EXPLORATION OF THE USE OF TREATMENT WETLANDS AS A NUTRIENT MANAGEMENT STRATEGY IN WISCONSIN

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Executive Summary

Phosphorus and nitrogen are naturally occurring elements that, in excess, contribute to poor water quality in aquatic ecosystems worldwide. Strategies have been developed to mitigate nutrient runoff from agricultural fields, a major source of excessive nutrient loads. *Treatment wetlands*[1] – created or re-established systems that are man-made and designed to accomplish a pollutant reduction goal – provide one strategy for nutrient management, but there remains a wide range of questions and concerns about their effectiveness and role within nutrient management programs, relative to other strategies.

The Nature Conservancy engaged partners to explore these issues by conducting a preliminary assessment of the scientific literature, as well as relevant policies and programs. Interviews were conducted with experts in this field on the effectiveness of using wetlands to reduce phosphorus and nitrogen loads to downstream waters as part of a nutrient management strategy in agricultural systems. The objective of this report is to outline the findings from the science and policy literature review and provide recommendations for moving forward with this strategy.

Numerous variables influence the effectiveness of a treatment wetland to reduce phosphorus and nitrogen, including hydraulic loading, wetland age, season, temperature, and inflow concentration of nutrients. These variables have been assessed in this report, and associated recommendations have been made toward improving site selection, design, and construction. However, due to the complexity and heterogeneity of treatment wetlands as well as inconsistencies in data reporting, assigning specific nutrient reduction amounts to any given treatment wetland remains problematic. More research is needed to fully understand the mechanisms driving phosphorus and nitrogen reduction by a wetland, especially to influence the current policies and programs that do not currently credit wetlands for their treatment capabilities.

This study leads us to three major conclusions. First, the implementation of existing best management practices and reduction of nitrogen and phosphorus applications beyond crop needs, may reduce nutrient loading to surface waters in agricultural watersheds. This will likely result in water quality improvements, and a decrease of time and effort to develop new technologies and strategies if loads were reduced at the source. Second, ensuring effective implementation of existing policies will also aid water quality improvement, especially if supported through expanded and standardized monitoring and assessment efforts. Finally, understanding the potential role of treatment wetlands as part of agricultural nutrient management strategies will take a multidisciplinary approach with engineers, conservationists, ecologists, policy makers, and biologists working together to design and construct the most efficient management practices to reduce phosphorus and nitrogen loading to surface waters.

[1] This report does not address or endorse the enhancement of existing wetlands – nor an intentional increase of nutrient loads to existing wetlands – in order to improve water quality. Such alterations would likely degrade wetland condition and could also impact other ecosystem services provided by wetlands. The Clean Water Act and Wisconsin's Water Quality Standards protect all the functional values of existing wetlands.

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In this document, **natural infrastructure** is narrowly defined as reestablished or newly-created wetlands that may act as sinks, sources, or transformers of nutrients, particularly phosphorus and nitrogen. This study specifically excludes the enhancement or alteration of existing wetlands toward water quality improvement. These created or re-established wetlands are referred to as treatment wetlands, which are man-made systems that are designed to accomplish certain goals, including the reduction of pollutants (Kadlec and Wallace 2009).

Introduction

Wisconsin is a water rich state, but the quality of water is at risk. In Wisconsin there are more than 84,000 miles of streams, more than 15,000 lakes totaling over 1.2 million acres in extent, 5.3 million acres of wetlands and enough groundwater to cover the entire surface of Wisconsin in 100 feet of water (WDNR 2015). These sources are used for drinking water, recreation, farming, and manufacturing and are vital to Wisconsin's fish, wildlife, and habitats. However, polluted runoff is one of the greatest threats to Wisconsin's water quality (WDNR 2105). *Nonpoint source* (NPS) pollution is responsible for approximately 58% of waterbodies not meeting their *designated uses*. Phosphorus and total suspended solids are two main pollutants causing the impairment (WDNR 2015).

Phosphorus and *nitrogen* are used in agriculture, and when used in excess, these nutrients may lead to NPS runoff entering waterbodies from fields, resulting in eutrophication, hypoxic zones, fish kills, and contamination of drinking water in receiving water bodies (U.S. EPA 2016b). Nitrogen can be removed from the water and soil in *treatment wetlands* through *denitrification*, a process that transforms nitrate into nitrogen gas and nitrous oxide. Phosphorus is reduced from the water column in a treatment wetland through various processes including vegetation uptake, adsorption to the soil, and *sedimentation* (Mitsch and Gosselink 2000).

A variety of strategies have been used to decrease phosphorus and nitrogen loads and their negative impacts, ranging from changes in cropping practices to the establishment or restoration of *natural infrastructure*. The US Environmental Protection Agency (EPA) defines natural infrastructure as an "interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife" (U.S. EPA 2000). The Nature Conservancy's (TNC) mission is to conserve the lands and waters on which all life depends. As natural infrastructure supports the needs of wildlife as well as people's needs, restoration of natural infrastructure is key to advancing TNC's mission. This project was conducted to assist TNC and partners in gaining a more detailed understanding of how natural infrastructure, particularly treatment wetlands, may provide water quality benefits focused on nutrients. In this report, the current and potential roles of treatment wetlands in nutrient management strategies are explored, and findings and recommendations are provided. It is our hope that this will serve as a reference document, and especially as a starting point for a growing conversation around wetlands and water quality that includes water quality specialists, wetland restoration practitioners, governmental agencies working on nutrient management (specifically those focused on NPS pollution), water users, wetland managers, non-governmental conservation organizations, and others.

Project Objective:

To explore, evaluate, and advance the role of treatment wetlands – created and reestablished – as a potential component of agricultural nutrient management strategies by assessing the state of the science, setting a focused research agenda, identifying gaps and opportunities in programs and policies, and inspiring a partnership and collaboration among subject experts, policy makers, and ecosystem managers.

Guiding Questions

1) What potential benefits do treatment wetlands, an example of natural infrastructure, provide to nutrient management and water quality?
2) How might treatment wetlands be valued and credited in water and nutrient management policies and programs relative to other Best Management Practices (BMPs)?
3) What successful examples may be found of treatment wetlands that demonstrate water quality benefits for downstream waters?

Project Goals:

Goal One: Develop an understanding of the known science on treatment wetlands especially as it relates to nutrient management, particularly phosphorus and nitrogen. This includes an assessment of the factors that influence nutrient cycling in wetlands.

Goal Two: Understand how treatment wetlands may be credited in water policies and programs as a nutrient management strategy and how treatment wetlands are "valued" compared to other agricultural best management practices.

Goal Three: Gain knowledge on the use of treatment wetlands as a nutrient management tool through interviews with experts in wetlands and nutrient management. Additionally, organize a partner meeting to discuss knowledge gaps and research needs in science and policy, develop recommendations for the use of treatment wetlands, and construct an agenda for moving forward.

Goal Four: Produce a document containing (1) information on the science behind wetlands as a nutrient management tool, (2) a review of the role of natural infrastructure in existing water policies and programs focused on nutrient management, and (3) recommendations for policies, programs, and research.

Scientific Literature Review

Introduction

NPS pollution is a major threat to the health of waterbodies. Synthetic fertilizers and manure with high concentrations of nitrogen and phosphorus are typically spread on farm fields in high quantities. Phosphorus and nitrogen, if applied in excessive amounts may be transported off agricultural fields and enter waterways. High levels of phosphorus and nitrogen in waterways may lead to eutrophication, resulting in an increase in algal growth. Eutrophication is a process in which a large algal bloom caused by warm weather and a large amount of available nutrients results in an anoxic or toxic environment. The Gulf of Mexico, Western Lake Erie, and the Bay of Green Bay are three places in the United States where nutrients mostly from agriculture have caused large algal blooms leading to contamination of drinking water, extensive fish kills, anoxic conditions, and dead zones (NOAA 2016; Bergquist 2015). Overall, there is a decrease in water quality when waterbodies receive excessive nutrient concentrations.

Wetlands occupy roughly 1.5 percent of the earth's surface but provide more than 40 percent of the world's renewable ecosystem services (Zedler 2003). They may act as the filtering kidneys of the ecosystem, abate floods, improve water quality, provide spots for high biodiversity and habitat, and provide many more ecosystem services. Treatment wetlands, created or reestablished, may serve as a natural infrastructure solution to NPS pollution problems.

This section of the report explains how nutrients are cycled within wetlands and the factors that impact the amount of reduction in nutrients in treatment wetlands. The following information may be used to assist in understanding how wetlands function to improve water quality, designing and siting treatment wetlands for water quality improvement, and determining knowledge gaps to understand limitations for application of existing knowledge as well as to guide future research. Four different aspects of each factor (hydraulic loading, residence times, season and temperature, vegetation, watershed to wetland ratio, wetland location, mineral content of soil, and age of wetland) are presented:

1. A definition
2. Details on how the factor affects nitrogen and phosphorus reduction
3. Case studies illustrating where and how the factor has been shown to influence phosphorus and/or nitrogen reduction
4. A summary of the missing information and research needs

Nutrient Cycling in Wetlands

Wetlands have the potential to reduce nutrients from inflow water by sorption to minerals and sediments, sedimentation and burial, vegetation uptake, biogeochemical transformations including denitrification, and microbial degradation (Fisher and Acreman 2004; O'Geen et al. 2010). To better understand these mechanisms, it is important to understand the phosphorus and nitrogen cycle in treatment wetlands.

