A Benefit-Cost Analysis using natural treatment systems, P removal structures, and a Phosphorous corrective fee to reduce excess nutrients in the Maumee River Watershed

By

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A paper submitted in partial fulfillment of the requirements for the degree of

Masters of Arts

In

Economics

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The University of Toledo

December 2016
Abstract

This paper looks at using surface flow and subsurface flow wetlands, sediment ponds, P removal structures, and a nutrient corrective fee as cost-effective solutions to reduce phosphorous loadings into Lake Erie from the Maumee River Watershed (MRW). Phosphorous is a leading nutrient in aiding the production of algal blooms on Lake Erie. A full Benefit-Cost Analysis (BCA) for the different solutions was conducted, with a phosphorous loading target reduction of 10%. Surface flow wetlands and the P corrective fee were found to be the most efficient. As a result, a combination of the two solutions, each reducing 20% Total Phosphorous (TP) was recommended as a politically feasible solution, to reach the targeted 40% P reduction.
Acknowledgements

The completion of this Masters Paper would not have been possible without the guidance and support of my advisor, Dr. Kevin Egan. Our numerous meetings and discussions were extremely helpful in the writing process of this paper. I would also like to thank Dr. Daryl Dwyer as well as Ryan Jackwood for all of their help with the environmental aspects of this document. Having background information on the natural treatment systems presented in this paper was crucial. Thank you as well, to the Ohio Department of Higher Education for making this research paper possible. And finally, thank you to all my family and friends for your support and encouragement!
Executive Summary

This paper looks at using surface flow and subsurface flow wetlands, sediment ponds, P removal structures, and a nutrient corrective fee as cost-effective solutions to reduce phosphorous loadings into Lake Erie from the Maumee River Watershed (MRW). A full Cost-Effectiveness (CE) Analysis for the different solutions was conducted, with a phosphorous loading target reduction of 10%. The first CE analysis performed was for sediment ponds, with many assumptions derived from literature review: a range of constructions costs between $0.10 and $0.50 per cubic foot of storage, annual maintenance costs equaling 25% of construction costs, ranges of flow and discharge the ponds are able to treat, a range of P removal effectiveness, as well as a range of discount rates. Present value costs over 20-year and 25-year lifespans were determined, as well as the total cost of constructing sediment ponds throughout the whole Maumee River Watershed (MRW) to reach a 10% P reduction. Cost per Kg P removed was also calculated based on 263,000 kg of P needing to be removed, to reach a 10% P reduction in the watershed.

The next CE analysis was for surface and subsurface flow wetlands. The assumptions for the wetlands were the same as for the sediment ponds; except construction costs were in terms of $/acre. Again, PV values were calculated as well as cost per Kg of P removed, for a watershed-wide 10% P reduction; over the two lifespans, as well.

Added benefits for wetlands were then included, producing a full Benefit-Cost Analysis for both surface and subsurface flow wetlands. PV $C and PV $B calculated in the wetlands chapter were used to derive PV $NB of both types of wetlands for a 10% P reduction throughout the MRW, over 20 and 25-year lifespans.
P removal structures followed. For P removal structures (PRSs), a one-time construction cost was assumed to be $4,989, with an annual cost to replace P sorbing materials of $1,213. Assumptions again were made based on P removal effectiveness; and a range of discount rates. PV costs and cost per kg P removed were also calculated; over the two lifespans. And lastly, for a P corrective fee, two different price elasticities (as well as the two lifespans) were used in the sensitivity analysis. Using and modifying Ohio State University Economist Brent Sohngen’s data, dollar costs per year were calculated for the MRW, as well as the fee amount (or percentage amount of fertilizer price increase), and dollar cost per acre per year. To be able to compare all solutions equally, PV costs with 20 and 25-year lifespans (as well as the two elasticities) were calculated, as well as costs per Kg P removed across the whole MRW. It is important to note, however, that there are minimal social costs with a P fee. The ‘costs’ are considered transfer costs and can be ignored in a social benefit-cost analysis or cost-effectiveness analysis. The only cost of a P fee would be any impact the fertilizer price increase would have on farmers’ yields; which has been shown to be negligible.

Based on my literature review, I estimated the present value total cost to achieve the 10% P reduction. The ranking based on cost-effectiveness analysis is: 1) corrective P fee (minimal social cost; primarily transfer cost), 2) surface flow wetlands (mean PV(C) of $13 million), 3) subsurface flow wetlands (mean PV(C) of $40 million), 4) sediment ponds (mean PV(C) of $172 million), and last 5) P removal structures (mean PV(C) of $606 million).

Excluding the P fee for a moment, the results show that across the first four included policy options (sediment ponds, surface flow wetlands, subsurface flow wetlands, and P removal structures), surface flow wetlands were the most cost-effective in each lifespan. Moreover, because wetlands provide additional benefits to society, beyond P reduction, I estimated net
benefits to society from the proposed wetlands restoration plans. Out of the two types of wetlands, surface flow wetlands had higher $NB in each lifespan scenario. Based on my literature review, surface flow wetlands robustly lead to positive $NB; while subsurface flow wetlands were assumed to have the same benefits per acre, but due to their higher cost per acre, were almost as likely to lead to negative $NB as positive $NB.

Out of the different natural treatment systems considered (surface flow, subsurface flow, and sediment ponds), the surface flow wetlands were the most cost-effective solution. However, it is important to note that it may not be efficient to install just one type of natural treatment system across the whole MRW. Each type of system/solution will be installed where it is the most efficient to do so in the watershed, to reach the targeted P reduction. In other words, there would likely be a combination of different systems implemented throughout the MRW to reach the targeted 40% TP reduction.

For example, with my assumed costs for each type of natural treatment system, the cheapest sediment ponds are lower cost than the most expensive surface flow wetlands. The same is true for subsurface flow wetlands. Though the minimum cost, sediment ponds and subsurface flow wetlands are still more expensive than the mean surface flow wetland cost. Thus, based on my literature review, my conclusion is to install mostly surface flow wetlands, with possibly some sediment ponds and subsurface flow wetlands where appropriate. Regarding P removal structures, there is little literature available at this time. Additionally, the projects are small scale, leading to very high-cost estimates when trying to use on a larger scale; 26,300 of these small scale structures in the MRW would be required, to achieve the 10% TP reduction. Thus, at this time, my conclusion does not support the use of P removal structures in the MRW.
The P corrective fee was found to be the most cost-effective out of all of the solutions. However, this policy option has never been done before, and to lower the overall uncertainty, I recommend that a combination of the two most cost-effective solutions be implemented (the P corrective fee along with surface flow wetlands). Additionally: since a corrective P fee has minimal social costs and surface flow wetlands are the next most cost-effective solution in P reduction, and that all the benefits surface flow wetlands provide to society lead to robust positive net benefits, I conclude the most efficient options are the corrective P fee and restoring surface flow wetlands on available public land in the MRW. And finally, subsurface flow wetlands and sediment ponds may be occasionally cost-effective to target sediment and P concentration ‘hot spots’.

In conclusion, I recommend that a combination of the two most cost-effective solutions be implemented; the P corrective fee along with surface flow wetlands. One possible application of these two solutions would be with each reducing 20% TP, to reach the targeted 40% TP reduction in the MRW.
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List of Abbreviations

BCA: Benefit-Cost Analysis

BMP: Best Management Practices

CE Analysis: Cost-Effectiveness Analysis

cfs: cubic feet per second

CW: Constructed Wetland

DRP / DP: Dissolved Reactive Phosphorous / Dissolved Phosphorous

FWS: Free-Water Surface (Wetland); also called Surface Flow Wetland

GLRI: Great Lakes Restoration Initiative

IJC: International Joint Commission

Kg: Kilograms

MRW: Maumee River Watershed

N: Nitrogen

NB: Net Benefits

OEPA: Ohio Environmental Protection Agency

O&M: Operation and Maintenance

P: Phosphorous

PV: Present Value

PVB: Present Value Benefits

PVC: Present Value Costs

TN: Total Nitrogen

TP: Total Phosphorous

TSS: Total Suspended Solids
US EPA: United States Environmental Protection Agency

WCW: Wolf Creek Watershed

WWTP: Waste Water Treatment Plant
CHAPTER 1: INTRODUCTION

In August of 2014, the city of Toledo suffered a ban on drinking water, resulting from a massive algal bloom on Lake Erie. Over 500,000 residents in the area were without drinkable tap water for a number of days.

