Naturstyrelsen], to send in applications for initiating wetland projects (P. Vang, personal communication, March 8, 2018). An application is reviewed back and forth by the EPA, the AA and the applicants as shown in Figure 10.

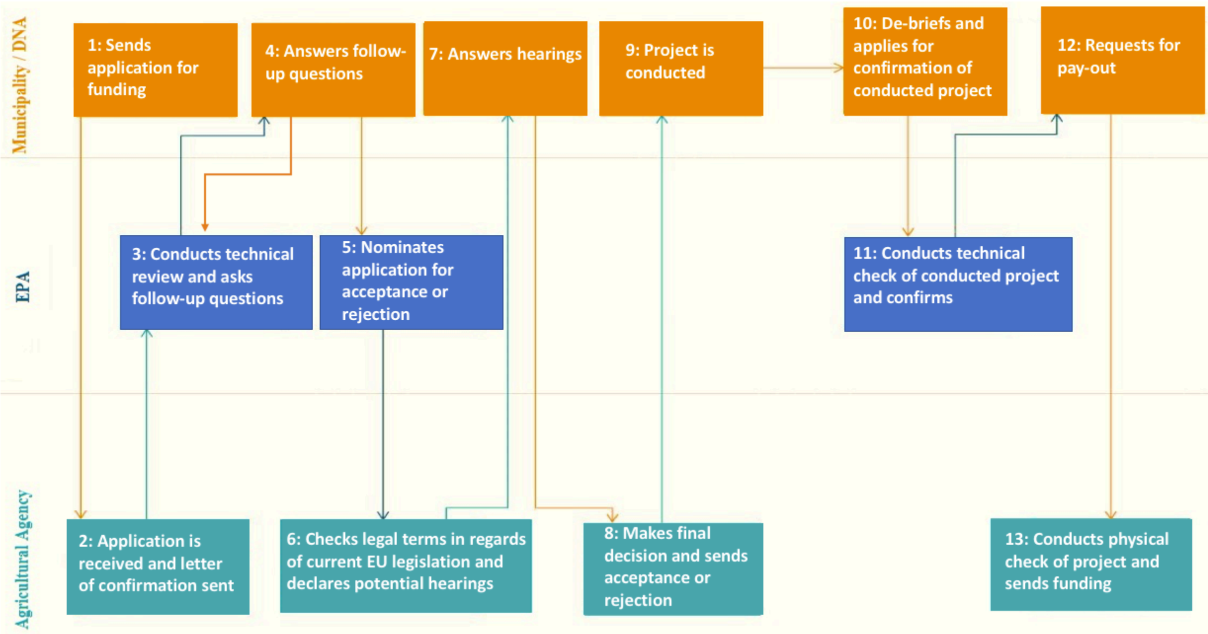

Figure 10. The process of applying for funding for a wetland project in Denmark. This process happens twice for a finalized project. First it happens when preliminary investigations are applied for and then it is repeated for construction of the wetland. Step 3 and 4 can bounce back and forth numerous times, until all follow-up questions have been answered sufficiently (personal communication, Maria Sloth Nielsen, May 4, 2018). The figure is translated and modified from Miljøstyrelsen [Danish EPA], (2018).

Despite the municipalities being the initiators of wetland projects, they do so accordingly to the course set in the RBMP. As shown in Figure 10, the process is rigorous and passes through many checks before funding is given. This shows that controllability in the process is high from the governmental institutions. The whole process is happening twice for projects that are constructed (M.S. Nielsen, personal communication, May 4, 2018). First, funding for a preliminary investigation is applied for. The preliminary investigation aims to reveal the feasibility, potential and possible environmental consequences of the project (Landbrugstyrelsen & Miljøstyrelsen, 2018, p. 15). If the preliminary investigation does not show any issues that could halt the project, the process is repeated and funding for the actual construction of the project can be granted (M.S. Nielsen, personal communication, May 4, 2018). Preliminary investigations also include a risk assessment of potential P-leakage from the re-created wetland (Landbrugstyrelsen & Miljøstyrelsen, 2018).

5.1.4 Meeting the environmental targets

The total expected N and P removal from constructed projects counts towards the goals set by the Danish government in the RBMPs (Naturstyrelsen [Danish Nature Agency], 2014). During the first RBMP period from 2009-2015 approximately 75% of the targets were fulfilled, measured as the calculated effects of the wetlands to remove and retain nutrients (P. Vang, personal communication, March 8, 2018).

5.1.5 Limitations to meeting the environmental targets

Maria Sloth Nielsen from the EPA mentions the following limitations to completion of projects as:

"The amount of applications and suitable areas. We also have a big problem some places with phosphorus leakage." (M.S. Nielsen, translated personal communication, March 8, 2018). Poul Vang, mentions that some projects from the first RBMP period was not created due to "[…] a land owner who did not want to participate or other issues, including phosphorus (leakage)" (P. Vang, translated personal communication, March 8, 2018).

In sum, the limitations to meet the environmental targets are manifold and complex, but a part of the problem is projected risk of P leakage from projects.

5.1.6 Risk assessment of P leakage

The risk assessment for possible P leakage is currently done as part of the preliminary investigations, following the instructions outlined in a guiding document called "Kvantificering af fosfortab fra N og P vådområder [Quantification of phosphorus loss from N and P wetlands]", available at the Danish EPA website (Miljøstyrelsen [Danish EPA], 2018a). The instructions claims to use "state-of-the-art" knowledge on the hydro-biochemical processes regarding P in re-created wetlands (Hoffmann et al., 2013, p. 4), and is complemented by a spreadsheet-based P-model made in Microsoft Excel (Miljøstyrelsen [Danish EPA], 2018a). The P-model can, based on data from soil samples, calculate the projected P retention or leakage from a wetland. Both the P-model and the instructions have been developed by Aarhus University, for the Danish EPA (Hoffmann et al., 2013). The instructions and the P-model were both published first in 2013 and have been reviewed continuously, most recently in January 2018. The use of the P-model was implemented on the 19th of September' 2013 (Peter Simonsen, personal communication, April 12, 2018).