Phosphorus

Phosphorus is an essential element for all living organisms. Plants must have phosphorus for growth and maturation. There are four different pools of phosphorus: one that is available to plants (dissolved inorganic phosphorus) and three that are not immediately available to plants (organic dissolved phosphorus, particulate organic phosphorus, and particulate inorganic phosphorus) (Mitsch and Gosselink 2000; Booth 2015). Phosphorus enters a wetland as dissolved and *particulate phosphorus*. Depending on the form of phosphorus a variety of physical, chemical, and biological processes will occur resulting in a wetland acting as a sink, source, or transformer. Adsorption/desorption, precipitation/weathering, mineralization/immobilization, sedimentation, and diffusion of phosphorus to the overlying water column determine the amount of phosphorus that may be retained in a wetland (Reddy and D'Angelo 1994; Mitsch and Gosselink 2000). Long-term removal of phosphorus from a given ecosystem can only occur when vegetation is harvested or when sediment bound phosphorus is removed from the system.

Table 1: Mechanisms in a wetland in which phosphorus inputs are reduced.[2]

Mechanism	Description
Sedimentation	Particulate phosphorus settles out of the water column
Adsorption	Chemical bonding of phosphorus to iron, aluminum, and calcium on soil particle exchange sites
Precipitation	Phosphorus binds to dissolved iron, aluminum, and calcium to form a solid or semi-solid
Uptake by Vegetation	Orthophosphates and some organic phosphorus taken up by plants and algae
Immobilization	Plant available and some organic forms of phosphorus are consumed by microbial communities and stored in their tissues

[2]Duration and quantity various by mechanism.

The Phosphorus Cycle in Wetlands

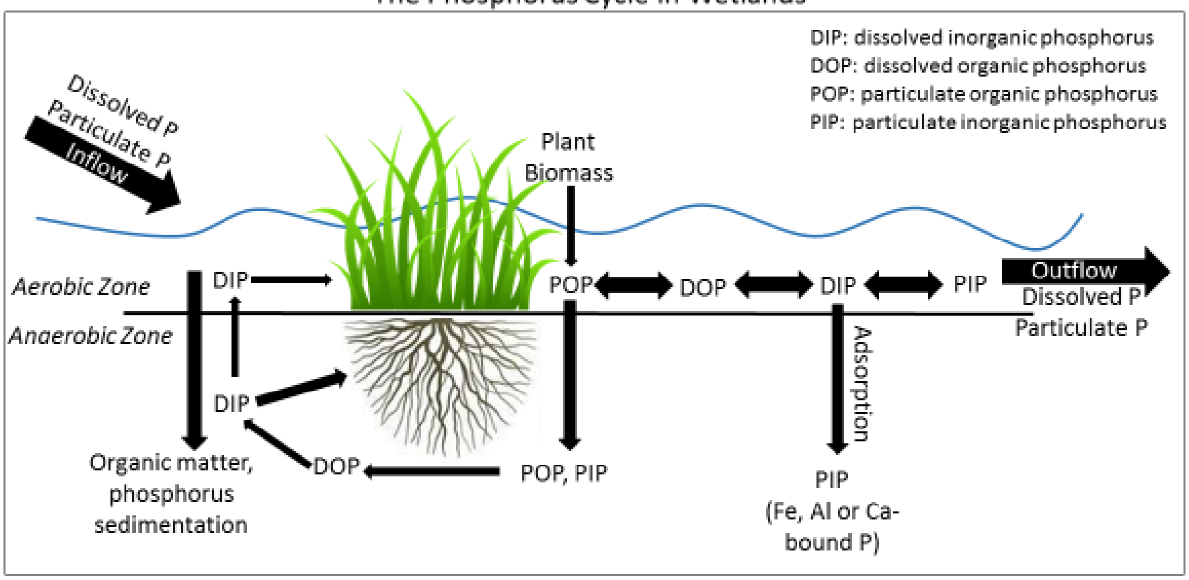

Figure 1: Phosphorus cycle of soluble and particulate phosphorus. Source: Reddy et al. 1999

Nitrogen

Nitrogen enters wetlands in organic and inorganic forms. Three main processes responsible for nitrogen retention and removal in a wetland are denitrification, sedimentation, and uptake by vegetation (Mitsch and Gosselink 2000; Reddy and D'Angelo 1994; Saunders and Kalff 2001). Nitrogen has a gaseous cycle and therefore can be permanently removed from soil and water column in a treatment wetland through *denitrification*.

Through *nitrification*, ammonia is converted into ammonium which is then converted into nitrate (NO_3^-) and nitrite (NO_2^-) by microbes in the water column and *aerobic zone* (Mitsch and Gosselink 2000). Denitrification is the process where anaerobic bacteria produce nitrogen gas (N_2) or nitrous oxide (N_2O) using end-products of nitrification (Mitsch and Gosselink 2000; Saunders and Kalff 2001). N_2 and N_2O gas are released into the atmosphere, thus removing it from the wetland. Between 70% and 90% of nitrogen may be removed from a wetland through denitrification (Gilliam 1994). The amount of available carbon impacts the amount of nitrogen reduced in a wetland, since the microbes needed for the nitrogen cycle depend on carbon (Woltemade 2000). Ammonium plus nitrite may also be converted to nitrogen gas through a process known as *anaerobic ammonium oxidation (anammox)*; however, more research is needed to fully understand the role anammox has in the nitrogen cycle in treatment wetlands (Burgin et al. 2011).

The Nitrogen Cycle in Wetlands

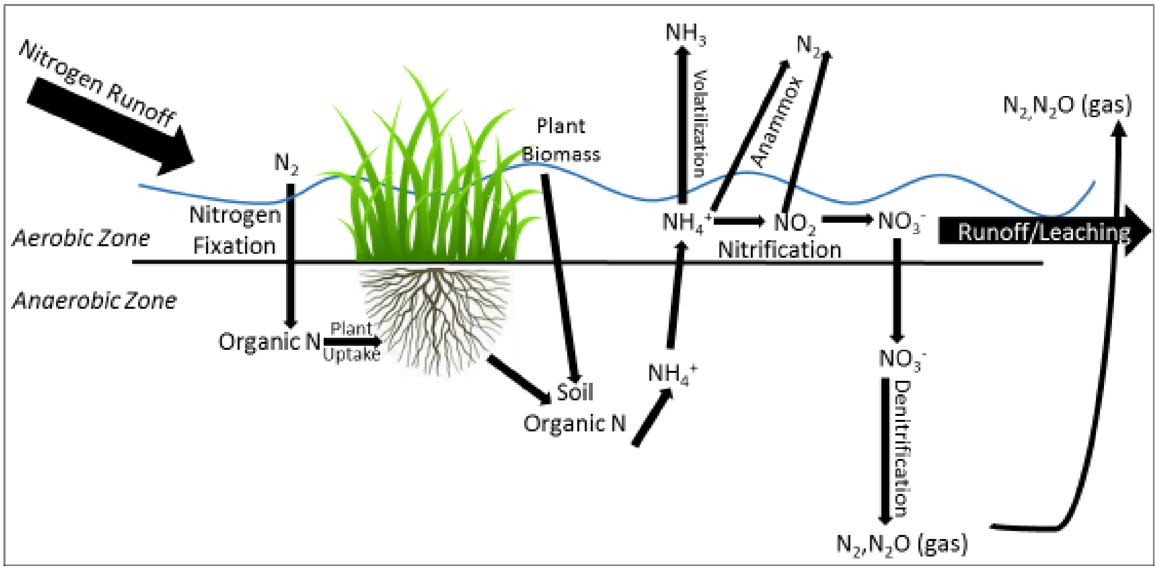

Figure 2: Nitrogen cycle in wetlands Source: Mitsch and Gossalink 1993

Factors Affecting Nutrient Reduction and Cycling

Many factors – both intrinsic and extrinsic to wetlands – may influence the effectiveness of a treatment wetland to reduce nutrients before the water enters downstream aquatic ecosystems. This section contains detailed information, based on a scientific literature review and input from experts, about some of the factors that influence how treatment wetlands reduce nutrients from entering the. The information presented may be useful when designing a treatment wetland.

One goal of this project was to review literature focused on the nutrient reduction potential of treatment wetlands in Wisconsin, but literature specific to Wisconsin and even the upper Midwest on treatment wetlands is sparse and inconsistent in reporting data. Therefore, the data presented here were drawn from a larger body of literature focused on existing natural wetlands, enhanced/restored wetlands, and treatment wetlands wherever studies were completed. Due to the inconsistency in data, it is inadvisable at this time to draw conclusions about exact amounts of nutrient reduction by treatment wetlands. However, there are trends, in the literature, which suggest the importance of a few specific factors that influence nutrient reduction in treatment wetlands: hydraulic loading, residence time, season and temperature, vegetation, watershed to wetland ratio, wetland location, mineral content of soil, and age of wetland. Many of these factors are inter-related and must be considered concurrently. The following factors are not arranged in priority order. There are other factors that affect how a wetland performs including mean slope, presence of carbon, soil pH, microbial activity, wetland shape, presence of wildlife, and water depth. Appendix B summarizes the factors listed below as well as additional factors that affect nutrient reduction in a treatment wetland.