The issue of algal blooms on Lake Erie, however, is not a recent one. In the decades leading up to the 1970s loadings of phosphorous (P) due to sewage treatment and anthropogenic sources degraded the water quality of Lake Erie. This prompted the US and Canadian governments to join together and sign The Great Lakes Water Quality Agreement in 1972. Due to this agreement, by the mid-1980s, Lake Erie’s phosphorous levels were reduced by half of the levels of P in the 1970s. However, in the early 2000s, problems with excess nutrients once again appeared in the Lake, and since have continued to worsen. In 2011, due to severe weather conditions and warmer temperatures, a widespread algal bloom was recorded; almost three times larger an area than any bloom previously recorded. This time, the nutrient runoff was not only attributed to sewage treatment loadings, but it was noted that urban and rural runoff were (and still are) significant factors leading to lake eutrophication, or algal blooms (International Joint Commission 4).

These algal blooms cause many other problems, as well, such as depleted oxygen zones in the Lake, which in turn kill certain species of fish. There are also many health concerns in regards to this issue. Many animals and humans have gotten sick from ingesting or swimming in the contaminated water. In economic terms, the algal blooms cause many external costs to society. The health concerns are one example of these external costs. Another example is the damage to Ohio’s economy and different industries, due to this issue. Many restaurants and
businesses had to shut down temporarily due to the water crisis, and Lake Erie’s tourism and fishing industries were damaged, as well (Dungjen and Patch).

Each year more than 7 million people flock to Ohio’s portion of Lake Erie to wildlife watch, fish, hunt, and for other recreational activities. As a result, more than $11.5 billion in travel and tourism revenue is generated each year; and $1.5 billion is generated in federal, state, and local taxes, supporting more than 117,000 jobs (Rissien). Lake Erie is home to one of the largest freshwater commercial fisheries in the world, but because of the poor water quality in Lake Erie, fewer people are making that trip to the Lake.

The nutrient that contributes significantly to the formation of algal blooms is phosphorous. Phosphorous is a key ingredient in farming fertilizers and enters the Lake via farmland runoff. The Maumee River Watershed (MRW) is the Lake’s largest source of P loadings. It is the single largest source of dissolved reactive phosphorous (DRP) that generates harmful algal blooms in the western basin of Lake Erie (International Joint Commission 5). The Maumee River Watershed has 4.2 million acres or 6,609 square miles. Roughly 2.8 million of those acres are agricultural (WLEB State of the Basin Report 7). A relatively small percentage of the water in Lake Erie comes from the Maumee River (roughly 3 to 5%), but the Maumee delivers 80% of the P loadings that enter the Lake (“Two Initiatives Could Improve Water Quality in Lake Erie”).

The International Joint Commission (IJC) has stated that a 40% reduction in P loadings that flow into the Lake, via the Maumee River, would return harmful algal blooms to their historic occurrence rate (International Joint Commission 46). This 40% reduction means that P loadings would have to be less than 1600 metric tons (MT) annually.
This paper details how sediment ponds, different types of wetlands (surface flow and subsurface flow), P removal structures, and a P corrective fee, are proposed solutions in reducing excess nutrients in the Maumee River Watershed.

More than 80% of Lake Erie’s pre-settlement coastal wetlands have been lost, which has significantly impacted water quality and habitats. According to LAMP (2006), “Phosphorous can be strictly managed, but unless natural land or habitat is protected and restored, only marginal response will be seen by many components of the ecosystem. It was determined that changes in land use that represent a return towards more natural landforms or that mitigate the impacts of urban, industrial and agricultural land use, are the most significant actions that can be taken to restore the Lake Erie ecosystem.” (taken from International Joint Commission 55). The IJC also states that the US and Canadian governments should commit to a goal of a 10% increase of coastal wetlands in the Western Lake Erie Basin by 2030, which would be an increase of 2,600 acres; also stating that this goal is feasible, conditional on funding, and would cost approximately $19 million. (International Joint Commission 56).

In this paper, I conducted a full Benefit-Cost Analysis to better determine the costs, effectiveness, and benefits of installing each type of system throughout the Maumee River Watershed (MRW) at a 10% TP reduction. In other words, each system was treated as the sole solution implemented throughout the whole MRW, to reach a 10% reduction. The results shown in each chapter can be interpreted as only one type of system being installed for a 10% P reduction in the watershed.

In order to reduce TP by 10% in the MRW, 263 tonnes TP per year, would have to be reduced. (Ohio Lake Erie Phosphorus Task Force II 32). This 263 tonne was converted into Kg (263,000 Kg) for the analysis. For simplicity, I compared all systems with a 10% TP reduction

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goal. In the final conclusion, a combination of the different (most cost-effective) systems is proposed, to reach the IJC’s recommended 40% TP reduction target.

Many different types of sources were compiled to form this paper. Regarding natural treatment systems (wetlands and sediment ponds); both a sediment pond and a subsurface flow wetland were constructed at Maumee Bay State Park, in Ohio. This data was used as one of the many references to conduct the analysis for subsurface flow wetlands and the sediment pond treatment systems. Oklahoma State University was the primary source of information and data for the P removal structure (PRS) section, and OSU Economist Brent Sohngen’s work was primarily used for the chapter on a nutrient (P) corrective fee.

For the natural treatment systems, a range of per acre costs were determined for the different types of systems, through literature. For sediment ponds, however, it was a cost per cubic foot. Maintenance costs over the lifetime of the various systems are also considered, as well as variation in the lifespan of each system (20 years and 25 years). Variation in the amount of flow treated is also included, for wetlands and sediment ponds. The amount of flow treated is a function of the systems’ P reduction. Present Value (PV) calculations of the systems’ total cost is calculated, using an annuity formula, with variation in the discount rate. These PV numbers, along with the effectiveness and costs of each system, are used to calculate cost-effectiveness for each of the solutions. A cost per Kg of P removed was calculated for each solution, at a 10% P reduction throughout the MRW. Specific details on the assumptions used are in the Methodology sections of each system’s chapter. See Chapter 2 for information on sediment ponds, and Chapter 3 for everything on wetlands.

Other wetland benefits were also added in the chapter about wetlands. It should be noted, that while wetlands have other benefits besides P removal, such as habitat restoration, etc., it is
the only solution that does have these extra benefits, in this study. The other solutions; sediment ponds, a P corrective fee, or P removal structures are assumed to have no additional added benefits.

Additionally, with the wetlands, I assume that there are no land costs; that they are built on publically available land in the MRW. I have performed a simple analysis using public land data provided by the Toledo Metroparks. The goal was to determine if there was a sufficient amount of public land in the watershed, to install wetlands with no land costs. From the Metropark data, the total available acres in the MRW, 50m or less from a waterway, was found to be 33,153 acres. For a 10% P reduction, the maximum amount of acres needed for Surface Flow Wetlands was 1,169 acres (as found in this paper). This means that roughly 3.5% of the total 33,153 available acres would need to be converted into Surface Flow Wetlands in order to reach the 10% P reduction. However, it is important to note that this number of acres includes all publicly owned areas, which could contain buildings, etc., where installing a wetland is not possible. Future research is needed on this matter, to detail specific sites where wetlands could/could not be installed. The main key from my GIS assessment is that there is enough publically owned land (greenspace, Metropark, etc.) to install wetlands without any type of land cost, to reach a 10% P reduction (as well as 40% P reduction). In other words, my assumption of no land costs is valid. A GIS map is attached in the appendix, showing the available public land parcels in the watershed. It is important to note, however, that there may be data limitations; there may be other land that was not included in the data set where wetlands could be installed. I simply got data from the area Metroparks and did not contact counties specifically for land ownership data. Again, more research in this area is needed.
For the P removal structure (PRS), assumptions were made on the one-time construction cost, and yearly P-sorbing material replacement costs. Variation in the lifespan and discount rate were included. Present Value (PV) calculations of the total cost is calculated, using an annuity formula. And a cost per Kg of P removed was calculated. See Chapter 4 for more information on PRSs.