5.1.7 Soil sampling

The preliminary investigation includes soil samples from the project area, which are taken using the guiding principles from Figure 11, to ensure a systematic method for soil sampling (Hoffmann et al., 2013). The project areas are bigger than the actual flooded area, to avoid that the surrounding area is flooded by extraordinary flooding events, which could disturb agriculture (M.S. Nielsen, personal communication, May 5, 2018).

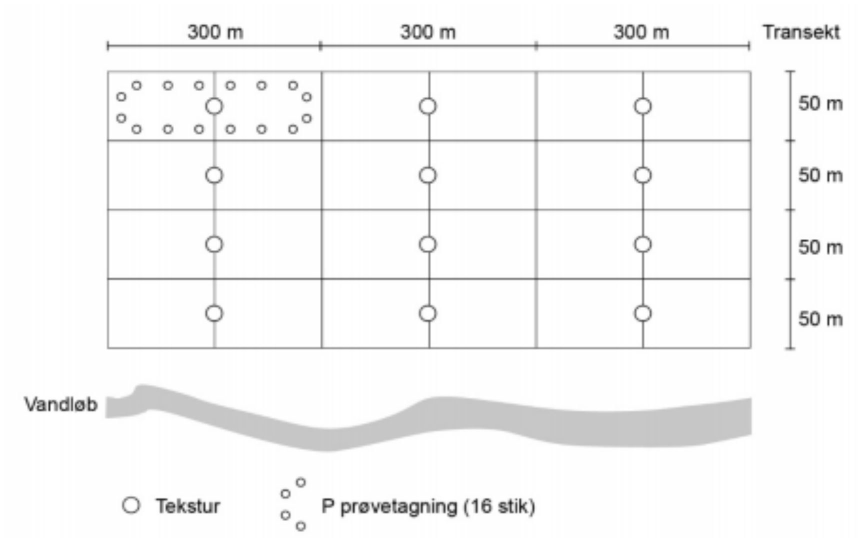

Figure 11. Guiding principle of soil sampling in project area. Legend translation: Tekstur [Texture], P Prøvetagning (16 stik) [P Sampling (16 spots)], Vandløb [Stream], Transekt [Transect]. Source: (Hoffmann et al., 2013, p. 6)

From the soil samples, soil 'texture' is determined through qualitative analysis describing the soil profile. The aim is to identify the soil types present and to know in which layer of the soil profile water is transported together with the hydraulic conductivity, which are incorporated in the P-model (Hoffmann et al., 2013, pp. 6–7).

For every single grid in Figure 11, 16 samples are collected and mixed into one, to give an average of that grid (Hoffmann et al., 2013). The samples are then analysed for bicarbonate dithionite to measure the amount of P which is bound to Fe (Hoffmann et al., 2013, pp. 9–10). The idea is to assess the amount of P, which can be mobilized when Fe (III) gets reduced under anaerobic conditions in the soil of the wetland (Hoffmann et al., 2013).

5.1.8 The P-model

All data from the soil samples are plotted into the P-model together with frequency of flooding, catchment characteristics and information about the design of the wetland (Hoffmann et al., 2013). The final output from the model is an estimate of the total P either retained or released from the wetland given as Kg P yr^{-1}, which is either retained or released. The P-model is not dynamic in response to time as this yearly rate does not change over time. This means that the P-model suggests an eternal and steady retention or release of P.

5.1.9 The P-model's limitations and the implications for current management

The lack of a time aspect in the P-model is a major limitation. The result of X Kg P yr^{-1} being released or retained is based on the pool of P in the soil bound to Fe. If this certain amount of P is released and leaves the project area each year, then the pool of P in the soil is reduced, which means the initial amount, which the P-model uses, is no longer valid. In my interviews with officials from the EPA, it was mentioned by Poul Vang that they are uncertain whether the time aspect of the P-model reflects reality or not. After talking about the Vilsted Sø case, he sums up: "So the question is: is it only 5 years where some phosphorus is released, or, if there is 70 tons of phosphorus in the soil, could it then still be mobile? How is the chemistry changing in the soil in the bottom of the lake? That's it, we do not know" (P. Vang, translated personal communication, March 8, 2018). As the quote suggests, there is a suspicion that the P-model does not account for a possible decrease of P leakage over time. Consequently, several projects cannot be done, since the P-model shows a high release of P from the assessed project areas (P. Vang, personal communication, March 8, 2018). The management practice is currently that every marine coastal water has a threshold of how much extra P can be tolerated within the catchment. The threshold is set to 1% of the current yearly supply to that coastal water (P. Vang, personal communication, March 8, 2018). For example, if Vejle Fjord (a Danish Fjord), receives 200 kg P yr^{-1}, then wetland projects in the catchment are allowed to cumulatively release up to 2 kg P yr^{-1}. When this is reached, the current management practice prohibits the re-creation of any additional projects that releases P in that catchment, unless they can be countered by other projects that retain P. Because a reduction in P leakage from wetlands over time is not currently accounted for in the P-model, this 1% threshold will remain crossed indefinitely, ultimately prohibiting future wetland re-creation.

5.1.10 Scale of the problem

By examining two excel spreadsheets from the Danish EPA (Miljøstyrelsen [Danish EPA], 2015, 2018b), which keep track of all wetland projects from 2011 until present, I have extracted the data for all wetlands that have been assessed for P leakage using the P-model, meaning all projects initiated from the 19th of September 2013. From this I found that out of the 21 projects that have data from the P-model, 13 of them are expected to leak P (Miljøstyrelsen [Danish EPA], 2015, 2018b). Thus, more than 60% of the projects are expected to leak P, reducing the possibility to initiate other projects in those catchments in the future.

5.1.11 Monitoring the unwanted P leakage from re-created wetlands

In 2014, the EPA initiated a new monitoring programme for re-created wetlands in collaboration with Aarhus University (M. Thomsen, personal communication, March 8, 2018). The project was initiated to monitor the effectiveness of re-created wetlands, both in terms of N removal and P retention/release. The monitoring programme is monitoring 10 re-created wetlands per year, starting 1 year after the restoration of the wetland (M. Thomsen, personal communication, March 8, 2018). The total amount of monitored wetlands is planned to be 50 by 2020. The data from this project is not yet available and the first report based on the results is planned to be ready in the late summer 2018 (M. Thomsen, personal communication, March 8, 2018), which means the results could not be included in this thesis.