Hydraulic Loading

Definition

The quantity of water and the rate at which it flows (surface or tile drained) into a treatment wetland.

Effect on Nitrogen and Phosphorus Reduction

Hydraulic loading influences the amount of nutrient reduction in a wetland by impacting the residence time and the concentration of nutrients entering the wetland. It is important to have an optimum hydraulic load in order to maximize the amount of phosphorus sedimentation in a wetland (Johnston 1993). When hydraulic loading is low particulate bound phosphorus may have a greater probability of settling out of the water column. Low hydraulic loading rates may also allow for greater opportunity for phosphorus uptake or sorption by biogeochemical processes, resulting in higher phosphorus retention. However, low rates of denitrification may occur where there are insufficient hydraulic inputs to maintain an *anaerobic zone*, as denitrification is an anaerobic process.

Precipitation and season affect the hydraulic load. Higher precipitation can lead to high erosion rates and greater hydraulic loading, resulting in higher concentrations of phosphorus, nitrogen, and other pollutants entering wetlands (Beutel et al. 2014). There may be greater potential for phosphorus and nitrogen reduction due to the large amounts entering the treatment wetland, but percent of removal may be less due to the large loads. Additionally, high hydraulic loading may minimize interactions between the vegetation and water for plant uptake of nutrients.

Case Studies

Groh et al. (2015) researched how treatment wetlands receiving tile drainage performed 18 years after installment in the Embarras River Watershed located in eastern Illinois. Hydraulic loading was determined to be the most important factor affecting the quantity of nitrogen removed from the inflow water. During a dry year the removal rate was between 97 kg and 160 kg Total Nitrogen per ha, while during a wet year the removal rate ranged from 543 kg to 1007 kg Total Nitrogen per ha. One potential reason for the greater amount of nitrogen removal during wet years is the greater amount of nitrogen input (Groh et al. 2015). The percentage removal efficiency during the dry years was higher than during the wet years – 63% removal during the dry year and 51% removal during the wet year; meaning that when loads were higher, the wetland was not as efficient at removal, compared to the dry years.

Information Needs

While studies note the high importance of hydraulic loading in how well a wetland may retain nutrients, there are few studies on the actual amount of flow that is ideal for maximum reduction of nutrients. One possible explanation is that the ideal hydraulic load will change with the size of a wetland and the location of the wetland in the watershed; both of these factors are discussed in greater detail, below.

Residence Time

Definition

The length of time in which water stays within a wetland

Effect on Nitrogen and Phosphorus Reduction

Residence time affects the formation of anaerobic and aerobic zones of the soil, as well as the amount of time particulate matter is able to settle out of the water column. In general, a longer residence time will allow more sedimentation of *particulate phosphorus* out of the water column. Sand grains will settle out of the water column fastest since they have a large particle size compared to clay grains which are smaller and will take longer to settle out. In general clay soils contain more phosphorus than sandy soils (Hillel 2007; Beilfuss and Hames 2014). Additionally, a longer residence time may increase the size of the anaerobic zone leading to potentially higher rates of denitrification.

In terms of phosphorus retention, prolonged deep flooding should be avoided to prevent anoxic-driven release of phosphorus bound to iron (Aldous et al. 2005). Denitrification occurs in the anaerobic zone of the wetland, therefore, it is important to understand the goals of the treatment wetland to appropriately design and construct a treatment wetland since nitrogen and phosphorus reductions occur by different processes. Boers and Zedler (2008) found that constant inundation of wetlands led to the greatest about of phosphorus uptake by Typha x glauca.

Case Studies

Few studies have investigated the ideal residence time to maximize nutrient reduction. Reinhardt et al. (2005) concluded that a residence time of 7 to 10 days resulted in a 50% reduction in dissolved reactive phosphorus (DRP) when the wetland occupied 4% of the catchment's area. Woltemade (2000) found that one to two weeks is ideal, in order to see a reduction in phosphorus and nitrogen in inflow concentrations, while other studies have reported a residence time of two days or longer is necessary for significant nutrient removal (Phipps and Crumpton 1994; Kovacic et al. 2000). Kovacic et al. (2000) found a residence time of 11 to 35 days resulted in nitrogen reductions of 38% of the total 3-year load. Kynkäänniemi et al. (2013) concluded that a residence times of 3 hours to 16 hours resulted in the 69 kg of the 193 kg of phosphorus entering the wetland to be retained.

Information Needs

Given the above factors, reduction in nutrients in a treatment wetland may require a residence time of three hours (Kynkäänniemi et al. 2013) to 35 days (Kovacic et al. 2000); therefore, it is difficult to conclude an optimal residence time for nitrogen and phosphorus reduction. Optimum residence time is highly dependent on other factors including the nutrient concentration of inflow water.

Season and Temperature

Definition

Summer, winter, fall, spring; temperature of soil and surrounding environment

Effect on Nitrogen and Phosphorus Reduction

The amount of phosphorus and nitrogen reduction may vary seasonally. There is variation in runoff from agricultural fields and variation in the presence, growth, and senescence of vegetation in the treatment wetland seasonally. During the spring and winter, maximum amounts of water may enter the treatment wetland from snowmelt and runoff (Kovacic et al. 2000). The majority of agricultural nutrient runoff occurs within a short time period during the spring months (Graczyk et al. 2011). Therefore, treatment wetlands have the potential to provide the most benefit during spring and winter, when high runoff associated with precipitation and snowmelt results in high nutrient loads entering the treatment wetland (Graczyk et al. 2011). At these times, there may be a greater amount of phosphorus and nitrogen leaving the treatment wetland since there is less vegetation to slow down the hydraulic loading. After the winter dormant season, warmer temperatures and increased sunlight during the spring increase plant growth, elevating rates of phosphorus and nitrogen uptake by plants (Beutel et al. 2014).

Temperature variations impact the rate of denitrification and decomposition of vegetation in a wetland. Warm temperatures enhance leaf litter decay as well as an excess of unneeded phosphorus by the microbes in the organic matter, resulting in potential high rates of phosphorus release and a potential net decrease of phosphorus removal rates (Beutel et al. 2014). Denitrification rates are maximized during the summer and decrease with decreasing temperatures. The optimum temperature range for denitrification in wetland soil is 20 to 25°C (68-77°F); below 15°C (59°F) denitrification rates are very low (O'Geen et al. 2010). During the summer months there is minimal removal of total phosphorus due to high temperatures which enhance phosphorus release from decaying plant biomass (Beutel et al. 2014).

Case Studies

Delevan Lake had been experiencing large algae blooms since the mid-1940s due to excessive nutrients. In 1992, Jackson Creek Wetland was constructed by enhancing a 15-acre wetland to a 95-acre wetland (Robertson et al. 2000). Agriculture is the dominant land use in the drainage area. The treatment wetland contained areas of sedge meadow, wet prairie, shallow-water marsh as well as three settling ponds. During winter and spring the greatest amount of nutrient runoff into Delevan Lake occurred; these seasons accounted for nearly all of the reduction of nutrients by the wetland. For example, in 1994 almost all the reduction occurred during February and all other months showed a net release of phosphorus from the treatment wetland. The release of nutrients from the treatment wetland to the lake may have been caused by an increase in microbial respiration in warmer temperatures (Robertson et al. 2000). During 1993, above normal precipitation resulted in higher hydraulic loading and greater release of nutrients from the wetland. Overall, it was concluded that the treatment wetland was not able to retain phosphorus consistently throughout a year.

Information Needs

The majority of the load of phosphorus and nitrogen enters a wetland during between March and June (Graczyk et al. 2011); therefore, studies should focus on the potential nutrient reduction during the spring. Additionally, more studies are needed that are specific to Wisconsin and the Midwest and agricultural settings. Additional research is needed on how seasonality may affect quantities of nutrients entering the wetland and the amount of nitrogen and phosphorus reduction during different seasons. Furthermore, the factors that contribute to wetlands acting as a sink or source during different times of the year need to be investigated.

Vegetation

Definition

The density, biomass, and species of vegetation present in the treatment wetland

Effect on Nitrogen and Phosphorus Reduction

Vegetation uptakes nutrients during the growing season removing phosphorus and nitrogen from the water column and soil. Removal of phosphorus and nitrogen by vegetation is not permanent unless harvesting occurred (Verhoeven et al. 2006). The quantity of nitrogen and phosphorus removed by vegetation depends on factors including season, concentration of nutrients in inflow, residence time, species, litter decomposition rates, and translocation of nutrients (Reddy et al. 1999). Plants with the following characteristics are known to remove the majority of nutrients: tolerance to constructed wetland conditions, rapid establishment, fast growth rate, and large biomass (Brisson and Chazarenc 2009).