And finally, for the P corrective fee, I again assumed a 10% P reduction and calculated the fee amount based on literature studied. Variation, again, in the discount rate and lifespan was also included.

There are many assumptions in this paper, and thus, I completed full sensitivity analyses for all systems. A uniform distribution was assigned to each variable, with the exception of the lifespan. The sensitivity analyses were completed in multiple Excel documents, to include each scenario and solution.
CHAPTER 2: SEDIMENT PONDS

INTRODUCTION

A sediment pond is used to target heavier sediment rolling along the bottom of a stream or river, and the P attached to the sediment. The pond aims to trap those heavier particles and prevent them from traveling further down the stream or river. Below is a summary of the relevant literature regarding sediment ponds.

2.1 LITERATURE REVIEW

Chapter 4 (Management Measures for Urban Areas) of a 1993 EPA study, titled “Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters,” states that the purpose of sediment ponds, or sediment basins, is to allow sediment to settle out of the runoff. This source says that sediment basins are used for drainage areas between 5 and 100 acres, and can be classified as temporary or permanent. The source lists construction and annual maintenance costs for a sediment basin. The construction cost is based on the size of the basin, or the storage capacity, in cubic feet. It says that for a basin that has less than 50,000 ft³ storage, the range of construction costs is $0.20 to $1.30 per ft³. For a basin that has more than 50,000 ft³ storage, the range of construction costs is $0.10 to $0.40 per ft³. The average, of course, was $0.30 per ft³. Maintenance costs for the basin were considered to be 25% of the total construction cost (4.78).

Section 7 of the 2004 EPA study, titled “Development Document for Final Action for Effluent Guidelines and Standards for the Construction and Development Category” also looks at sediment basins. This source used a constant value of $13,068 per acre-foot (or $0.30 per
cubic foot) to estimate costs “for all site sizes and all options.” (7.11). It was stated that since this document was a little dated, the EPA “evaluated a number of additional sources to determine if the cost factor of $0.30 per cubic foot was still valid. Based on a review of 32 recent references, it was determined that the value of $0.30 per cubic foot was still valid. As a result, this value was used to determine the unit costs of all sediment basins…” (US EPA, Section 7: Approach to Estimating Costs 7.11). This source also lists maintenance costs as 25% of the total construction costs (7.14).

Bjorneberg and Lentz (2005) looked at the effectiveness of sediment ponds with, and without, Polyacrylamide (PAM) -treated irrigation furrows. Installing PAM greatly reduces erosion on furrow-irrigated fields. It was stated that sediment ponds effectively remove suspended sediment as well as attached particulate P from furrow irrigation runoff. Two small sediment ponds (5.8m$^2$) were installed on two fields to receive runoff from a PAM-treated or control furrows. The ponds’ retention time was 60 minutes. It was noted that a longer retention time would allow more sediment to settle in the ponds. PAM reduced sediment and total P losses from irrigation furrows by 50% to 80% by reducing soil erosion and increasing infiltration. This reduction in total P losses reduced the loading into the sediment ponds. In turn, this reduced the mass of sediment and total P retained in the ponds. “However, the percentages of sediment and total P retained were not different between PAM and control [without PAM]. The average retention percentages across both treatments were 86% for sediment and 66% for total P for the three field years. The combined effect of PAM and sediment pond treatments reduced mass transport of sediment 95% to 99% and total P 86% to 98%.” (Bjorneberg and Lentz 593). It was noted that both PAM and the sediment pond had little to no effect on DRP. “Applying PAM to
irrigation furrows and installing sediment ponds at the end of the field were an effective combination for reducing sediment and total P losses from furrow-irrigated fields, but these practices only reduced DRP losses by decreasing the volume of water that ran off the fields.” (Bjorneberg and Lentz 593).

A study by Fox (2011), titled "Evaluation Of The Efficiency Of Some Sediment Trapping Methods After A Mediterranean Forest Fire." compares a Log Debris Dam (LDD) and a sediment pond to trap sediments after forest fires. This study gave an excellent background on how sediment ponds work. During rainfall, runoff flows into the pond, flows velocity drops dramatically, and a large fraction of the sediment load is deposited. “The proportion of the sediment load deposited is called the trapping efficiency, and it has been found to range from 54% to 85% for ponds with volumes ranging from 30 m³ to 260 m³, but no consistent trends were observed for either pond or erosion characteristics.” (Fox 259). The sediment pond studied was 12m by 10m wide (or 0.03 acres). The cost of the sediment basin “was estimated at 8 € m⁻³ for excavation and removal of soil materials from the site and 75 € m⁻³ for the provision and installation of stabilizing rocks. The volume was 180 m³ for a total cost of 14,940 € (roughly $16,000 U.S. dollars)” (Fox 262). 180 m³ converts to 6,357 ft³. This means that the cost per ft³ for this sediment pond was roughly $2.52 per ft³. Cost efficiencies were calculated for both methods. It was noted that sediment basins have a few advantages over the LDDs. One is that sediment basins can always be emptied, or dredged, and continue to be used in removing sediments. Also, sediment basins trap more sediment than LDDs. In conclusion, it was stated that compared with the LDDs a sediment basin was a more expensive method, but more efficient in trapping sediments.
Edwards et al. (1999) studied the efficiencies of N, P and sediment removal via sediment ponds. Simulated runoff with sediment, N, and P, was passed through an experimental sedimentation basin. Six runoff events were tested for each of two treatments: one-day and three-day detention times. Runoff concentrations were monitored for TSS (total suspended sediment) and different forms of N and P. For all tests, an average of 94% of the sediment, 76% of the N, and 52% of the P was retained by the sediment pond. It was observed that the three-day detention time scenario retained a lot more sediment than the one-day.
2.2 MAUMEE BAY STATE PARK SEDIMENT POND

A sediment pond was constructed at Maumee Bay State Park (MBSP). This sediment pond information was obtained by an EPA grant proposal by the University of Toledo, in 2012. The 1-acre sediment pond, on 3.5 acres of available land, was completed in July of 2014. For an engineering firm to produce designs and to hire construction contractors, it was estimated to cost $250,000. However, this estimate was a bit higher than the actual cost of $180,000. This means that the sediment pond cost roughly $51,000 per acre, based on the actual cost of $180,000. The sediment pond was constructed on public land, so there were no land costs.

Maintenance costs for the sediment pond include dredging the pond when it can no longer retain any further sediments. Also, transportation costs to transport the dredged sediment away from the sediment pond is also a factor to consider. (University of Toledo USEPA Grant Proposal. “Reduction of Sediment and Bacteria Loadings to Public Beaches at Maumee Bay State Park via Enhanced Riparian Habitat”).

The sediment pond installed in the WCW reduces P by 20%, and TP reduction is estimated at 20-40% (Jackwood).

As stated, the sediment pond was $51,000 per acre ($180,000 for 3.5 acres). But, general sediment pond costs can be calculated another way; as dollars per cubic feet of storage (see Chapter 4 of EPA’s 1993 study, “Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters.” in the Literature Review section of this paper). The sediment pond at MBSP has 150,000 cubic feet of storage (10 ft deep x 300 ft length x 50 ft. wide). It is important to note that storage capacity depends on depth, length, width of pond, which can vary.
Using the $180,000 total cost and the 150,000 cubic feet of storage, the cost per cubic foot of storage was calculated to be $1.20 per cubic foot of storage. This number in general falls within the total range cited in Chapter 4 of the EPA’s 1993 study, “Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters.” The total range was $0.10 to $1.30 per cubic foot of storage; for basins greater than and less than 50,000 ft$^3$ storage.

The subsurface flow wetland and sedimentation pond are on the high end of the cost range found in the literature. As experience is gained and many more wetlands and sedimentation ponds are built in the MRW, it is expected the costs will decrease in-line with the literature reviewed here. In particular, most wetlands will not need pumps, etc., and will not have the additional remediation task of reducing *E. coli* bacteria.