Mette Thomsen from the EPA explains the reasoning behind initiating the monitoring program like this:

> "The focus of this project has been to meet a critique, which came on behalf of the EU (EU Court of Auditors, 2013). Back then nitrogen was 'the new black', so you really wanted to be able to say that you monitored that. One thing is that we calculate how much we retain, but what is the actual retention? Why do we place wetlands where we do?" (M. Thomsen, translated personal communication, March 8, 2018).

Additionally, the monitoring program was a response to a public debate, which questioned to which extent re-created wetlands can remove N and if they are as efficient as the EPA claims (M. Thomsen, personal communication, May 14, 2018).

This suggests that there was a focus on N removal rather than P retention, when the monitoring project was designed. It also highlights the fact that management of re-created wetlands is overall based on calculated effects, rather than actual measured effects. As shown in the case of Vilsted Sø (see section 3.3.2) P mobilization can change drastically from year to year. Thus, to meaningfully say something about P leakage from a re-created wetland, data from prior to the restoration and for several years after are needed.

In Denmark, there is a large system of measurement stations which takes water samples from streams, lakes, fjords and ground water (Miljøstyrelsen [Danish EPA], 2017a). The system consists of both stationary and mobile stations. In 2017, employees from the Danish Agency of Water and Nature Management (today a part of the Danish EPA) conducted an analysis of 179 wetland projects. These were investigated to see if there was sufficient monitoring data to conclude anything on the P leakage or retention from them. The analysis showed that there was not sufficient data for any of the re-created wetlands (Styrelsen for Vand- og Naturforvaltning [Agency of Water and Nature Management], 2017).

5.2 Research question 2 – Can current management be improved?

Research question 2: How can Denmark's current management approach be improved, drawing on knowledge from scientific and grey literature?

5.2.1 Overview

The current management of re-creation of wetlands holds some limitations regarding P leakage assessment as shown in results from research question 1. The instructions and the P-model, which current management follows for P risk-assessment, was published in 2013 and latest reviewed in January 2018. It claims to be 'state-of-the-art' in terms of knowledge of how P acts in re-created wetlands. In this section I will use insights from my literature review and conversations with experts to investigate if the P-model can be improved.

This section is structured by first summarizing the knowledge from my literature review and comparing it to the P risk-assessment (instructions and P-model) used in the Danish management. Then alternative management options are identified and finally it is summarized how this knowledge can improve the Danish management practice.

5.2.2 Summary of reviewed literature compared to Danish P-model

The literature review supported the use of P bound to Fe in soil samples as a good basis for the Danish P-model, but also revealed several fundamentally important factors for P dynamics in wetlands that are currently overlooked. It is widely recognized that flooding a soil can lead to a reduction of Fe (III) to Fe (II) hence releasing dissolved P, which then can leak to the subsequent waterways (Hoffman et al., 2012; Kjærgaard & M. Forsmann, 2014; Li et al., 2012; Laakso et al., 2016; Prem et al., 2015; Ronkanen, Marttila, Celebi, & Kløve, 2016; Schoumans et al., 2013; Tang et al., 2016). This is especially the case with former agricultural land, where P has accumulated due to fertilization (Hoffman et al., 2012; Schoumans et al., 2013; Smolders, Lucassen, Bobbink, Roelofs, & Lamers, 2010). The reduction of Fe (III) to Fe (II) and the associated release of P is at the core of the Danish P-model as the only P which is measured in soil samples is P bound to Fe (Hoffmann et al., 2013, p. 10). However, aluminium (Al), sulphur (S) and calcium (Ca), which are currently not accounted for in the Danish P-model, are also fundamentally important for P dynamics in wetlands. Table 2 describes these different aspects that are not considered in the Danish P-model.

Table 2. An overview of key aspects identified in the literature review, which are not included in the Danish P-model. (Own illustration, 2018).

Subject	Key aspects not included in the Danish P-model	References
Al	Al plays an important role for retention and release of P in wetlands. P can be accumulated in wetlands through sorption and precipitation to Al. Al oxides are not redox sensitive, making it an important element of P retention, as it potentially can resorb P that was released by Fe.	(Cui, Xiao, Xie, & Zhang, 2018; Dotro et al., 2017; Hoffman et al., 2012; Huang, Huang, & Zhu, 2016; Ippolito, 2015; Jin, He, Kirumba, Hassan, & Li, 2013; Laakso et al., 2016; Prem et al., 2015; Reddy & DeLaune, 2008; Ronkanen et al., 2016; Schoumans et al., 2013; Tang et al., 2016)
S	S plays an important role in the sediment-cycle, because it can precipitate Fe, hence removing Fe from the pool of available Fe to precipitate with P. Therefore, a narrow focus on Fe-P relation, which ignores the role of S can be misleading.	(Li et al., 2012; Reddy & DeLaune, 2008; Smolders et al., 2010; Sun, Sheng, Yang, Di Bonito, & Mortimer, 2016; Tang et al., 2016; van der Welle, Roelofs, & Lamers, 2008; Wu et al., 2013)
Ca	P adsorption to Ca is identified as very common in the literature. It is highly sensitive to pH levels. Under alkaline conditions Ca adsorbs P very well. If conditions change to acid conditions, the P is released quickly. Ca does not only act as a buffer of P, but also as a potential risk in case of pH alteration from alkaline to acidic.	(Dotro et al., 2017; Gunnars, Blomqvist, Johansson, & Addersson, 2002; Hoffman et al., 2012; Huang et al., 2016; Jin et al., 2013; Luca et al., 2017; Mander, Vohla, Poom, Jordforsk, & Instituut, 2003; Reddy & DeLaune, 2008; Ronkanen et al., 2016; Xu, Xu, Wu, & Muhammad, 2006)

Al plays a crucial role of P-mobilization in re-created wetlands as it commonly binds a lot of P. In contrast to Fe, Al is not sensitive to redox conditions and hence does not release any P during anaerobic conditions (Reddy & DeLaune, 2008, p. 352). The Danish P-model does not include any Al measurements (Hoffmann et al., 2013), which means that the pool of Al is unknown. Since the soil samples are only measured for P which is bound to Fe, the pool of P bound to Al is also unknown. Due to this, it is possible that when P is released from Fe particles, it could bind to Al particles instead. When it is not measured, and included in the P-model, uncertainty around this aspect remains high. The literature review and conversations with Swedish experts shows that Al is included in several cases where soil samples are also used to assess the risk of P leakage in Swedish re-creation of wetlands (Ekologgruppen, 2017; Heiberg, n.d., 2012).