High rates of nutrient uptake and storage occur in the spring when vegetation growth is substantial. There may be a release of nutrients from vegetation, during decay of plant material, usually at the end of the growing season (Beutel et al. 2014). Plants may release between 35% and 75% of phosphorus into the water column and as organic litter (Richardson and Craft 1993). The release of phosphorus from plant material is often rapid with 20% to 50% of the total phosphorus released in a few hours and 65% to 85% over the course of a couple days (Dunne and Reddy 2005). However, prior to senescence, 25% to 75% of the phosphorus and nitrogen may be translocated to roots where it can be stored and used for the next growing season (Reddy et al. 1999; Dunne and Reddy 2005). Plant uptake accounts for 16% to 75% of total nitrogen removal in wetlands (Reddy and D'angelo 1994).

Case Study

McJannet et al. (1995) researched the nitrogen and phosphorus uptake of 41 wetlands plants. It was concluded that of above-ground phytomass tissue nutrient concentrations ranged from 0.25 to 2.14% dry weight for nitrogen and 0.13 to 1.07% dry weight for phosphorus (McJannet et al. 1995). Plant size, calculated by the maximum species biomass, explained 67% of the variation in the nitrogen tissue concentration, but only 5% of the variation in the phosphorus tissue concentration (McJannet et al. 1995). See McJannet et al. 1995 for detailed figures of percent dry weight nitrogen and percent dry weight phosphorus in various wetland plant species.

The net annual nitrogen uptake by emergent wetland plant species varies from 0.5 to 3.3 g N /m^2/yr, where reeds and bulrushes are at the lower end of the range and cattails are at the higher end of the range (U.S. EPA 2000). *Scirpus fluviatilis* (river bulrush) uptakes 1.7 g N /m^2/year from wetland soil (Nichols 1983). *Typha angustifolia* (narrow-leaf cattail, invasive in Wisconsin), accumulated between 4.7 and 5.9 g P /m^2 and 46.7 and 56.9 g N /m^2 in a wetland located off the shore of Lake Teganuma in northeast Tokyo (Sharma et al. 2006).

A study was completed in Cooperstown, NY to understand the potential phosphorus removal of reed canary grass and cattails since they are known to uptake large amounts of phosphorus (Gazzetti 2011). There was no significant difference between the phosphorus concentration the above-ground portion of cattails and reed canary grass, 0.275% and 0.250% respectively (Gazzetti 2011).

Information Needs

In order to guide selection of species at treatment wetlands, more information is needed about which species retain phosphorus and nitrogen best in their roots and rhizomes. Additionally, there is a lack of information on the species best used for treatment wetlands nutrient uptake, as well as the best methods to use when harvesting vegetation (including the best time for harvesting vegetation). There are minimal quantitative data on the result of harvesting vegetation from a treatment wetland as it relates to the amount of phosphorus and nitrogen that would be permanently removed from the system. It is difficult to predict the amount of reduction by vegetation (especially during different seasons) based on literature values since not all studies have considered the concentrations of phosphorus and nitrogen stored in the roots and rhizomes. Finally, there is a need to consider and avoid the impacts of using invasive species to reduce nutrients, are sometimes planted intentionally to uptake nutrients; however, introducing invasive species reduces habitat quality on-site and may threaten other sites.

Watershed to Wetland Ratio

Definition

The size of a constructed wetland in an agricultural field compared to the catchment area; this may include surface drainage and/or tile drainage.

Effect on Nitrogen and Phosphorus Reduction

Generally, the larger the size of a treatment wetland in relation to the watershed the greater potential to reduce nitrogen and phosphorus loads. A large wetland to watershed ratio can increase the residence time of the water, allowing more particulate phosphorus to settle out and providing more time for dissolved phosphate sorption to sediment (Kynkäänniemi et al. 2013). Studies have concluded a large range of ideal sizes of treatment wetlands when compared to the watershed. For example, O'Geen et al. (2010) concluded the ideal treatment wetland size is between 3% and 6% of the catchment. However, other studies suggest that a wetland to watershed ratio as low as 0.3% may result in a significant nutrient reduction. In such a setting, Kynkäänniemi et al. (2013) observed 36% annual reduction in total phosphorus, 9% annual reduction in dissolved phosphorus, and a 36% annual reduction in total suspended sediment in newly constructed wetlands in Sweden. Reinhardt et al. (2005) concluded a treatment wetland was able to retain about half of its agricultural DRP load requires a surface area that equals about 4% of its catchment area with a 7-day residence time.

Overall, the larger the treatment wetland, the greater chance for more reduction of nitrogen and phosphorus. Woltemade (2000) concluded that small wetlands can provide water quality benefits during low flow conditions; however, during large runoff events small wetlands may be overloaded with the volume of runoff because the wetland volume is too small to allow for potential nutrient reduction. The concentration on the inflow water also affects the needed size of the treatment wetland for reduction of phosphorus and nitrogen.

Case Studies

Treatment wetlands were constructed to treat tile drainage at the Franklin Research and Demonstration Farm in central Illinois through a partnership among TNC, University of Illinois at Urbana-Champaign, Illinois State University, McLean County Soil and Water Conservation District, McLean County Natural Resources Conservation Service, and the Franklin Family. These efforts revealed that a wetland about 6% of the catchment area removed about 50% of incoming nitrates from tile water (Betts 2014; Lindenbaum et al. 2011).

Information Needs

Although on a relative basis, wetlands that are large relative to their watersheds are most effective, it was not possible to specify an exact preferred size of a wetland relative to its catchment area because the amount and type of reported information varied dramatically among available studies on concentrations of nutrients in the inflow, hydraulic loading, etc. Additionally, more long term monitoring of the wetland effectiveness is needed to understand if different wetland sizes reach saturation.

Wetland Location

Definition

The relative position of a wetland within its watershed.

Effect on Nitrogen and Phosphorus Reduction

Overall, wetlands intended to improve water quality on a watershed scale should be located place where they will intercept a significantly large percentage of the flow passing through the watershed. If the constructed wetland is located in an area where it can intercept the majority of the flow, the wetland will also likely receive the majority of the nutrients leaving the field through runoff resulting in the potential for reduction (Woltemade 2000). Wetlands designed for trapping particulate phosphorus and located close to the source can substantially reduce phosphorus loadings as found in a constructed wetland in Sweden (Kynkäänniemi et al. 2013).

Case Study

A modeling exercise was completed in Walnut Creek, Iowa to understand the importance of wetland location. In the model, wetlands were placed where they received 4% of the annual nitrate load from the catchment and reduced the load by 4%. When the wetlands were placed in a location where they would receive 70% of the annual nitrate load from the catchment, the load was reduced by 45%. This computer simulation concluded that wetlands need to be located where they will intercept the most inflow water (Woltemade 2000).

Information Needs

Although there are many variables to consider, further field-based investigations are needed to supplement modeling, in determination of the importance of treatment wetland location in the watershed.

Mineral Content of Soil

Definition

The amount of minerals (Fe, Al, and Ca) in the soil.

Effect on Nitrogen and Phosphorus Reduction

The mineral content of the soil is an important consideration mostly for the amount of phosphorus that will be retained in a wetland. Phosphorus adsorbs to aluminum (Al) and iron (Fe) in acidic soils and calcium (Ca) in alkaline soils and impacts the amount of phosphorus that is adsorbed in the sediment of a wetland. Flooding promotes the creation of non-crystalline forms of Fe, Al, and organic matter increasing the phosphorus adsorption capacity (Ardón et al. 2010). A solid understanding of soil properties, especially mineral content, is needed to guide the selection of treatment wetland sites and to maximize nutrient reduction potential at those sites.

Information Needs

The phosphorus adsorption capacity of wetland soils has generally not been researched or considered prior to design and construction of treatment wetlands. Common soil tests used to understand the fertility of the soil, Bray, Mehlich, and Olsen (Ketterings and Barney 2010), have been used to quantify plant available phosphorus within wetlands. Soil total phosphorus is also commonly quantified, but this accounts for a portion of phosphorus which may never become plant available or released from mineral structures. These phosphorus soil test may not lead to an understanding of overall wetland soil phosphorus retention potential since the tests were not designed for this purpose. Additionally, these test were designed to understand the phosphors availability of upland soils, not wetlands soils, which indicates that different and more detailed soil test are needed to better understand phosphorus retention and plant availability in wetland soils.

Utilization of oxalate extractions to test wetland soils or soils being considered for treatment wetlands permits exploration, as this extraction can be used to quantify the amount of loosely adsorbed soil phosphorus and amorphous aluminum and iron with the soil (Nair 2014), which are the dominant potential binding sites for phosphorus adsorption (Reddy and D'Angelo 1994). The molar ratio of phosphorus to iron can be calculated, known as the Phosphors Sorption Ration (PSR), and the PSR can be used to predict if the wetland soil would be more likely to release phosphorus or adsorb phosphorus (Nair 2014). Oxalate extractions are not widely used or available in Wisconsin or the US (personal communications with Aaron Marti, WDR and Marshfield Soil and Forage Analysis Laboratory), but recent studies suggest that this extraction may be useful for predicting the phosphorus retention capacity of wetland soils (Marton and Roberts 2014, Nair 2014). More research is needed to test the PSR and associated concepts in Wisconsin soils, including treatment wetland soils.