Fig. 1: Maumee Bay State Park Sediment Pond

Photo 1: Maumee Bay State Park Sediment Pond

(Courtesy of Dr. Daryl Dwyer and the Dept. of Environmental Sciences, University of Toledo)
2.3 METHODOLOGY

This MBSP sediment pond data is one of the many references used to conduct the analysis for the sediment pond treatment systems, with most of the cost estimates coming from the other papers reviewed in the previous section.

Maintenance costs over the lifetime of the sediment pond systems were considered, as well as variation in the lifespan of each system. Here, I assumed a 20-year lifespan. In other words, each system lasts 20 years before any maintenance costs are required. I also calculated a 25-year lifespan as well, for the sensitivity analysis. Maintenance costs for the sediment ponds was 25% of the total construction cost (US EPA, Chapter 4: Management Measures for Urban Areas 4.78). For sediment ponds, I used a 20% to 40% P reduction, in terms of effectiveness. Variation in the amount of flow (in cubic feet per second) treated is also included. For the sediment pond, a range between 8 cfs and 10 cfs per acre (Jackwood).

In order to have a “cfs” comparison, in terms of the amount of flow/ discharge coming down the Maumee River, I used the data from the Ohio Lake Erie Phosphorus Task Force II (see Appendix for table). I converted the discharge in m³/year (in millions) into cubic feet per second. So the mean discharge is 6,266 m³/yr. (millions) coming down the Maumee River (100% of flow). This number is calculated to be 7,012 cubic feet per second, for 100% of the flow in the Maumee River. This 7,012 cubic feet per second was used as a constant for all systems. Of course, is it not very feasible to treat 100% of the Maumee River flow in one single treatment system. Therefore, assumptions were made in the variations of percentages of flow that each type of system can treat, explained in the next paragraph.
Variation in the percentage of flow treated was also accounted for. The amount of flow treated is a function of the systems’ P reduction. This percentage of flow varies, based on the TP reduction within the system. Variations in both of these were considered.

Present Value calculations of the systems’ total cost was calculated. This formula is the addition of PV of construction cost, plus O&M costs. To “de-annualize” the O&M costs for each system, an annuity formula was used. The formula included each lifespan of 20 and 25 years, and a range of discount rates. A range of 2% to 4% was used regarding the discount rate. According to Boardman et al. (2011), a range of discount rates should be used for the sensitivity analysis in a cost-effectiveness analysis. These Present Value (PV) numbers were then multiplied by the number of cubic feet needed throughout the MRW (via the assumed amount of cfs per acre each system can treat); to get a total one-time cost for reducing TP by 10% across the watershed. These total cost numbers for the whole watershed were then divided by the 263,000 Kg removed (assuming a 10% TP reduction across the watershed) to get dollars per Kg removed for the whole watershed, for installing sediment ponds.

It is important to note how the ‘total cost throughout the watershed’ calculations for sediment ponds was derived. For the sediment pond, it was a cost per cubic foot of storage that the pond has. For simplicity, I assumed that all sediment ponds were 10 feet deep, like the one in Maumee Bay State Park that was constructed. I converted one acre into terms of square feet (43,560 ft²) and multiplied that number by the 10-foot depth assumed. This means that a one-acre sediment pond has 435,600 cubic feet of storage. This variable was a constant throughout the analysis, assuming all ponds were 10 feet deep. The number of acres needed was calculated for the whole watershed, via the amount of cfs per acre that the system can treat. This was used to derive the total number of cubic feet of storage that would be needed throughout the MRW.
The cost per cubic foot of storage was then multiplied by this number to get a total cost for a 10% TP reduction throughout the watershed.

The sensitivity analysis including all calculations and assumptions was done in an Excel spreadsheet, over 350 draws. The Excel sheets are available upon request. A breakdown of these assumptions and calculations is in the next section. The numbers provided in the following result section’s tables are rounded.
2.3.1 CALCULATIONS: ASSUMPTIONS & EXCEL WORK

Sediment Pond Excel assumptions:

a. MRW Discharge (ft³/Sec) for treating mean flow (average flow of 7,012 cfs between 2007 and 2012 -constant) (Ohio Lake Erie Phosphorus Task Force II)

b. Range of Construction Costs: $0.10 to $0.50 per cubic foot of storage (US EPA, Chapter 4: Management Measures for Urban Areas)

c. O&M cost: 25% of construction cost range (US EPA, Chapter 4: Management Measures for Urban Areas)

d. Percentage of flow treated: depends on P reduction effectiveness

e. Total Discharge treated (ft³/Sec) based off of percentage of Flow treated

f. Range of flow (cf/s): 8cfs-10cfs per acre (Jackwood)

g. Range of P reduction effectiveness: 20%-40% (Jackwood)

h. Discount rate 2, 3, and 4% variations (Boardman et al.)

i. PV Total Construction Cost (same as letter b.)

j. PV O&M calculated using an Annuity Formula (Boardman et al.)

k. PV Total Cost (PV construction cost + PV O&M cost)

l. Acres Needed via range of cfs treated per acre

m. Cubic feet of storage per one acre assuming all ponds are 10ft deep (constant)

n. Total cubic feet of storage throughout MRW via acres needed

o. Total Cost for a 10% TP reduction across the MRW

p. Cost per tonne of P removed for a 10% TP reduction in the whole watershed (263 tonnes removed)

q. Cost per Kg of P removed (263,000 Kg removed in order to reduce TP by 10%)
## 2.4 RESULTS

Table 1: 20 Year Lifespan Excel Summary Statistics for Sediment Ponds

<table>
<thead>
<tr>
<th></th>
<th>Sediment Pond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic Feet Needed for the whole MRW</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>119 mill cf</td>
</tr>
<tr>
<td>Median</td>
<td>113 mill cf</td>
</tr>
<tr>
<td>Min</td>
<td>76 mill cf</td>
</tr>
<tr>
<td>Max</td>
<td>191 mill cf</td>
</tr>
<tr>
<td>St. Dev</td>
<td>27.8 mill</td>
</tr>
<tr>
<td>Total Cost for a 10% TP Reduction throughout the whole MRW</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>$172 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$168 mill</td>
</tr>
<tr>
<td>Min</td>
<td>$34 mill</td>
</tr>
<tr>
<td>Max</td>
<td>$450 mill</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$89.7 mill</td>
</tr>
<tr>
<td>Total cost throughout the MRW per kg P removed</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>$657</td>
</tr>
<tr>
<td>Median</td>
<td>$625</td>
</tr>
<tr>
<td>Min</td>
<td>$142</td>
</tr>
<tr>
<td>Max</td>
<td>$1,847</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$338</td>
</tr>
</tbody>
</table>
2.5 SENSITIVITY ANALYSIS

Table 2: 25 Year Lifespan Excel Summary Statistics for Sediment Ponds

<table>
<thead>
<tr>
<th></th>
<th>Sediment Pond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic Feet Needed for the whole MRW</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>117 mill cf</td>
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<tr>
<td>Median</td>
<td>113 mill cf</td>
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<tr>
<td>Min</td>
<td>76 mill cf</td>
</tr>
<tr>
<td>Max</td>
<td>191 mill cf</td>
</tr>
<tr>
<td>St. Dev</td>
<td>24.9 mill</td>
</tr>
<tr>
<td>Total Cost for a 10% TP Reduction throughout the whole MRW</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>$190 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$181 mill</td>
</tr>
<tr>
<td>Min</td>
<td>$43 mill</td>
</tr>
<tr>
<td>Max</td>
<td>$454 mill</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$100.4 mill</td>
</tr>
<tr>
<td>Total cost throughout the MRW per kg P removed</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>$722</td>
</tr>
<tr>
<td>Median</td>
<td>$691</td>
</tr>
<tr>
<td>Min</td>
<td>$142</td>
</tr>
<tr>
<td>Max</td>
<td>$1,850</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$362</td>
</tr>
</tbody>
</table>
2.6 DISCUSSION

These results represent if sediment ponds were the only solution installed in the MRW, to reach a 10% P reduction. As we can see, with a 20-year lifespan, sediment ponds have an average total cost of $172 million, for a 10% P reduction in the watershed. With the 25-year lifespan, the average total cost of a 10% P reduction is raised to $190 million. The average cost per Kg of P removed if sediment ponds were implemented watershed-wide, with a 20-year life, was $657; and $722 with a 25-year life. With a 25-year lifespan, however, the total cost and cost per kg dollar amounts should be smaller than the 20-year lifespan numbers. In other words, adding five years on to the lifespan of the sediment ponds should make them more cost-effective. In this case, it is important to note that there are numerous random variables generated, or ranges used, skewing the results.