S has been identified to play an important role in mobilization of P in wetlands, due to its interaction with Fe (Reddy & DeLaune, 2008, p. 356). When there are sulphur-rich reducing conditions, the dissolved Fe will precipitate as FeS_x (Smolders et al., 2010, p. 5). This means that there is less dissolved Fe available, which can precipitate with P, under aerobic conditions as shown in Figure 12. This 'breaks' the Fe-P redox wheel of sedimentation, where P is released under anaerobic conditions, but some is re-captured when it reaches an aerobic environment.

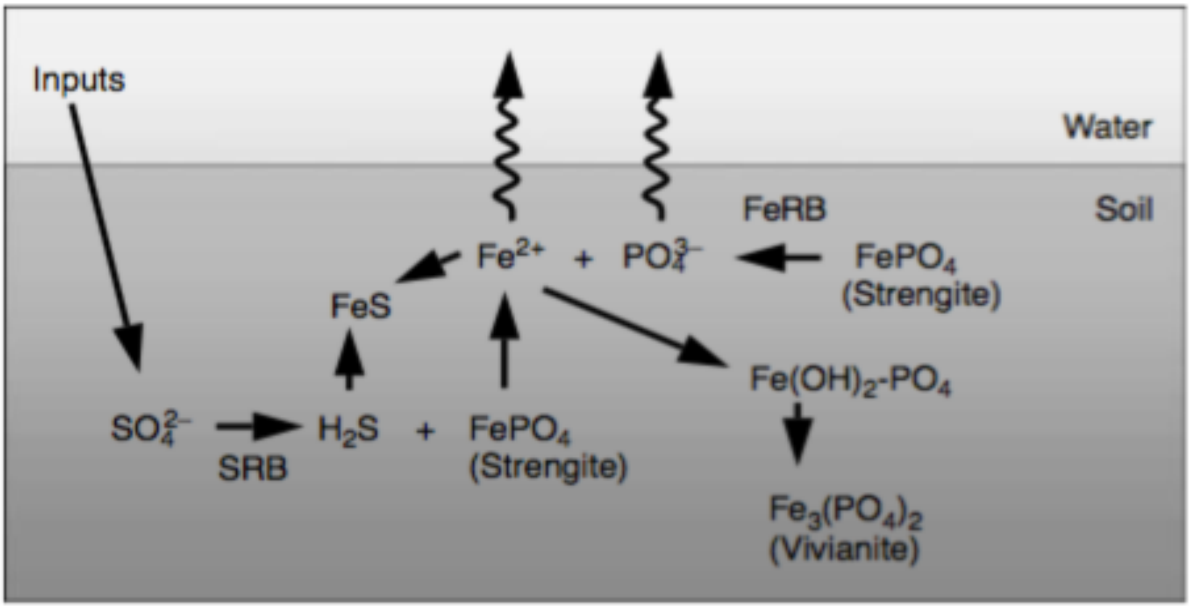

Figure 12. A conceptual figure showing the interactions of S, Fe and P in a waterlogged soil (e.g. wetland during flooding). It is shown how S can precipitate with Fe as FeS, which is reducing the amount of Fe in the redox wheel. Source: (Reddy & DeLaune, 2008, p. 389)

S is mainly introduced to the aquatic environment through atmospheric deposition which is precipitation driven (Ellermann et al., 2015, p. 41). The amount of S present in the wetlands, is not incorporated into the Danish P-model. This could be very relevant as the current calculations are based on the ratio between Fe and P. S can come in and break the cycle, by 'stealing' the Fe which will skew the ratio (Smolders et al., 2010). Modelling the amount of S available in the specific project is likely not easy, but attempts could be made. In fact, models of spatial deposition of S exists (e.g. Figure 13), which could possibly be included in the Danish P-model to improve it.

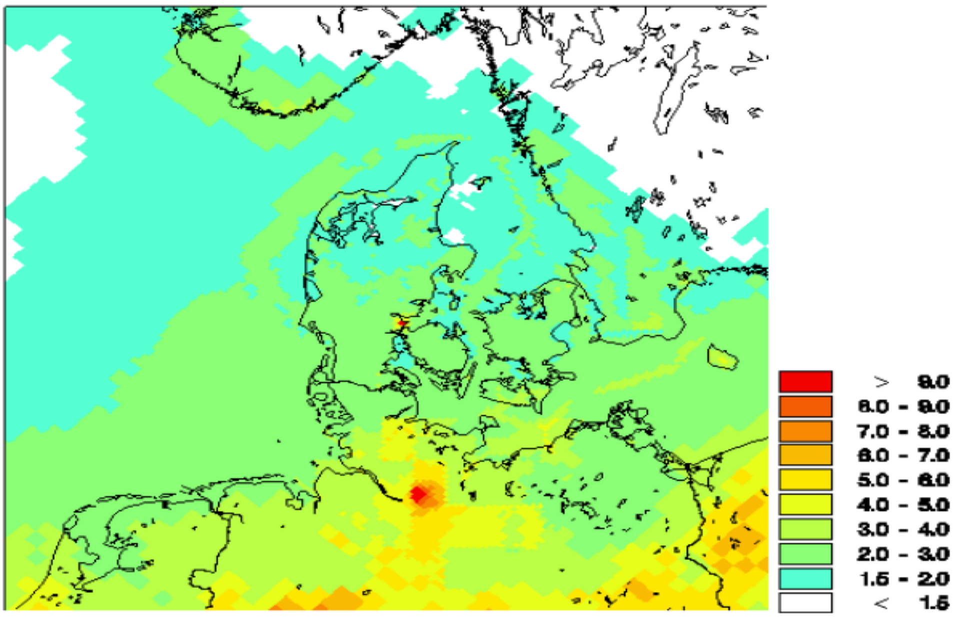

Figure 13. A map showing the modelled total anthropogenic driven deposition of S compounds measured in kg S/ha (Ellermann et al., 2015, p. 44)

Ca can bind P in wetland sediments, and commonly does so. It bind the P strongly, as long as pH is alkaline (Jin et al., 2013; Reddy & DeLaune, 2008; Ronkanen et al., 2016; Windolf, Tornbjerg, Hoffmann, & Kronvang, 2016). Natural conditions in a water body alters the pH. During the growing season algae will grow and uptake CO2 from the water, raising pH (Reddy & DeLaune, 2008). On the contrary, the decomposing of the algae lowers pH, due to acidic by-products from bacteria (Reddy & DeLaune, 2008). As wetlands in the Danish agricultural landscape often have a high nutrient loading, it will also have a high growth of algae, making it likely that the variations in pH are high over a season. This finding indicates that Ca plays an important role in mobilization of P in wetlands, but it is very hard to predict as pH varies naturally.