Age of Wetland

Definition

The length of time since the wetland was constructed or re-established.

Effect on Nitrogen and Phosphorus Reduction

The age of a wetland may impact its potential to retain phosphorus; "saturation" is not a major concern with nitrogen, since it is a gaseous cycle and can be released from the system as nitrogen gas and nitrous oxide (Fisher and Acreman 2004). Treatment wetlands often require time to mature to reach peak removal efficiency; one to three years may be needed (O'Geen et al. 2005).

The age of the wetland may affect the amount of adsorption sites that are available for phosphorus adsorption (Fisher and Acreman 2004; Beutel et al. 2014). Maximum phosphorus retention capacity of soil/sediment is generally reached following saturation of all sorption sites (Reddy et al. 1999). Phosphorus sorption sites of natural wetland soils are typically saturated after a few years of operation (Kadlec and Wallave 2008; Vohla et al. 2011; Beutel et al. 2014). However, there have not been studies that have focused on exactly when a treatment wetland is saturated with phosphorus.

In addition to the potential for treatment wetlands to retain incoming phosphorus, the potential for wetland re-establishment or construction activities to release legacy phosphorus must also be considered. Ardón et al. (2010) found that restoring wetland hydrology from former agricultural fields can lead to the mobilization of legacy phosphorus. During *anoxic* conditions iron bound phosphorus may be reduced, resulting in the release of iron-bound phosphorus, mineralization of *organic phosphorus* under aerobic conditions during dry periods may also lead to phosphorus release from wetland soils (Ardón et al. 2010). Legacy phosphorus can be released for over a decade from restored wetlands; a study completed in North Carolina concluded that legacy phosphorus may be released from 3 to 16 years after the restoration of the wetland (Ardón et al. 2010).

Case Studies

Groh et al. (2015) studied nitrogen removal in 18-year-old treatment wetlands. These treatment wetlands removed between 90 and 1013 kg N/ha/yr resulting in a net reduction of 54% to 62% of the inflow load, tile inputs. Kovacic et al. (2000) found there was a 38% reduction in the 3-year load of the study. Overall, it was concluded that the wetlands continued to remove nitrate at the same rate as when they were constructed; there was no nitrogen saturation point of the wetland.

Information Needs

The majority of studies focus on infant wetlands and the length of the study does not allow the wetland to reach full development; studies should increase the time period of their studies (Kadlec and Wallace 2008). Additionally, there is a lack of research on if and when phosphorus saturation occurs in wetlands. Most studies on wetlands and nutrient reduction are limited to several years in duration, making it difficult to know the nutrient reduction 'lifespan' of a wetland. Research is being conducted on the Phosphorus Sorption Ratio (PSR) (see Mineral Content of Soil Section).

Considerations for Siting and Designing a Treatment Wetland for Nutrient Reduction Goals

Nutrient reduction may be optimized in sites with the following conditions and qualities. For a comprehensive list of considerations, see Appendix B.

→ A hydrologic load that optimizes nutrient reduction.
→ A long residence time.
→ Temperatures that promote denitrification and minimize the release of nutrients.
→ Vegetation that uptakes a large quantify of nutrients and has minimal release of nutrients.
→ A large watershed to wetland ratio.
→ Positioned to capture the maximum amount of nutrients.
→ Soil that has a high mineral content.

Conclusion

Wetlands are dynamic and heterogeneous systems; there are no two wetlands that will behave identically, in terms of nutrient reduction, due to the numerous factors that influence this function. With an initial literature review, it was concluded that there is great inconsistency among studies; therefore, exact numbers on phosphorus and nitrogen reduction in wetlands are not provided in this report. Kadlec and Wallace (2009) also concluded that with the complexity of treatment wetlands, it is not advised to develop an equation to determine the amount of treatment that may occur. Treatment wetlands are designed with different goals, resulting in reductions in phosphorus and nitrogen being reported in loads, concentrations, and percentages, making it difficult to compare research results. Furthermore, studies measure different types of nutrients, meaning some measure organic phosphorus, *inorganic phosphorus*, and plant available phosphorus, while other studies measure only total phosphorus. More research with consistent monitoring is needed to better understand and further quantify the role wetlands may play in nutrient management. However, the relative influence of a variety of factors is known, and may be considered when selecting among potential sites and designing treatment wetlands (Appendix B).

Policy Review

The Clean Water Act (CWA) was enacted in 1972 making it illegal to discharge pollutants without a permit. The CWA set out to make all waters fishable and swimmable by 1983 and all pollution discharge eliminated by 1985. While these two goals were not completely achieved, the CWA was responsible for vast improvements in point source pollution. Beginning, in the mid-1970s, municipal and industrial dischargers of phosphorus in the Great Lakes Basin were required to limit their discharge to 1 milligram per liter. In 1992, Wisconsin established a statewide technology-based limit of 1 milligram per liter phosphorus for all municipal and industrial dischargers.

The CWA requires states to identify designated uses for each waterbody (i.e. recreation, fishing, and/or drinking). States also establish water quality standards to protect those designated uses. If a waterbody does not meet its designated use, it is placed on the *303(d) impaired water list*. *Total Maximum Daily Loads (TMDLs)* are developed which limit the load of pollutants causing the impairments for each waterbody on the 303(d) list. TMDLs allocate appropriate pollutant loads to both nonpoint and point sources to allow for the implementation of practices to decrease the amount of pollution.

On December 1, 2010, Wisconsin approved phosphorus water quality standards, known as the phosphorus rule (see Table 2). The goal of phosphorus rule is to protect water quality and ensure Wisconsin waters are meeting designated uses for current and future generations. The Wisconsin phosphorus rule includes unique compliance options: *water quality trading*, *adaptive management*, and *multi-discharger variance*. The goal behind all the compliance options is that point sources have the potential to support implementation of nonpoint source pollution projects which reduce phosphorus in the same watershed more cost-effectively. Limitations to the programs include: insufficient political support, unwilling partnerships, eligibility constraints, and economic limitations.

Table 2: Wisconsin phosphorus water quality standards. Source: Wisconsin Chapter NR 102

Phosphorus Criteria NR 102	
Rivers	100 μg/L
Streams	75 μg/L
Reservoirs	30 – 40 μg/L
Lakes	15 – 40 μg/L

Water Quality Trading

Water Quality Trading (WQT) is a compliance option for meeting water quality standards that provides point sources the flexibility to acquire pollutant reductions from other sources in the watershed to offset their point source load. Point sources may work with other point sources or nonpoint sources to have them implement practices to reduce their pollutant load. The goal is to generate *credits* to offset the current level of pollution. Practices are assigned a different number of credits for different pollutants based on the amount of reduction they will provide (WQT How to Manual 2013). WQT program credits are determined by models rather than via on-the-ground monitoring of implemented *best management practices (BMPs)* on a site by site basis. Models are useful tools, but more data are needed on the benefits of different BMPs to accurately credit them.

Currently, wetlands are credited only for the amount of acres they take out of production in an agricultural field. No credits are given for the amount of phosphorus and nitrogen a wetland may retain or remove.

> *"Load reductions are generated for land placed out of production such as the conversion of agricultural land back to wetland.* Credits *may not be generated by using wetlands to treat runoff" (WDNR 2013a).*

To determine whether a point source is in compliance with its effluent permit, monitoring of the effluent and modeling of field practices is completed. Monitoring of individual practices (i.e. buffer strips, cover crops, filter strips, etc.) is not required in WQT resulting in little to no incentive for the constructed practices to be monitored for their actual on-the-ground effectiveness.

Recommendation

There is a need to increase monitoring of how treatment wetlands perform in Wisconsin to gain a better understanding of potential credits for wetlands and reduction of nitrogen and phosphorus. In order for there to be a change in the amount of credits for wetlands, there would need to be greater confidence in the science on how wetlands reduce nitrogen and phosphorus. The use of treatment wetlands should be approved on a site to site basis, based on factors known to affect nutrient reduction (see Factors Affecting Nutrient Reduction and Cycling).

Adaptive Management

Adaptive management is a compliance option provided to point sources to meet phosphorus limits established in NR 217 – Effluent Standards and Limitations for Phosphorus. NR 217 states that all publicly owned treatment plants and privately owned domestic sewage plants may not exceed 1mg/L total phosphorus as a monthly average. The 2010 update to Wisconsin's phosphorus rules requires municipal and private waste water treatment plants as well as industrial facilities to reach a discharge concentration of 0.075mg/l; in streams and 0.1mg/l in rivers if the water bodies they are discharging into are not meeting water quality standards. When a point source commits to adaptive management, they agree to implement practices within their own facility, township, or watershed that will improve water quality. Constructed wetlands and wetland restoration are listed as allowable BMPs in an adaptive management strategy.