The average number of acres needed across the watershed was roughly the same between the lifespans, at approximately 271 acres. Future research is needed on where to physically install sediments ponds in the MRW. A SWAT (Soil and Water Assessment Tool) model would be beneficial since it could identify the areas of high sediment. Sediment ponds could, therefore, with this modeling, be installed in sediment ‘hot spots’, and this would render them more cost-effective in P removal.

However, in the overall conclusion section (Chapter 6), I will conclude that sediment ponds are not cost-effective for P removal, compared to the other solutions in this paper.
CHAPTER 3: WETLANDS

INTRODUCTION

In my research, I came across several excellent sources involving P reduction in constructed wetland systems and their various costs. Importantly, many of these sources have found Constructed Wetlands to be cost-effective solutions in reducing nutrients, compared to other measures.

3.1 LITERATURE REVIEW

3.1.1 CONSTRUCTED WETLANDS IN GENERAL

According to the EPA’s (1999) study, titled “Preliminary Data Summary of Urban Stormwater Best Management Practices,” the standard unit cost (dollars per cubic foot of treated water volume) for a Constructed Wetland ranged from $0.60-$1.25/cf (in 1997 dollars). This interval was a typical base capital construction cost for a CW. The base capital cost for typical application of a CW was $125,000 (in 1997 dollars with a 3% inflation rate) for a 50-acre residential site, with 35% impervious cover. This was not including land costs. The study then talks about design, contingency and permitting costs, which are usually described as a percentage of the construction cost. 32% of the total costs covered design, contingencies, permitting process and erosion and sediment control. O & M costs, again, are usually described as percentages of the base construction cost. Annual maintenance costs for Constructed Wetlands were listed as 2% of the construction cost, since CWs do not require a lot of maintenance.

Weiss et al. (2007) conducted a cost-effectiveness analysis on six BMPs and their abilities to remove TSS and TP from Urban rainfall runoff. Annual O and M costs were
calculated for all six of the BMPs, one of which was constructed wetlands, in general. The other BMPs were dry extended detention basins, wet/retention basins, infiltration trenches, bioretention systems and sand filtration. These were then converted to present value based on a 20-year lifespan and then added to the initial construction costs. The study calculated the present O and M costs with a 67% confidence interval, to be a function of water quality volume. The annual O and M costs were presented as percentages of the total construction cost. The study lists constructed wetlands’ O and M costs as 2% of total construction costs. Also listed are various other sources of collected data, estimating annual O and M costs as 4-14.1% of total construction costs. TP removal for a stormwater wetland was stated to be 42%. (This is shown in Table 4 on page 226 of the study). The quantity of TSS and TP removed over the 20-year life span were also calculated as functions of water quality volume. The study showed that, from the six BMPs investigated, constructed wetlands were the least expensive to build and maintain. It is important to note that this study assumes appropriate land is available, which may not be the case in every situation.

A study by Trepel (2010), titled "Assessing The Cost-Effectiveness Of The Water Purification Function Of Wetlands For Environmental Planning" focuses on reducing nitrogen inputs from nonpoint sources in Northern Germany. The effects of improved wastewater treatment on nutrient load reduction are compared to the effects of wetland restoration on improved nitrogen retention (peatlands are the dominant wetland type). Phosphorous inputs from point sources were reduced by nearly two-thirds compared to the previous five-year period: 1980-1985. This improvement was due to a 2.1 billion € investment in improving wastewater treatment plants, since 1985. However, nitrogen inputs from nonpoint sources were little
improved. “Because the measures implemented affected the nitrogen and phosphorus load from point source differently, the cost-effectiveness is calculated for three cost allocation strategies.” (Trepel 321). The first strategy assumes that the costs were used either for N or P reduction only. The second strategy assumes that 67% of the costs were spent on P reduction and 33% on nitrogen reduction. This makes sense because wastewater treatment plants reduced phosphorous more than nitrogen. The third strategy assumes that costs were used equally for reduction of N and P loads from point sources. It became apparent that Germany needed to do more, to improve its water quality. So, in 2002, the state developed a peatland action plan, “to rehabilitate the water purification function provided by this wetland type.” “For quantification of the effect of different water management and land use scenarios on nitrogen retention, the web-based, flow-path-oriented decision support system (DSS) WETTRANS was developed.” (Trepel 322). The cost-effectiveness of the planned peatland projects is calculated from the difference in nitrogen output obtained from a scenario analysis, where the present situation is compared with a future scenario. The project costs include the land cost as well as an additional 15% of project management costs. The additional 15% cover costs for hydrological planning and consultancy as well as the rewetting measures. As for the wastewater action plan, the costs for the reduction of 1 kg N vary between 10 and 65€ (between roughly $11 and $72). The reduction of 1 kg of P range between 71 and 146€ (between $79 and $163). The high variation in the cost-effectiveness was caused by different “hydromorphological constraints” of the North Sea and Baltic Sea drainage basin in this area of Germany, and by the three different cost allocation strategies, mentioned. Nitrogen retention and their cost-effectiveness were calculated for 34 potential peatland restoration project sites. With a lifespan of 10 years, the cost-effectiveness for a reduction of 1 kg of nitrogen varies between 1 and >50€. This variation is due to the different present conditions of
the wetlands, which determine their potential load reductions. It was stated that compared to measures taken during the waste water action plan, wetland restoration is a cost-effective strategy for reducing nitrogen loads. The study goes further, stating that with 10% of the budget spent on the wastewater treatment plan (210 million €) 20,000 ha of rewetted wetlands could be constructed, and reduce nitrogen loadings by 10%. However, in order for this to become a reality, more funding and political support are needed.