5.2.3 The lack of a time aspect in the Danish P-model

The literature review did not reveal any evidence to suggest that re-created wetlands would have a constant release or retention of P over time, as is implemented in the Danish P-model. In the book "Biogeochemistry of wetlands" (Reddy & DeLaune, 2008, p. 328), the term 'phosphorus memory' is used. The term is used to describe the historic P load and accumulation in wetlands. Simply put, a wetland can retain P through chemical precipitation, sedimentation and plant uptake, which all accumulates to a total amount of P in the wetland (Verhoeven et al., 2006). If there is a high accumulation of P in the wetland, the risk of P leakage grows accordingly, meaning that unless P is removed, there will be a theoretical maximum of P that can be accumulated in a wetland.

5.2.4 Alternative options for mitigating P leakage

In the research, several options were identified to mitigate P leakage from re-created wetlands. The first option is to harvest vegetation (Hoffman et al., 2012), which includes removing biomass that has taken up P from the area. This follows the above-mentioned concept of P memory, since P needs to be removed from the wetland for it to function as a long-term P sink. Removed biomass could be used for animal feed, fertilization or energy purposes (Mander et al., 2003).

Another option is to purposely introduce Fe, Al or Ca to wetlands which can bind P (Qualls, Sherwood, & Richardson, 2009; Reddy & DeLaune, 2008; Zou, Zhang, Wang, Zhang, & Yu, 2018). Doing this does not include a way to remove the P from the wetland, which pushes the problem further into the future, and is therefore not a recommended path for long-term P retention. Another method is to pass the outlet of a wetland through a filter of porous material covered in oxidized Fe which can bind the P passing through the filter (Lisa Heiberg, personal communication, April 17, 2018). The porous structure ensures the constant presence of oxygen, which are essential for P to bind to Fe. This option would include the possibility to remove the P from the area, when the filter is changed, and utilize it for other purposes – e.g. fertilization. The option of filtering was also identified in the literature review as a recommended best option for a steady P removal (Mander et al., 2003, pp. 33–34).

5.2.5 Summary

Denmark's current management approach is limited by the P-model, as it does not include some important elements (Al, Ca, S) that influence P dynamics. It is also not dynamic over time, which arguably is not reflecting reality very well. In this section I have highlighted some of the elements that could be included in the P-model, but I also emphasise that the processes influencing P-dynamics in re-created wetlands are highly complex and is not limited to what have been covered here. Other important factors barely covered here includes pH, oxygen and temperature (Reddy & DeLaune, 2008). These factors do vary a lot due to climatic factors and local variations can be very high (Prem et al., 2015).

5.3 Research question 3 – Would adaptive management benefit Danish management?

Research question 3: How would an adaptive management approach address the current limitations in management of wetlands as nutrient retainers in the Danish landscape?

5.3.1 Why is AM relevant for Danish management?

In the specific Danish case of P leakage from re-created wetlands, both uncertainty and controllability are high, as found from research question 1 and 2, respectively. Controllability is high, as shown in results from research question 1, since the process of re-creating a wetland is carefully planned and goes through a rigorous process involving many guidelines and check schemes. In other words, the Danish government can carefully control exactly how and where they would like re-created wetlands to be constructed (or whether to have them re-created at all). Uncertainty is high, due to highly complex biogeochemical processes in the wetlands regarding adsorption, precipitation and release of P. These processes are not yet fully understood and the results of research question 2 show that the current 'state-of-the-art' guidelines used in Denmark do not include all relevant elements, e.g. Al, S and Ca dynamics.

Theory suggests that management with these conditions can benefit from implementing AM (Allen & Garmestani, 2015). Drawing on the insights and research from this thesis work, the following results show how the Danish government can address the current limitations in wetland management, with a focus on improving the management of re-created wetlands by reducing uncertainty regarding P leakage.

5.3.2 Status quo compared to AM

The Danish government have already taken several steps that are like what an AM approach would suggest. Firstly, the Danish government have developed clear goals for the aquatic environment in the RBMPs. However, these goals aim to reduce the pollution in the aquatic environment, rather than improving the knowledge level of management which is a key element in AM (Allen, Cumming, Garmestani, Taylor, & Walker, 2011).

Secondly, they have held expert workshops on the P leakage issue where the current practice has been discussed among experts with scientific insights on the issue (P. Vang, personal communication, March 8, 2018). The result was that currently there is no better alternative to the P-model, which means the use of it will continue (P. Vang, personal communication, March 8, 2018). The choice of using the model, despite its uncertainties can be interpreted as a fear of causing harm or a fear of taking risks in management choices. Poul Vang from the EPA expresses his thoughts about the expert workshop:

> "[…] it is my personal perception that the model we have chosen is a 'worse-worst case' calculation, that is, everyone is saying that it (the P problem) is probably not so big, but on the other hand, now we have this model and the we don't have anything that proves it is less, which is why we use this so far." (P. Vang, translated personal communication, March 8, 2018).

5.3.3 How AM can address Danish management limitations

The current limitations that the Danish government face in terms of managing the potential P leakage from wetlands is closely connected to the use of the P-model, which is imperfect as it does not calculate a dynamic leakage over time and it does not consider relevant elements as Al, S and Ca. Uncertainty is high in management decisions regarding P leakage, not only because the P-model is imperfect, but also because there is a lack of systematic monitoring of the P mobilizations in wetlands. The current monitoring program (see section 5.1.11) does not look to provide useful monitoring data for P mobilizations in the future. The biggest limitation is possibly the long-term consequences, which for some catchments are that projects cannot be done, due to the 1% P threshold.