Adaptive management focuses on in-stream water quality improvements; therefore, monitoring is required to determine if water quality improvements have occurred. Additionally, annual reports are completed on the quality of the water. Monitoring conducted on the same day between May and October is mandatory over a 20-year period to determine if the implemented practices have resulted in meeting phosphorus standards. Monitoring is completed instream and downstream of where the practices are implemented on a cumulative basis, resulting in a lack of understanding of how the individual practices perform. However, penalties or procedures have not been established in the event that water quality standards are not met after 20 years of monitoring.

Recommendation

In addition to monitoring implemented practices on a cumulative basis, each practice should be monitored individually to better understand the relative contributions of each type of practice to nutrient reduction goals. Monitoring individual practices will lead to more on-the-ground data on the practices, especially *edge-of-field practices*. Additionally, monitoring should be constructed year-round, due to seasonal variability in treatment wetland effectiveness, as well as other BMPs. The majority of nutrient runoff from fields in Wisconsin occurs between March and June (Graczyk et al. 2011); significant water quality impacts may be missed if monitoring does not start until May. Within monitoring requirements, there is an opportunity to address research gaps, standardize monitoring, and improve overall study design. The use of treatment wetlands should be approved on a site-by-site basis, account to factors that are known to influence nutrient reduction effectiveness.

Multi-Discharger Variance

Multi-Discharger Variance (MDV) is a time extension for point sources needed to meet permit limits; the point source commits to a step-wise reduction of phosphorus. MDV is not permanent nor a final compliance option for point sources. During each permit term, the point source is required to reduce its phosphorus discharge by an agreed upon amount. Point sources must either enter into an agreement with DNR to implement a project to offset the amount of phosphorus by which their discharge exceeds the permit or make payments to county Land Conversation Departments of $50 per pound for the amount phosphorus by which their discharge exceeds their permit.

The final MDV package for Wisconsin was submitted to EPA for their approval at the end of March 2016. If the EPA approves MDV, it will become an additional phosphorus compliance option for point source permit holders experiencing difficulties meeting phosphorus limits.

Section 319 and Nine Key Element Plans

The 1987 amendments to the CWA established the Section 319 Nonpoint Source Management Program. Through Section 319, funds are provided to states and tribal agencies to implement their approved nonpoint source management program. They can be used to support a large variety of activities including technical assistance, financial assistance, education, demonstration projects and monitoring (U.S. EPA 2016a). In order to receive Section 319 funding for a proposed project there must be a watershed plan that includes the outlined nine key elements as identified by EPA, and the project must be part of watershed plan implementation (U.S. EPA 2008). Region 5 of EPA, which includes Wisconsin, has developed guidelines and consideration for incorporating wetland re-establishment and creation within nine key element watershed plans (U.S. EPA 2013).

Wisconsin released their FY2016-2020 Nonpoint Source Program Management Plan in September 2015 which meets the EPA CWA requirements and ensures Wisconsin's eligibility for Section 319 funding. Nine key element plans require a description of the NPS management measures that will be implemented to achieve the stated load reductions. The consideration of treatment wetlands in these plans would increase understanding of their potential use in Wisconsin as a NPS pollution strategy. Additionally, nine key element plans must have a monitoring component. However, monitoring of individual practices is not required. Instead, monitoring is conducted in stream to measure if the stated reduction loads have been met.

The Upper Duck Creek Nine Key Element Plan includes wetland construction and restoration to improve water quality in the Lower Fox River Watershed to meet TMDL goals. The identified locations for potentially restorable are based on watershed planning for wetland restoration based on ecosystem services, including the potential for sites to address water quality (Miller et al. 2012); sites should be further evaluated based on factors listed in this report. This plan also identifies potential funding sources of the Great Lakes Restoration Initiative, Adaptive Management program, and Water Quality Trading program.

Chapter NR 151 – Runoff Management

Chapter NR 151 details agricultural performance standards and manure management prohibitions, a process for agricultural implementation, non-agricultural performance standards, and transportation facility performance standards. In NR 151, Wisconsin uses performance standards rather than requiring certain practices such as buffer strips or conservation tillage to allow the parties to determine the best practices based on their knowledge of their land, past practices, and resource availability. Overall, using performance standards allows for improved targeting and prioritization and recognizes that some practices will be more beneficial in different parts of the state. Treatment wetlands play a role in NR 151; farmers may implement treatment wetlands on their feidls as a BMP if it is deemed appropriate. Since Wisconsin has chosen performance standards, there should be substantial outreach to farmers regarding different **management practices** they may implement to reduce NPS pollution. In NR 151 there are also site specific performance standards to meet TMDLs, and where applicable wetlands should be used.

Recommendations

1) Deal with the problem at the source
    - Edge-of-field practices can be beneficial but have a limited capacity to reduce nutrient loads. It may be more cost effective and more beneficial to the environment to understand how to reduce the amount of phosphorus and nitrogen that is placed on contributing agricultural fields. Ju *et al.* (2009) demonstrated experimentally that additions of nitrogen fertilizer could be cut in half without loss of yield or grain quality.

Reducing nutrient inputs by decreasing the amount of fertilizer could be beneficial agronomically, economically, and environmentally (Vitousek *et al.* 2009).

  - The *Wisconsin Phosphorus Index (P-Index)* is an assessment tool for managing runoff phosphorus losses from cropland (UW-Madison 2014). Use the P-Index to assist farmers in understanding the source of their phosphorus, hopefully reducing the amount of phosphorus that will run off the field. A research project in the Pleasant Valley watershed in southwest Wisconsin, found about 12% of the crop and pasture lands have a P-Index of 6, meaning 6 pounds of phosphorus will be lost from the agricultural field annually. These fields were found to be contributing about a third of the phosphorus load. If the fields were managed differently and the P-Index changed from 6 to 3lbs/acre/year there would be a 35% decrease in phosphorus loads (WDNR 2013b – cited from conversation with L. Ward Good).
  - A paired watershed study was completed in two 5,000 ha watersheds in southwest Wisconsin, including the Pleasant Valley watershed described above; both watersheds were ranked in the top 6% for high phosphorus and sediment loads (Carvin et al. 2016). After three years of baseline monitoring, farmers implemented field- and farm-based practices to reduce phosphorus and sediment input to streams in one of the watersheds. Three years after implementation, monitoring concluded total phosphorus loads were significantly reduced by 55% in the test watershed compared to the control watershed (Carvin et al. 2016). This project found that by focusing conservation practices on the highest contributing fields, can lead to significant reductions in phosphorus concentrations in streams (Carvin et al. 2016).

2) Address research needs
3) Expand and standardize monitoring
  - As treatment wetlands are implemented within various programs monitoring requirements should strive to address broader research needs, in addition to site-specific goals.
  - Greater consistency should occur in the collection and reporting of data on the effectiveness of treatment wetlands. This includes how reductions are measured (pounds, percentages, or loads), as well as the type of nutrients measured (dissolved phosphorus, total phosphorus, organic nitrogen, nitrate, etc.).
  - Develop a centralized platform for aggregating and storing monitoring data from treatment wetlands. In addition to encouraging data standardization, this would also provide opportunities to address research needs and assess treatment wetland among sites and at broader scales.
4) Fund and continue efforts to create a modeling tool to predict nutrient reductions via edge-of-field conservation practices, to complement SnapPlus which focuses on cropping practices.
  - Currently SnapPlus, which aids farmers in identifying how best to use on-farm nutrients and accurately use commercial fertilizer, does not include any edge-of-field *practices* except two types of grass filter strips. A tool that expands consideration to additional edge-of-field conservation practices including treatment wetlands should be developed.

WDNR has already initiated this work with Dr. Laura Ward Good and a team at UW-Madison; it would be very beneficial to continue this effort.

5) Expand existing programs and ensure effective implementation
   - Nutrient Management Plans have the potential to assist farmers in understanding the amount of fertilizer (manure or synthetic) that is needed on fields for crops. It may be useful to have information made publicly available if it would further the understanding of soil nutrients and appropriate conservation practices.
   - Voluntary programs and policies may not have the potential to generate the results and improvements in water quality that are wanted. Ensuring effective implementation is key when addressing NPS pollution.
6) Encourage the development of TMDLs and 9 Key Element Plans
   - Within an approved TMDL for a waterbody, nutrient reductions requirements are assigned for all point and nonpoint sources in a watershed; however, when a TMDL has not been developed for a waterbody, reductions are based on an individual point source's permit to achieve water quality standards. Point sources may support TMDL development because reduction goals may be appropriately distributed among other point and nonpoint sources, toward overall TMDL goals.

Research Needs

While innovative work has been completed in Wisconsin on treatment wetlands (see Doherty et al. 2014), more research is needed to better understand the functions and uses of treatment wetlands. The following is preliminary and has been listed in priority order. Further collaboration with scientists and practitioners is needed to further identify, define, and prioritize research needs.