A study by Gren et al. (1997) looked at cost-effective nutrient reductions to the Baltic Sea. This source discussed nutrient reduction strategies for the nine countries that surround the Baltic Sea. P and N loads must be reduced by 50%, in order to restore the area’s water quality; suffering from eutrophication. The nutrient loads to the Baltic Sea can be decreased by three classes of measures, according to the study: “measures reducing the nutrient emissions from sources with deposition on the Baltic Sea and on land within the drainage basin which is transported by water streams, which we denote by \( M_r \) where \( r = 1, \ldots, f \) different deposition measures” (Gren et al. 343) (i.e. runoff; reductions in agricultural deposition of fertilizers and manure), land use measures (i.e. reducing leaching; planting cover crops), and retention measures (i.e. wetlands and buffer zones; restorations of wetlands). Under the first class of measures, the study distinguishes between reductions in loadings from air emissions, manure, fertilizer, etc. It is assumed that there is merely “one measure for reducing nutrient deposition from each type of emission source.” (Gren et al. 343). The model is then described; nutrient retention measures are assumed to be on the coast of the Baltic Sea, to achieve the high reduction target in a cost-effective way. The study explains that a one-unit reduction in the nutrient emission from a sewage treatment plant located on the coast implies one-unit reduction in the
load to the Baltic Sea. However, a “one-unit emission reduction from a plant located upstream generates a load reduction of less than one unit. Thus, the cost of a marginal reduction in the nutrient load to the Baltic Sea is lower for a measure located at the coast than if the same measure is implemented upstream in the drainage basin.” (Gren et al. 346). It is stated that a measure which reduces both N and P loads will be used more than a measure that just reduces one of the two nutrients. Land use changes and changes in manure deposition would reduce both N and P. “Cost effective nutrient reductions are determined by the costs of potential nutrient reduction measures and their impacts on the nutrient loads to the Baltic Sea. The impacts are functions of nutrient transports, leaching, and retention.” (Gren et al. 347). Different sources were used to estimate/calculate N and P loadings for all areas around the Baltic Sea. “The total calculated anthropogenic loads of nutrients amount to 728,000 tons of N per year, and approximately 37,000 tons of P per year.” (Gren et al. 349). However, taking into account the other sources (for example, background leaching from outside the drainage basin, or air emissions from other countries) the calculated tons of N per year is then 1,000,000. The study states, however, that there is much uncertainty in their estimates. The agricultural sector accounts for a little more than ½ of the total load of N, and 1/3 of the total load of P. Also, sewage from households and industries was found to be a major source of both nutrient loadings into the Sea; accounting for 2/3 of total N loadings, and 1/3 of total P loadings. It was found that Poland had the highest nutrient loadings of all the nine countries surrounding the Baltic Sea; Germany was also high. From these results, it is expected that a reduction in N and P loadings from agricultural sources, as well as sewage systems, would play “an important role for cost-effective nutrient reductions.” The costs of marginal nutrient reductions from each of the three measures are then calculated/estimated. Rough estimates were calculated, and it was determined that nutrients from
sewage leaks could be reduced by 60% on average, based on population allocation. The study states that “Except for changes in spreading time of manure, the costs of land use measures are calculated as the difference in profits between the land use measure and the most profitable alternative land use.” (Gren et al. 352). It also states that the cost of this time change in manure spreading would just be the amount of money it takes to store the manure for six months. Based on field experiments, leaching is assumed to be reduced by 0.2-0.5, depending on the nutrient and region around the Sea. Also, based on studies involving wetlands; it has been assumed that the wetland N and P retention vary between 0.1-0.5, depending again on the location. The study points out that these wetlands are considered restored; not built on land where, previously, there was not a wetland. Out of all the possible nutrient solutions, it was found that an increase in a Sewage Treatment Plant’s nutrient cleaning capacity was the least cost. Also, it was found that the wetland restoration was another ‘cheap’ measure (in reducing both N and P loadings). It was found that the minimum cost of a reduction in N loadings was higher than those of P. At 50% reduction levels, N reduction costs are five times greater than P reduction costs. The study explains that most of the sewage plants, etc. that emit P, are along the coast of the Baltic Sea, making it less costly to reduce the P loadings. At the targeted 50% reduction, the annual minimum costs for N and P are 12,000 millions SEK and 3,000 millions of SEK respectively. It is noted that simultaneous reduction in N and P are less costly than reducing each nutrient loadings separately. Also, the study states that as the percentage reduction of both N and P increases, the costs of reducing said loadings increase as well; with N reduction costs soaring above the reduction costs of P at 40% and above. A full sensitivity analysis is then presented since there were many assumptions. Also included, in this section, is an example of how costs considerably increase if the cost-effective scenario is changed to a policy where each country has
to reduce its nutrient loadings by the same percentage. This scenario was found to be very inefficient; increasing the costs of both N and P by about four times. In conclusion, it is noted that the countries with the highest N and P discharges, such as Poland, would have to account for a larger share of that 50% reduction target; meaning that Poland would have to reduce their N and P loadings more than the other countries that surround the Baltic Sea.

More recently, wetlands were restored in the Everglades located in Florida. The South Florida Water Management District (SFWMD) gives some details about the project. Since 1994, the State of Florida has invested greater than $1.8 billion toward reducing P levels in Everglades-bound waters through nutrient source controls and construction projects. Farming BMPs and Stormwater Treatment Areas (STAs) were implemented to remove P. It was stated that five Everglades STAs are currently operational with an effective treatment area of 57,000 acres, including 12,000 acres completed in 2012. In “Water Year” 2014, the constructed wetlands treated more than 1.3 million acre-feet of water and reduced P loads by 81%. As of January 2015 when this document was published, “the STAs have treated more than 14.7 million acre-feet of water and have retained approximately 1,874 metric tons of phosphorus.” (South Florida Water Management District). Also as of January, the BMPs and STAs together have prevented roughly 4,582 metric tons of P from entering the Everglades.

Milano (1999) details restoration of the Biscayne Bay area, one of the restoration projects that the SFWMD’s partially funded. According to the study, in the first decade of implementing of the Biscayne Bay Restoration and Enhancement Program, the Miami-Dade Department of Environmental Resources Management has restored and enhanced approximately 300 (121.5
hectares) acres of wetlands. Ten different sites were restored; four of which were either partly or entirely funded by the SFWMD. Site 1, the Bear Cut Preserve Wetlands Restoration, is 21.5 acres and was completed November 1996. This site is located at the north end of Key Biscayne. The Scope of the Restoration project included: Clearing and removing exotic vegetation; selective clearing of 4 acres; excavating 41,600 cubic yards of dredge spoil material; planting 10 acres of mangroves; 6.2 acres of high salt marsh; 2.8 acre tidally flushed pond; installing 0.5 acre fresh/brackish water pond; a network of inter-tidal flushing creeks. The total cost was $800,000, or a $37,209 per acre cost.

The second site, the Bill Baggs Cape Florida State Park Wetlands Restoration, is 85 acres and completed in April 1999. This site is located on the south end of Key Biscayne. The Scope of Restoration included: clearing exotic vegetation; removing 30,000 cubic yards of solid waste; removing 600,000 cubic yards of dredge spoil material; creating 75 acres of tidally connected mangrove wetlands; installing 3 flushing connections and culvert connection; installing a network of inter-tidal flushing creeks, and creating 10 acres of freshwater wetlands. The total cost was $2.8 million, or a $33,000 per acre cost.

Site 3 is the Florida International University Bay Vista Campus Wetlands Restoration, with a size of 2 acres, completed at the end of 1995. This site is located in North Miami. The Scope of the Restoration project included: selective clearing and removing exotic vegetation; transplanting 65 desirable native trees; installing four inter-tidal flushing channels excavating and removing 10,000 cubic yards of dredge spoil, and planting 2 acres of Rhizophora mangle on 3 feet centers. The total Cost was $140,000 ($70,000 per acre).

Site 4 is the Virginia Key Dune/Wetlands Restoration, completed at the end of 1999 with a size of 5 acres. This site is also located in North Miami. The Scope of Restoration included:
clearing exotic vegetation; excavating and removing 13,000 cubic yards of fill material; planting
2 acres of dune community; planting 4 acres of wetlands; and installing one major flushing
channel, culvert, and a connecting intertidal creek. The total Cost of this site was $180,000
($36,000 per acre).

Site 5 is the National Bulk Carrier Site Phase 1 Enhancement, completed in June 1994
with a size of 140 acres. This site is located in south Miami-Dade County. The Scope of
Restoration included: doing a detailed topographic survey; mapping and existing plant
communities and soils; and removing exotic vegetation. The total Cost of this site was $300,000
or roughly $2,143 per acre.

The sixth site mentioned is the Oleta River State Park Wetlands Restoration, with 13
acres, completed in 1990. This site is located in Miami, Florida. The Scope of Restoration
included: clearing and mulching of exotic vegetation; excavating 55,000 cubic yards of Intra-
Coastal Waterway dredge spoil material; planting 13 acres of *Rhizophora mangle* on 3 feet
centers and installing a network of intertidal creeks. The total Cost of this site was $300,000
($23,076 per acre).

Site 7 is the second part of site 6; Oleta River State Park Wetlands Restoration. The Size
of this site is 45 acres and has yet to be completed. The Scope of Restoration includes: clearing
and removal of exotic vegetation; removing all on-site solid waste remaining from remnant
marina; excavating of 58,000 cubic yards of dredge-fill material; filling a L-shaped canal with
167,000 cubic yards of clean fill; installing a network of intertidal creeks; and planting 28.5 acres
of tidally connected *Rhizophora mangle* forest. The Approximate Cost for this site was estimated
at $1.5 million or an estimate of $33,333 per acre.
Site 8 is the Oleta River State Park Mangrove Enhancement, with a size of 1900 L.F. (roughly 2.3 acres), this site was completed in 1990 and is located in North Miami, Florida. The Scope of Restoration included: stabilizing 1,900 linear feet of eroding mature Rhizophora mangle forest with natural lime-rock boulders and filter fabric, and installing a network of intertidal creeks. The total Cost of this site was $430,000 (or roughly $186,957 per acre).