An AM approach would address all the limitations above. An AM approach would embrace the uncertainty as a premise of managing socio-ecological systems such as wetlands in the agricultural landscape (Allen & Garmestani, 2015). This means that it would be recognized that it is impossible not to take decisions that would have negative environmental consequences, but by doing so, management can be improved in the long run (Allen, Fontaine, et al., 2011). Current practice uses a model to avoid risk, but does not invest in long-term monitoring of projects, which would reduce uncertainty over time. An AM approach would flip these priorities by recognizing that modelling a phenomenon like P mobilization in wetlands is extremely difficult and the method should be improved through taking risks and monitoring the outcomes as described in Figure 8. If Denmark implements an AM approach on this issue, then the long-term limitations would be addressed, as more knowledge would be gained on P leakage from wetlands, making it easier to do good management and avoid P leakage from re-created wetlands.

6 Discussion

The results of this thesis show that Denmark's current approach of re-creating wetlands to reduce N and P in the aquatic environment is limited as it in a long-term perspective may not be most effectively contributing to that. This is an urgent problem as N and P use have already exceeded a critical planetary boundary on a global scale and locally it causes oxygen depletion in Danish waters (Hansen et al., 2017; Steffen et al., 2015). The current management practice of assessing the risk of P leakage based on the P-model will most likely lead to fewer projects being constructed over time, as the majority of projects are expected to leak P. This is the case due to the combination of the P-model projecting a worst-case scenario and because it does not consider a possible decrease of P leakage over time. Eventually this development will significantly reduce the possibility to mitigate N and P pollution as re-creation of wetlands would halt under the 1% threshold of additional P supply, making current management unsustainable.

The results also suggest that assessing P leakage from wetlands is very difficult and involves a lot of uncertainties regarding the dynamics of P in re-created wetlands. The current P-model used in Denmark fails to capture these uncertainties because it does not consider key aspects of P dynamics in wetlands (e.g. Al, S and Ca).

The best way to improve the P-model would be to draw on actual monitoring data, from wetlands where the assessments have been made, so a comparison would be possible between the model and reality. If the current monitoring program would measure continuously long-term P leakage, it may reveal that re-created wetlands react similarly to the case of Vilsted Sø, where there was a peak of P leakage shortly after restoration and then a decrease to pre-flooding levels over time (see section 3.3.2).

Finally, the results show that the use of AM is appropriate in this case because of high uncertainty and high controllability in management (Allen, Fontaine, et al., 2011). This however, involves taking risks, which contrasts with the current risk avoidance practice in the Danish EPA. In the following section I will discuss how AM could possibly be implemented by the Danish government on the management of P leakage from wetlands.

6.1 Possible AM implementation in Denmark

6.1.1 Technical working group

The goal of implementing AM on this case in Denmark would be to learn through controlled and planned experiments. The optimal people to do this job would have expert knowledge on biogeochemistry of wetlands. I suggest that a technical working group would be in charge of implementation of AM, which includes: ongoing management decisions, planning, research and monitoring of re-created wetland. Having a technical working group with experts is common practice in implementation of AM (Allen & Garmestani, 2015; Ogden & Innes, 2009; Williams et al., 2009).

The idea of the working group is that they can approve re-creation of wetlands in different locations with different design features (i.e. features that have been shown to influence P mobilization). They should carefully and transparently state what the goals of these management choices would be (i.e. what can we learn from these choices and why?). Management choices could among others be; to implement a filter with Fe particles to fix P leaving a wetland, harvest vegetation from the wetland to remove P and to re-create wetlands on soils where the Al, S and Ca content is measured (see sections 5.2.2 and 5.2.4). These are all examples where new knowledge could be gained from long-term monitoring of the outcomes.

6.1.2 Stakeholder engagement

The working group should be in charge, but relevant stakeholders should be involved in the process. Stakeholder involvement is key in AM and is used to best resolve difficult trade-offs in management practice (Allen & Garmestani, 2015). In the Danish case the stakeholders would include; Danish EPA, Danish AA, Danish ministry of Food and Environment, the EU, Danish municipalities and landowners. The current system works based on applications from landowners via municipalities, which means that the working group can only choose project areas and management options amongst the applications that are sent in. The working group should choose interesting projects from the pool of applications and then involve the municipality and the landowners from these projects into the process.

It is very important to have relevant representatives from the EU on board with implementing AM, since there is a risk of a short-term increase in P surface waters, as occurred in the Vilsted Sø case (see section 3.3.2). This short-term spike in P would look bad to the EU if they did not agree to this risk beforehand. The Danish minister of food and environment should also be on board as the minister is in charge of both the AA and the EPA.

6.1.3 Long term monitoring

An implementation of an AM approach on wetland creation in Denmark would, among others, include a long-term monitoring program of P leakage from different types of re-created wetlands.

Monitoring is a key element of AM, as it is recognized to be the best tool of learning which management option actually works the best, in the complex social-ecological systems (Allen & Garmestani, 2015).

Since 2014, a monitoring program have been running, with funding from the Danish government, where the idea is to monitor different types of re-created wetlands (see section 5.1.11). However, the wetlands are only monitored for one year and then the measurement station is moved elsewhere. This means that no long-term data will be gathered on the P-mobilization from the wetlands. Had the monitoring been continuous, then the data could possibly be used to include a time aspect in the P-model, which is crucial for good long-term management. This unique opportunity to compare the projected leakage or retention projected by the P-model with actual long-term monitoring data from those wetlands, has almost been missed. The P-model has been used since 2013 and the current monitoring programme started in 2014 and is planned to run until 2020. It was considered of higher importance to have a larger dataset, than having continuous data from the same areas within the budget (M. Thomsen, personal communication, March 8, 2018). This was partly decided to satisfy the European Court of Auditors, by having a larger dataset (M. Thomsen, personal communication, May 14, 2018). However, there is still a chance to get some valuable data, if continuous measurements of P would be implemented immediately and continue until the end of the project.

6.1.4 Framework for possible AM implementation in Denmark

The implementation could follow the following structure adopted and modified from (Ogden & Innes, 2009):

1: Establish management objectives for the re-creation of wetlands

- The overall management objectives should be to reduce uncertainty of P dynamics in wetlands (i.e. improve the current P-model). Objectives should emphasise learning on P dynamics rather than an immediate reduction in P leakage from re-created wetlands. The long-term objective would still be to reduce P leakage, as improving the P-model would reduce uncertainty in management decisions. The advantage of this objective over current practice is that it would enable a better long-term management of wetlands, compared to the current practice where projects are halted due to an expected P-leakage, but uncertainty regarding the leakage is not noticeably reduced.