- Develop a paired watershed study to determine watershed-scale impacts of wetland creation a restoration (re-establishment of lost wetlands) on water quality.
- Establish more long-term (15+ year) studies are needed to understand the potential effectiveness of treatment wetlands as nutrient reduction tool
- Better describe relationships and tradeoffs among nutrient reduction and other goals since wetlands are being advertised for multiple goals
- Increase vegetation monitoring in treatment wetlands to determine the amount of nitrogen and phosphorus removal potential as well as measure the amount of nitrogen and phosphorus stored and translocated to the roots and rhizomes of vegetation in treatment wetlands, especially in Wisconsin and Midwestern landscapes.
- Determine the ideal time to harvest vegetation and the amount of nitrogen and phosphorus that may be removed from a wetland through harvesting.
- Determine the ideal hydraulic loading to maximize nutrient reduction.
- Determine wetland acreage required to reduce nutrients, relative to inflow nutrient concentrations.
- Determine the optimal residence time for nutrient reduction.

- Better understand the factors that influence whether and when a wetland will as sink versus a source of nutrients.
- Understand the implications of using invasive species to reduce nitrogen and phosphorus in treatment wetlands.
- Conduct on-the-ground experiments to understand the importance of treatment wetland location, to complement ongoing modeling efforts.
- Test the applicability of the PSR as a predictor of soil phosphorus retention capacity, particularly in all temperate wetlands (natural, created, reestablished, restored, and treatment)

Conclusion

This study explored scientific literature on treatment wetlands and their potential use as a nutrient management strategy, specifically in agricultural setting. There are major gaps in fully understanding how wetlands could be used as a BMP in an agricultural setting. However, it is important to remember that treatment wetlands are only one tool in the toolbox. Treatment wetlands, by themselves, will not solve all nutrient runoff and water quality problems. Better nutrient application procedures are needed including improved timing of application, implementation of other BMPs, and preservation and restoration of riparian vegetation strips. On-the-ground research is the best way to improve our understanding of treatment wetlands and other BMPs' potential to reduce nutrient pollution into nearby waterbodies. When constructing wetlands on agricultural land it is necessary to gather as much data as possible about the site and neighboring sites. Using treatment wetlands as a potential nutrient management strategy is a multidisciplinary field that requires input from engineers, ecologists, biologist, and conservationists. The hope is that this report and study advance a conversation about treatment wetlands and other innovative conservation practices to reduce pollutants entering waterbodies.

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Appendix A: Definitions

303(d) Impaired Waters List: waterbodies which do not meet their designated uses as defined by the Clean Water Act are considered impaired waters and placed on the 303(d) list.

Adaptive Management: phosphorus compliance option where point sources and nonpoint sources work together to improve water quality to meet standards**.**

Aerobic zone: area of wetland soil or water column with microbially-available oxygen.

Anaerobic ammonium oxidation (anammox): process where nitrite and ammonium ions are converted into diatomic nitrogen.

Anaerobic zone: area of wetland soil with low concentrations of microbially-available oxygen.

Anoxic conditions: areas of a wetland soil or water column with no microbially-available oxygen.

Best Management Practice: methods or techniques found to be the most effective and practicable means in achieving an objective (i.e. water quality standards).

Credit: units of pollution reduction available for trading in a water quality program, generated for every unit of pollution reduction beyond a baseline level.

Denitrification: microbially-facilitated process by which nitrate is converted to nitrogen gas (N_2 or N_2O).

Designated Uses: each waterbody is assigned a use – recreational, public health and welfare, wildlife, fish and aquatic life – to which are assigned a set of expectations for a waterbody's performance. A public drinking water supply and subcategories for fish and aquatic life are in the process of being added to designated uses in Wisconsin; the rulemaking effort is expected to extend through 2016 (WI NPS program management plan).

Edge-of-field practices: nutrient reduction practices located to intercept runoff from agricultural fields including drainage water management, wetlands, bioreactors, buffers, terraces, and sediment control.

Inorganic phosphorus: phosphorus in compounds not synthesized into organismal tissues (living or dead).

Management Practices: in-field nutrient reduction practices including the use of cover crops, reduced tillage, and changes in fertilizer application rates, timing, and methods.

Multi-Discharger Variance: an opportunity for point sources to make advances towards water quality improvement by a time extension for point sources experience difficulty meeting phosphorus limits.

Natural Infrastructure: The EPA defines natural infrastructure as the "interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife" (EPA 2012). While existing wetlands and other habitats impact water quality, for purposes of this project natural infrastructure is defined as created or reestablished wetlands that may act as sinks, sources, or transformers of nutrients, particularly phosphorus and nitrogen.

Nitrification: biological oxidation of ammonia (NH_3) and ammonium (NH_4^+) to nitrite followed by the oxidation of nitrite (NO_2) to nitrate (NO_3).

Nitrogen: an element found naturally in the environmental that is essential for plant growth.

Nonpoint Source Pollution: pollution from diffuse source or sources, rather than from a single source. Examples include runoff from agricultural fields and urban areas.

Nutrient Management Plan: a written strategy for obtaining the maximum return from on- and off-farm fertilizer applications by outlining amounts, timing, locations, and methods.

Organic phosphorus: phosphorus in compounds synthesized by organisms.

Particulate phosphorus: insoluble phosphorus bound to or within solid particles (organic and inorganic).

Phosphorus: an essential element needed for plant growth.

Sedimentation: the process by which particles in suspension settle out of the water column.

Total Maximum Daily Load (TMDL): regulatory term in the US Clean Water Act which sets the maximum amount of pollutant a waterbody can received and still meet its designated use.

Treatment Wetland: a created or re-established system that is man-made and designed to accomplish a reduction goal for pollutants.

Water Quality Trading: A compliance option that provides point sources with the flexibility to acquire pollutant reductions from other sources in the watershed to offset their point source load to comply with a permit limit (WDNR).

Wetlands: ecological systems that have the following characteristics 1) predominance of hydric soil, 2) inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions ,3) under normal circumstances supports a prevalence of such vegetation (16 U.S. C. Section 3801(a)(18)).

Wisconsin Phosphorus Index (P-Index): a tool used to predict the phosphorus loss from agricultural fields due to runoff; the P-Index calculates this loss using land use characteristics and natural conditions including land slope, soil phosphorus levels, and average precipitation levels.

Appendix B: Factors Affecting Nitrogen and Phosphorus Reduction

Factor	Definition	General Affect	Affect on Nitrogen Reduction	Affect on Phosphorus Reduction
Hydraulic Loading	The quantity of water and the rate at which it flows (surface or tile drainage water into a wetland)	Hydraulic load affects the residence time of the wetland and overall soil saturation of water and nutrients.	Nitrate removal efficiency decreased with increase hydraulic load (O'Geen et al. 2010). Wetland that received the highest amount of nitrogen in the load had the lowest efficiency in removing nitrogen (Kovacic et al. 2000).	Flooding of a wetland can result in anoxic conditions which drops redox potential resulting in iron bound phosphorus to potentially be released. This results in a greater SRP release from a wetland then during 'moist' periods (Aldous et al. 2005; Ardón et al. 2009). As hydraulic load increases the residence time decreases resulting in a decrease in phosphorus sedimentation (Braskerud 2002).
Residence Time	The length of time in which water stays within a wetland	Residence time impacts the formation of *anaerobic* and *aerobic* layers of the soil as well as the amount of time particulate matter is able is able to settle out the water column. Longer residence times results in a greater amount of sedimentation of particulate phosphorus and increase in denitrification from the formation of the *anaerobic* zone.	A study in Illinois found that a residence time of a week or more led to the greatest nitrogen reduction (Woltemade 2000). Ideally a residence time of 2 days or longer is necessary for significant nitrate removal (Kovacic et al. 2000; Phipps and Crumpton 1994).	Greater residence time results in increased sediment resulting in an increase in phosphorus retention (Saunders and Kalff 2001; Johannesson et al. 2015).

Season	Fall, Summer, Winter, Spring	Decrease in nutrient reduction of soluble nitrogen and phosphorus will likely occur in the fall when vegetation begins to die (Fisher and Acreman 2004). Higher precipitation can lead to greater hydraulic and pollutant which can affect treatment efficiency and mass removal (Beutel et al. 2014).	During a 3 year study period it was seen that the most (95%) of the total nitrogen entered the wetland during the spring and winter (Kovacic et al. 2000).	Roughly 80% of total phosphorus runoff loads occurred between March and June; less than 1% of total phosphorus runoff loads occurred between September and October (Graczyk et al. 2011). Total phosphorus outflow from a wetland displayed seasonal variation where elevated levels in summer months were seen (>0.1mg/L) and low levels in the spring and fall (<0.03mg/L) (Beutel et al. 2014). 50% less phosphorus export in summer months when hydraulic load was included (Braskerud 2002). There is minimal removal of total phosphorus and reactive phosphorus in the summer due to the high temperature which enhances phosphorus release from decaying plant biomass (Beutel et al. 2014).
Temperature	Temperature of soil and surrounding environment	Temperature affects the rate of decomposition and denitrification through regulation of metabolic activity rates.	Denitrification rates are maximized during summer and decrease with decreasing temperatures. The optimum temperature range for denitrification is 20°C to 25°C, and below 15°C result in very low rates of denitrification (O'Geen et al. 2010; U.S. EPA 2000).	Warm water temperatures enhance leaf litter decay resulting in high rates of phosphorus release (Beutel et al. 2014).