Site 9 is the Highland Oaks Wetlands Restoration project, with a size of 13 acres and has yet to be completed. This site is located in Miami-Dade County, Florida. The Scope of Restoration includes selective removing 8.2 acres of exotic vegetation; planting 3 acres of littoral shelf native vegetation; planting 3.0 acres of forested freshwater wetland; planting 8.2-acres of vegetation; and re-establishing 250 feet of historical riverbed of the Oleta River. A cost estimate was given at $260,000 (an estimate of $20,000 per acre).

And finally, Site 10 is the Chicken Key Bird Rookery Restoration, with a size of 7 acres and completion date of March 1997. This site is located in the south Biscayne Bay Miami-Dade, Florida. The Scope of Restoration included: clearing and removing 4 acres of exotic vegetation; excavating 33,000 cubic yards of dredge spoil (Spoil sold by contractor reducing restoration cost); restoring 1,200 LF of dunes; planting 150 LF of experimental mangrove in PVC encased tubes; planting 3.7 acres of red mangroves on 3 foot centers; installing 3 flushing channels (8’-15’ wide); and installing a network of tidal creeks (900 LF). The total cost of this site was $600,000 or $85,714 per acre.

Over all ten sites, the minimum cost per acre was site 5, with $2,143 per acre. The maximum cost per acre was site 8, with $186,957. The mean cost per acre was calculated to be $52,737.30. However, it is important to note that a lot of the sites’ constructions entailed dredging and/or plant removal or reestablishment, which drives up the cost per acre of
construction. For example, site 9 did not include any dredging of material and was the next lowest construction cost per acre ($20,000 per acre; second to site 5, which also did not have any dredging costs).

Closer to home, there have been numerous GLRI grants in recent years to restore wetlands around Lake Erie. According to the Great Lakes Coalition website, 171 acres of wetlands were restored in Oak Harbor, at the cost of $1.3 million (a cost of roughly $7,600 per acre). The 171-acre Blausey Tract is one area at the Ottawa National Wildlife Refuge where farmland is being transformed into wetland habitat. The project is working on restoring the natural flow of water through the wetlands and into Lake Erie tributaries. This project was completed late in 2013, providing more habitat for fish and wildlife and improving water quality in nearby Lake Erie tributaries. ("Coastal Wetlands Restored Along Lake Erie.").
3.1.2 BACKGROUND INFORMATION ON DIFFERENT TYPES OF WETLANDS
BOTH SURFACE FLOW AND SUBSURFACE FLOW

Jan Vymazal’s (2010) study, titled “Constructed Wetlands for Wastewater Treatment” gives detailed information about the various types of wetlands used. Vymazal states that the classification of wetlands is based on vegetation type and hydrology. There are free water surface (FWS) and subsurface flow; which can be further classified according to flow direction (vertical or horizontal). Also, various types of constructed wetlands could be combined into hybrid systems, to achieve better treatment performance. In the picture below (Fig. 2), under the “Emergent” type of vegetation, would be the surface flow (water level above the surface) and subsurface flow (water level below the surface). Within the surface flow system, the direction can only be horizontal; Horizontal Surface Flow, or a FWS wetland. However, within the subsurface flow system category, the direction of flow could be either horizontal or vertical; Horizontal Subsurface Flow or Vertical Subsurface Flow.

Fig 2: Wetland Classifications

(Vymazal, “Constructed Wetlands for Wastewater Treatment” 531)
Each type of wetland system was discussed, along with its percentage of P reduction. First, FWS wetlands were discussed. The source stated that they are “efficient in removal of organics through microbial degradation and settling of colloidal particles. Suspended solids are effectively removed via settling and filtration through the dense vegetation... Phosphorus retention is usually low because of limited contact of water with soil particles which adsorb and/or precipitate phosphorus.” (Vymazal, “Constructed Wetlands for Wastewater Treatment” 532). It is also stated that besides municipal wastewater, FWS wetlands with emergent vegetation have been used to treat various types of wastewaters, and that sizing is done based on either volume or area.

Horizontal Subsurface Flow Wetlands are then discussed. It describes a Horizontal Subsurface Flow wetland as one that consists of gravel or rock beds sealed by a layer (either natural or not) of an impermeable material and then planted with wetland vegetation. “The wastewater is fed at the inlet and flows through the porous medium under the surface of the bed in a horizontal path until it reaches the outlet zone, where it is collected and discharged.” (Vymazal, “Constructed Wetlands for Wastewater Treatment” 534). The source states that unless special materials are used to increase P retention, then the removal of P is usually low in Horizontal Subsurface Flow systems.

Finally, Vertical Subsurface Flow systems were detailed. In this type of wetland, the water percolates downward through a media, usually sand. Water is given in batches; all of the water goes through the system before a new batch of water is added. Again, it is stated that unless a special material is used, P removal is small. The source also reported that, compared to both Horizontal Flow systems, Vertical flow systems require less land.
Efficiencies were then given for each different type of wetland, in removing various nutrients, etc. Free-Water Surface wetlands reduced TP by a range of 34% to 50%; Horizontal Subsurface Flow Wetlands reduce TP by 50%, and Vertical Flow wetlands reduce TP by 56%.

Costs for each type of wetland were then identified. It was noted that the capital costs for a Free-Water Surface flow wetland are usually less than the capital costs for Subsurface Flow systems. Also, all of the wetlands have very low operation and maintenance costs compared to conventional treatment systems.

Another study by Vymazal (2007), titled “Removal of Nutrients in Various Types of Constructed Wetlands.” also contains a chart to detail the different types of wetland systems (Fig. 3).

Fig 3: Wetlands Flow Chart Classification

(Vymazal, “Removal Of Nutrients In Various Types Of Constructed Wetlands” 49)
The source states that soluble reactive P is taken up by plants or may become sorbed to wetland soils and sediments. Also, that P transformations in wetlands are peat/soil accretion, adsorption/desorption, precipitation/dissolution, plant/microbial uptake, fragmentation and leaching, mineralization and burial. All these components were considered when evaluating the wetlands’ effectiveness at removing P; however, soil accretion only occurs in FWS wetlands. FWS or Surface Flow systems reduce TP by 48.8%; Horizontal Subsurface Flow Wetlands (HSSF) reduce TP by 41.1%, and Vertical Subsurface Flow Wetlands (VSSF) reduce TP by 59.5%. In conclusion, the source states that the removal of TP varied between 40 and 60% for all types of constructed wetlands “with removed load ranging between 45 and 75 g Nm^{-2} yr^{-1} depending on CWs type and inflow loading.” (Vymazal, “Removal Of Nutrients In Various Types Of Constructed Wetlands” 63).

Chapter 7 of the EPA’s (1999) study, titled “Manual: Constructed Wetlands Treatment of Municipal Wastewaters,” details the various costs incurred with a constructed wetland. Items included in the capital costs are land costs, site investigation, excavation, liner, media, plants, inlet and outlet structures, fencing, misc. piping/pumps, engineering, legal, contingencies, contractor fees. The cost data was obtained from nine different wetland systems around the U.S.: five VSBs (vegetative submerged beds) and four FWS (free water surface) wetlands. FWS wetlands are also known as Surface Flow wetlands. The source states there is some evidence of economies of scale, in terms of cost per acre of the constructed wetlands. The construction costs for FWS wetlands could potentially range from $34,600 per ha to $237,200 per ha ($14,000 to $96,000 per acre). In the table presented in this manual, however, the per acre cost was a range between $14,000 and $36,000 roughly. The cost per acre, of course, is site specific, depending
on the size of the system, the number of cells and berms, if a liner was installed, etc. Additional costs include site investigation and engineering design, pre/post treatment components, and land costs if applicable. If clearing and grubbing cost need to be incurred, this can range from $4,940 to $12,355 per ha. Excavation and earthwork are also factors, and piping or other structures may be needed. Miscellaneous costs included engineering design, legal fees, construction contingencies, and profit and overhead for the construction contractor; expressed as percentages of the total construction costs. Operation and Maintenance Cost were listed next. The O&M Costs of constructed wetland systems are relatively simple and require minimal time. Animal control, mosquito control, and NPDES monitoring are the most time-consuming aspects of wetland O&M (if necessary). Crites and Ogden (1998) listed Operating Costs for a FWS wetland to range from $0.10 to $0.30 per 1,000 gallons of treated water.