2: Determine the risks to the aquatic environment that are caused by P leakage from re-created wetlands

- There is already a good knowledge base regarding the effects of P leakage from re-created wetlands. It mainly causes a eutrophication risk in freshwaters, which are P-limited in their growth of algae. The current knowledge can be utilized. Despite AM emphasising that taking risk is a necessity, environmental risks should be considered in the implementation (Ogden & Innes, 2009). An example of utilizing this knowledge could be to make experiments in catchments which mainly have N-limited waters, as the potential extra P would cause less ecological harm there.

3: Develop alternative management options

- Drawing on scientific knowledge and practices elsewhere, alternative management options should be developed. As showed in this thesis, this could include harvesting of vegetation or to fixate and remove P with filters. However, management options are not limited to interventions like those, they should also include different designs of re-created wetlands in different types of settings (e.g. different soil types and flooding regimes). To learn more about P dynamics in re-created wetlands, projects must be done in different settings in different ways so that knowledge can be gained on the effect of these differences. This step should be seen as a part of the process visualized in Figure 8.

4: Evaluate these alternatives against the established objectives

- All management options should be compared by relevant stakeholders to ensure that they will help with achieving the objectives. Since the objective is learning about P dynamics and improving the P-model, emphasis should be on management options that could provide new insights through implementation combined with proper monitoring. An example could be to choose options that are similar, but have specific differences, like a design feature or soil composition. This would make it easier to isolate the effect of the specific difference and could then enhance learning and reduce uncertainty in management decisions over time.

5: Implement the preferred management options

- Implementation should be done accordingly to the reasoning of Figure 8. In the current system, it is often local contractors who carry out the wetland projects, there is no need to change this for an AM approach.

6: Monitor the effectiveness of the management options in achieving the desired objectives

- Wetlands should be monitored closely, over a long period of time (e.g. 10+ years). Monitoring should include wetlands and their upstream and downstream waterways. All relevant parameters like e.g. P, N, Fe, Al, S, Ca, pH and oxygen should be measured. By having upstream and downstream measurement, a mass balance can be made to calculate the effectiveness of the wetland to retain P and remove N.

7: Modify the management options when they are not successful in meeting the objectives

- If management options are not benefitting the objectives, then they should be altered. This would be the case if it is discovered that the knowledge gaining is jeopardized by unforeseen events.

6.2 Is it realistic to implement AM in the Danish government?

To implement AM on the P leakage case in Denmark, the management practice must change from its current state of risk avoidance. The current worst-case calculations will in the long run result in fewer projects being done, meaning that the benefits that wetlands provide will not be achieved. The fear of causing short-term harm is arguably overruling the long-term goals in current practice. For AM to be implemented, the Danish government must start to take risk in management, in order to reduce uncertainty over time. This can be difficult as public institutions are known to be less flexible in terms of taking risky decisions as employees would often rather take the “tried and true” option than a new and risky one (Walters, 1986, pp. 30–31). This is another reason for why the technical working group should be in charge of implementation, with the mandate from the Danish government. The Danish government would need support from the EU as they most likely would criticize any impairments of the aquatic environment, even if they are short-termed.

The Danish EPA is already showing initiative to change management by taking different initiatives to improve the management - e.g. by arranging an expert workshop and setting up a monitoring program - which only needs to have some changes before it would follow the AM recommendations. This indicates that AM could be a possible way forward. The fact that this issue is only a part of the broader management in the EPA, also makes it more likely that AM could be adopted on this specific case, because it is not an organizational change that is needed, solely the practice on this matter.

A major challenge for implementation is that AM is useful only if there is a long-term investment of willingness to carry it through (Allen & Garmestani, 2015). Therefore, it is suggested in the literature that AM should focus on problems which always are in high priority, despite the change of political winds (Allen & Garmestani, 2015, p. 195). On one hand the Danish government changes with national elections which can disrupt the long-term goals of AM. On the other hand, the overall goal is to meet the goals set in the WFD and the ND, which operates with long-term goals and it seems unlikely that the goals will change with political winds.

6.3 Is re-creating wetlands a sustainable solution?

The management practice of re-creation of wetlands only constitutes a small part of a bigger problem. Sustainability science emphasizes the importance of challenging the root cause of a problem through system thinking – for example by recognizing that sustainability challenges can only be addressed when the natural and societal interconnections are studied systematically (Jerneck et al., 2011). The case of the aquatic environment in Denmark is a complex social-ecological system, which is influenced by legislation, actors, climate and biological processes as shown throughout this thesis.

As mentioned in the introduction, the anthropogenic use of N and P on a global scale have exceeded the 'safe operating space' of human development (Steffen et al., 2015). In addition to that it is worth to look at the global distribution of N and P use, which is shown in Figure 13.

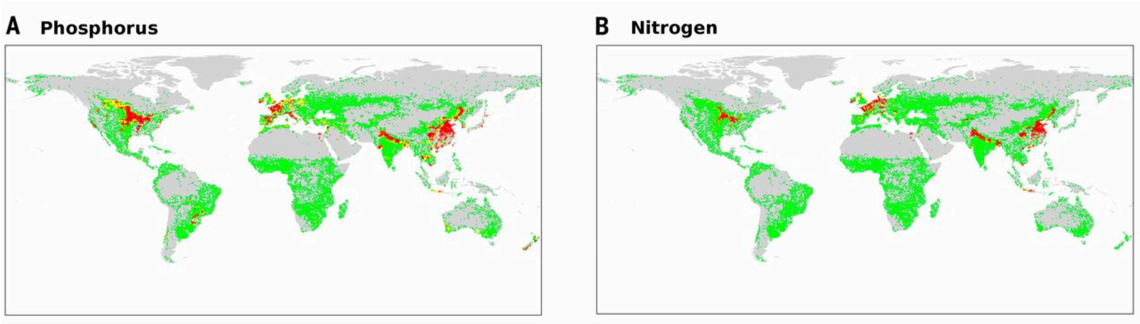

Figure 13. (A) the global distribution of anthropogenic P use. (B) the global distribution of anthropogenic N use. Source: (Steffen et al., 2015).