Vegetation	The density, biomass, and species vegetation present in the treatment wetland	Vegetation encourages sedimentation, provides a carbon source for denitrification, controlling sediment oxygen and water content via respiration, transpiration and influencing humic content (Fisher and Acreman 2004). Vegetation must be harvested to permanently remove nutrients from the system; if the vegetation is not harvested the nutrients may contribute to a release of nitrogen and phosphorus (O'Geen et al. 2010; Reddy and D'Angelo 1994). For example, up to 30% of the nutrients in plants are lost by leaching during the first few days of decay (Vymazal 2007).	Estimates of net annual nitrogen uptake by emergent wetland plant species vary from 0.5 to 3.3 $gN/m^2/yr$ – reeds and bulrushes are at the lower end of the range and cattails are at the high end of the range (U.S. EPA 2000). 1.7g/m^2 nitrogen was translocated from the wetland soil to the shoots of Scirpus fluviatilis (river bulrush) in a Wisconsin marsh (Nichlos 1983). Plant uptake accounts for 16-75% of total nitrogen removal (Reddy and D'angelo 1994). As vegetation in a plant community matures and more established, the organic litter will accumulate which will provide a suitable seedbed for wetland plants and critical carbon for denitrification (Woltemade 2000).	The presence of vegetation, especially the stems and leaves will decrease the flow of water resulting in higher residence times and greater sedimentation rates leading to higher phosphorus retention (O'Geen 2010). 3.8gP/m^2 were translocated from the wetland soil to the shoots of Scirpus fluviatilis (river bulrush) in a Wisconsin marsh (Nichlos 1983). Phosphorus storage that is above ground in the macrophytes is usually short lived where most of the P is released during decomposition (Reddy et al. 1999). Plants die back annually and release 35-75% of phosphorus back into the water column (Richardson and Craft 1993). Release of phosphorus from plant material is often rapid with 20-50% of the total phosphorus released in a few hours and 65%-85% during longer periods (potentially days) (Dunne and Reddy 2005). High rates of P uptake and storage occur in spring when vegetation growth is substantial – much of the P is released back into the environment during decay of plant material – only an estimated 10-20% of plant P is lost through burial the rest is lost to the system (Beutel et al. 2014).

Wetland to Watershed Ratio	The size of the constructed wetland compared to the catchment area	Studies have shown that a wetland to watershed ratio of 0.1% to 6% to see a significant reduction in phosphorus and nitrogen (O'Geen et al 2010; Kynkäänniemi et al 2013; Kadlec et al 2000; Braskerud 2002).	Constructed treatment wetland designs should have a watershed to wetland area ratios between 15% and 20% to optimize nitrogen reduction (Kovacic et al 2000). A demonstration farm in McLean County, IL found that a wetland comprising 6% of the watershed resulted in a 50% reduction of incoming nitrates from inflow tile drain water (Lemke 2015; Betts 2014).	Higher wetland to watershed ratio increases residence time resulting in greater phosphorus retention by increasing particle settling and sorption capacity (Kynkäänniemi et al. 2013). 0.3% wetland to catchment ratio (0.08ha wetland) in a 26 ha catchment resulted in a 36% reduction of TP, 9% reduction of DP, and 36% reduction of TSS (Kynkäänniemi et al. 2013).
Wetland Location	The relative position of wetland within its watershed	To increase the amount of reduction of nitrogen and phosphorus, the wetland must be located where it will intercept a large percentage of the flow (Woltemade 2000). The location of the wetland dictates the amount of runoff that enters the wetland.	When a wetland was modeled to intercept 70% of the runoff in the watershed there was 45% removal of annual nitrate, compared to when the wetland was modeled to intercept 4% of the runoff there was only a 4% removal of annual nitrate (Woltemade 2000).	Wetland should be located close to the source of phosphorus to increased accumulation and sedimentation (O'Geen et al. 2010).
Mineral Content of the Soil	The amount of minerals (Fe, Al, and Ca) in the soil	Phosphorus adsorbs to aluminum (Al) and iron (Fe) in acidic soils and calcium (Ca) in alkaline soils and impacts the amount of phosphorus that is adsorbed in a wetland.	NA	Phosphorus adsorbs Al and Fe in acidic soils and Ca in alkaline soils therefore the presences of these elements will result in greater phosphorus reduction. Formation of phosphate compounds decreases availability of phosphorus to be released from a wetland (Busman et al. 2009).

Age of Wetland	The length of time since the wetland has been created or re-established	The age of the wetland may impact its potential to retain phosphorus because of the adsorption sites may become unavailable (Ardón et al. 2010).		Overtime wetlands lose the ability to remove phosphorus (Fisher and Acreman 2004). Phosphorus removal by sorption to wetland sediment and P uptake during new plant growth are significant only in the first few years of the constructed treatment wetland operation (Beutel et al. 2014).

Mean Slope	Slope of the catchment and/or the wetland	A great slope can lead to greater erosion leading to more particulate phosphorus released from the catchment/watershed resulting in a higher nutrient load of particulate phosphorus into the wetland.	NA	NA
Amount of Carbon	The amount of carbon available in the soil	Nitrogen Cycle: ammonia is oxidized to nitrite by nitrifying bacteria in *aerobic* conditions and nitrate is converted to free nitrogen in *anaerobic* conditions by denitrifying bacteria.	Plant material is needed to provide organic carbon for denitrifying bacteria to convert nitrate into nitrogen gas (Braskerud 2001; O'Geen 2010; Woltemade 2000).	NA

Soil pH	Measure of how acidic or basic the soil is.	Differences in the pH of the soil may result in more ideal conditions for phosphorus or nitrogen reduction by wetlands.	Denitrification occurs much more slowly under acid conditions than at neutral or alkaline pH conditions (Nichols 1983)	Wetlands with organic soils and acidic pH have the lowest Phosphorus Sorption Index (PSI) due to the lack of mineral components in the soil that will bind with phosphorus (Bruland and Richardson 2006). Soils with a neutral pH are the most efficient use of phosphate (Busman et al. 2009).
Microbial Community	The amount of microbes in the soil		Increase in microbial activity may result in an increase in denitrification (Fisher and Acreman 2004)	plant available phosphorus forms are consumed by microbes turning phosphorus into organic P which is unavailable to plants.
Wetland Shape	Width and length measurements	Effects the residence time of water (Kynkäänniemi et al. 2013).	NA	Wetland shape (L:W) was positively related with phosphorus and particular retention (Johannesson et al. 2015). Rectangular shapes result in a decrease in water velocity resulting in more particle settling leading to greater phosphorus retention (Kynkäänniemi et al. 2013).
Phosphorus concentration in porewater	The concentration of phosphorus in the porewater compared to the concentration of phosphorus in the soil	NA	NA	when the phosphorus concentration in the porewater is high, more phosphorus will be retained in the soil (Dunne and Reddy 2005).
Water Depth	Depth of the water in the wetland	Depth of water may impact resuspension – when the wetland is shallow particles may be re-suspended during storm events or other high flow conditions (Braskerud 2002).	NA	NA

Appendix C: Partner Meeting

Twenty-five individuals representing nine agencies, organizations, and institutions met on August 23rd in Madison, WI to consider science needs and policy implications of employing treatment wetlands in nutrient reduction programs. Participants included representatives of the Army Corps of Engineers (Chicago and Buffalo districts), Wisconsin Department of Natural Resources, US Fish and Wildlife Service, University of Wisconsin – Madison, University of Wisconsin – Green Bay, The Nature Conservancy, Natural Resource Conservation Services, Gathering Waters, and Wisconsin Wetlands Association. The format of the meeting was mostly discussion with short presentation highlighting the major conclusions of the science and policy reviews contained in this report. A dynamic discussion occurred and a great deal of interest was expressed in how to move forward on the potential use of treatment wetlands to improve water quality.

Possibilities for moving forward

- → Determine the implications of permitting and regulating treatment wetlands; this includes NR 103.
- → Determine the branding of treatment wetlands – are treatment wetlands the appropriate terminology?
- → Explore NR 353 which was created to streamline wetland restoration projects.
- → Dive deeper into the literature to gain a more comprehensive understanding of the use of treatment wetlands as a potential nutrient management strategy.
- → Explore the development of short term planning and guidance for treatment wetlands.
- → Ensure the conversation continues to address both phosphorus and nitrogen.
- → USGS is currently monitoring various edge-of-field practices and these data should be considered when thinking about different practices to use.
- → Research the effect of potentially increasing water temperature through establishment of treatment wetlands on downstream waterbodies and the impact of climate change.
- → Further discussions and meetings should include regulators
- → Make sure there is agreement among the interested parties on the exact definition of the "treatment wetland".
- → Explore the validation of various models used to predict the amount of phosphorus and nitrogen reduction by treatment wetlands or other conservation practices with on-the-ground data.
- → Explore the idea of creating a Wetlands Initiative, similar to Wisconsin's Buffer Initiative.

Appendix E: Additional Resources

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