The distribution shows that a few regions with intensive agriculture accounts for the majority of N and P use, which suggests that a more uniform distribution on a global scale could both have a positive effect on global crop production and reduce negative environmental impacts locally (Steffen et al., 2015).

In the case of Denmark Figure 13 shows that P use is still within the safe operating space, where N use have exceeded into the high risk zone in most of Jutland, which hosts the majority of Danish livestock production (Knudsen, Østergaard, & Schultz, 2000; Wiggers, 2003). With this global perspective of N and P use in mind, it is interesting to discuss whether the solution to Denmark's problems with nutrient pollution in the aquatic environment should solely be addressed with mitigating measures as re-creation of wetlands, or if there are simply too many nutrients applied in Danish agriculture?

The main source of nutrient runoff to the aquatic environment is runoff from agriculture and especially the application of manure on intensely farmed fields (Knudsen et al., 2000; Kronvang et al., 2001). Currently Denmark has a significant production of pigs consisting of 28 million pigs annually, of which approximately 90 percent are exported (Danish agriculture & Food Organization, 2018). In 2015 a new law was passed, called Landbrugspakken [Agricultural package], which among other deregulations: deregulated the agricultural sector by removing mandatory riparian zones between agriculture and surface waters, allowed for more fertilization, and allowed farmers to have more animals per ha of farmland (Danish Ministry of Food and Environment, 2015). The overall focus of this law package was to deregulate the agricultural sector to make it more productive and compensate the environment through mitigating interventions, such as re-creation of wetlands.

In my opinion it would benefit the Danish aquatic environment if the nutrient source was questioned more, instead of solely focusing on symptomatic treatment. With the fact that Denmark export 90 percent of its pig production, one could ask if is it really a good idea for Denmark to act as what can be considered an international hub for feed-to-pig conversion? Maybe the production of pigs should be more scattered, to reduce concentrations of nutrients and thereby nutrient runoff. Or maybe the production should be reduced, as more and more focus is on reducing meat consumption to reduce emissions of greenhouse gases, as argued by the United Nations Food and Agriculture Organization (Grasty & FAO, 2013). It should be kept in mind that wetlands do have other benefits than removing nutrients from agriculture, e.g. that they provide habitats, store carbon and acts as flood water buffers which builds resilience of downstream systems to expected extreme runoff events caused by climate change (see section 3.3.3).

6.4 Limitations and further research

This thesis should be seen as an input to the ongoing debate around management of wetlands in Denmark. It shows how there are possible important missing elements in the P-model used by the Danish government. However, it should also be noted that the articles used in the literature review to critique the Danish P-model, are mostly studies of different biogeochemical aspects of wetlands, which have been studying very different wetlands. It shows that Al, S and Ca can play important roles in P mobilization in wetlands, but it does not necessarily mean that this applies for all Danish wetlands. This limitation to the study calls for further research into the topic. The identified limitations make a great topic for further research, which combined with an AM approach could improve the management and thereby contribute to long-term sustainability in the Danish surface waters. Further research could also include the feasibility of implementing AM in the Danish government, which have not been investigated in this thesis.

7 Conclusion

The effort of re-creating wetlands in Denmark to remove and retain nutrients has shown effective to reduce the pollution of N and P in the aquatic environment (see section 3.3.1). However, the identified risk of P leakage from wetlands has led to the use of a P-model, which is limited and limiting for management of this social-ecological problem (see section 5.2). The current practice will halt the development of re-created wetlands over time as it in most cases presumes a constant leakage of P, which with current practice in the Danish government would result in less and less projects being done over time (see section 5.1.10). The results for this thesis does not show any evidence that confirms the lack of a time aspect in the P-model reflects reality. This thesis does not provide a silver bullet to management of wetlands and P mobilization, but suggests possible measures which could improve the current P-model, for example the inclusion of Al, Ca and S in the P-model and implementation of long-term monitoring, which could improve the management over time. This thesis also provides an alternative to current practice, which is to implement AM on re-creation of wetlands, as it is a promising management option in cases which are characterized by high uncertainty and high controllability. Implementing AM requires a willingness to take risks, which could temporarily lead to worse conditions for the aquatic environment, but would most likely reduce the uncertainty of P leakage over time, hence improve the long-term management. Therefore, legislative bodies like the EU and the Danish ministry of Food and Environment needs to buy in on the implementation for it to be successful.

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9 Appendix

Appendix A

Interview guide for semi-structured interview with EPA officials regarding current management of wetland re-creation and the limitations.

Interviewed: Poul Vang and Maria Sloth Nielsen.

What is your name and function here at the Danish EPA?

Can you briefly explain why the EPA is funding re-creation of wetlands?

Can you briefly explain who are the actors/stakeholders involved in an EPA funded wetland?

What is the usual timeframe from application to realization of a re-created wetland?

Are the EPA funding all re-created wetlands in Denmark? If not, who else is?

What is most important for the EPA, when processing an application for re-creating a wetland? Other important things?

Are the effects of wetland re-creation measured? If yes, how?

How is the funding made from the EPA? (e.g. buying land, leasing land, one-time payment, on-going payment).

What is the biggest challenge in EPAs work regarding wetland creation?

What the biggest challenge for Denmark to fulfill the WFD 2027 goals for surface waters according to you?

On the EPA website, there is a manual explaining how P-leakage is assessed, can you explain how the process of this is?

Why is the EPA using this method, explained in the manual?

Is there any debate around the assessment of potential P-leakage? If, yes, what is it about?

Appendix B

Interview guide for semi-structured interview with EPA official regarding the current monitoring program of re-created wetlands.

Interviewed: Mette Thomsen

What is your name and function here at the Danish EPA?

Can you briefly explain what the monitoring program of wetlands is about?

What is the reasoning behind the design of the monitoring program?

How is the monitoring done, practically speaking?

Is both the inlet and outlet monitored to assess the mass-balance of nutrients in the wetlands? And what about the actual wetland?

When does monitoring of a wetland in the project begin? Is it for example shortly after the re-creation?

Are there any preliminary results from the monitoring program?

Do you have anything to add, which you find should be included?