Chapter 8 of this source, contains specific case studies of constructed wetlands. A 7.4-acre wetland built in Arcata, CA had a construction cost of $30,000 per acre, with no liner, berm, or land expenses incurred. Similarly, roughly a 50-acre wetland in Mississippi was constructed with no liner nor land cost, but with a berm cost; at the cost of $14,000 per acre. A 22.2-acre wetland in Gustine, CA, was constructed at the cost of $36,750 per acre; with no land nor liner cost, but with a berm cost. As stated, there is some evidence of economies of scale with the Mississippi wetland compare to the other sites, as we can see from the size and cost per acre differences. (US EPA. "Chapter 7: Capital and Recurring Costs of Constructed Wetlands.")
3.1.3 SURFACE FLOW WETLANDS

A Free-water Surface (FWS) Wetland (or Surface Flow wetland) consists of channels or basins, sometimes with a natural or synthetic liner to prevent leakage. In a FWS constructed wetland, the emergent vegetation is flooded to a specific depth. These wetlands can most effectively be used “as tertiary treatment after secondary treatment facilities.” Phosphorous will be removed during start-up through adsorption, and also through plant uptake. Plant uptake of P during the growing season is rapid, but the nutrient is released back into the water when the plant dies. However, the plants could be maintained or harvested as soon as their uptake starts to diminish in order to prevent the wetland from becoming a source of P. The sources states that there is a wide variation of cost for these systems owing to a lack of design uniformity. “The total capital cost of a FWS constructed wetland will include earthwork, pipe installation, liner, seeding and overflow tank installation. Permitting and operation and maintenance costs must also be considered.” (“Constructed Wetland Systems”).

In a study led by Mannino et al. (2008), a cost-effectiveness analysis was conducted to compare seminatural Free Water Surface (FWS) wetlands with traditional wastewater treatment plants (WWTP). The study stated that, compared to WWTPs, “a seminatural wetland involves low construction and maintenance costs over the long term, does not consume non-renewable energy, and does not produce sludge to be disposed.” (Mannino et al. 118). The data for the wetland was collected by observing a plant for three years, in Italy. The wetland is 50 m wide and 4.14 km long, with a depth of 80cm; divided into three subsystems. It was stated that this FWS wetland removed 43.82% of TP. The data was gathered into “development cost and maintenance cost categories to facilitate the comparison of operational phytodepuration [FWS
wetlands] and traditional wastewater-treatment plants.” (Mannino et al. 122). The study compared the service costs of three different FWS wetlands (with different incurred construction costs) with three different WWTPs (selected according to the type of sludge disposal) scenarios. WA, WB, and WC were broken down into Development Costs, Ordinary Maintenance Costs, and Extraordinary Maintenance Costs. Land costs were not considered in this study. The lifespan of all systems was set at 20 years, and a discount rate of 5% and also 10% were used. All maintenance costs were also based on the 20-year lifespan. Wetland A (WA) included plantation costs, the addition of soil and shaping of banks, plantation management care, and harvesting and regeneration costs. Wetland A had a 1,427,532.19 Euros ($1,593,768.31) for a total area of 51 acres. This converts to $31,250.36 per acre.

The results stated that FWS seminatural wetlands are “economically competitive with traditional technological plants for secondary wastewater treatment, given equal depurative effectiveness and independent of the discount rate.” (Mannino et al. 127). Independent of the discount rate, FWS wetlands were found always to have a lower service cost. The traditional WWTPs were found to be efficient in their construction but were not cost-effective in terms of service costs. It was found that developmental costs were significantly higher for FWS wetlands than for WWTPs, but Ordinary Maintenance Costs for the WWTPs were found to be greater than those for FWS wetlands. Disposal was one of the Ordinary Maintenance Costs, which is why the cost was so high for WWTPs; as wetlands do not produce any sludge. Energy consumption also played a role in the higher Maintenance Costs for the WWTPs; the wetlands have relatively low or zero energy consumption, while WWTPs have very high levels. These factors contributed to the overall costs of WWTPs being much higher than those of FWS wetlands. The study also notes that the extra benefits of wetlands make them more financially competitive.
Gachango, Pedersen, and Kjaergaard (2015) do a complete cost-effectiveness analysis for a Surface Flow wetland in Denmark. In this study, three Surface Flow Constructed Wetlands were analyzed. The first wetland (SFCW1) is 0.8 ha, the second (SFCW2) was 2.3 ha, and the third (SFCW3) was 0.8 ha. “Three general categories of costs have been considered in the implementation and use of SFCW: (1) the establishment costs, (2) annual and periodic operational and maintenance costs, and (3) the relevant opportunity costs.” (Gachango et al. 1480). The establishment costs include a consultancy fee, excavation costs, installation of pipes and pumps, and vegetation establishment. Given the low elevation of the three studied farms, the installations of drainage pipes and pumps were necessary. The study states that wetland vegetation establishment costs may be experienced in a situation where the processes need to be enhanced for monitoring purposes. O&M costs of the three wetlands mainly involve routine checks of the sites, pump operation, and maintenance. Finally, opportunity costs associated with the installations of the wetlands were considered. In this case, the opportunity costs were the forgone net revenue for putting the agricultural land out of production. In this study, the opportunity cost was the cost of renting land. This cost was calculated based on the size of the wetland and the net profit per acre. Present Values for all costs were calculated (Establishment costs, O&M costs, and Opportunity costs) and were added together to get the PV of total costs for each wetland. The establishment costs were considered one-time costs, while the O&M and the Opportunity costs were calculated as annual costs over the lifespan of the systems, using an annuity formula. The study used a lifespan of 20 years and a 3% discount rate. “The cost-effectiveness of each of the three Surface Flow CW was calculated by dividing each of the wetlands present value (PV) of the total costs, by the amount (kg) of nutrient removed at different efficiency levels over the economic life of the wetland.” (Gachango et al. 1481).
Across the three wetlands, the construction costs ranged from roughly $7,000 to $17,000 per acre. For these numbers, I only included consultancy fees and excavation costs. The other two; vegetation establishment and infrastructure, are not always needed when constructing wetlands.

The study also does a sensitivity analysis, changing the lifespan of the systems to 25 years. TP reduction was stated to range from 30% to 50% for all three wetlands. For the 20-year lifespan scenario, the cost of reducing 1 kg of P ranged between 55.03€ and 1148.46€/kg P retained (a range between $59.87 and $1,249.50 per kg P retained). Under the 25-year lifespan assumption, the cost of reducing 1 kg of P ranged between 47.12€ and 1043.53€/kg P retained (between $51.25 and $1,135.94 per kg P retained). It is stated that variations in the different wetland costs may result in increased cost-effectiveness. For example, if the wetland did not need pumps or vegetation installed, like the three wetlands studied.

Kadlec and Knight (1996) states that surface-flow wetlands cost between $10,000 and $100,000 per hectare ($4,049 to $40,486 per acre), with a median of $44,600 per hectare ($18,057 per acre), depending on system size. (724-725).

A 1991 article by S.C. Reed, titled “Constructed Wetlands for Wastewater Treatment” gave ranges of costs for each type of wetland (Surface and Subsurface Flow). For free water surface systems, based on data from 19 sites, the average cost was $22,200 per acre, with a maximum of $ 65,000/acre and a minimum as low as $2,071/acre. (Reed).
3.1.4 SUBSURFACE FLOW WETLANDS

Subsurface Flow vegetated bed systems consists of gravel or other media and emergent vegetation. “A Subsurface Flow system is normally a lined earthen pond about 2 feet deep filled with rock media. The rock-filled cells typically have vegetation in a top layer of finer rock.” The plants in an SF wetland system take up nutrients during the growing season, but nutrients may be returned to the system when the plants die, and the plant matter is not removed. Like in the FWS wetland, however, the wetland and its plants can be maintained. Phosphorous removal occurs just like in the FWS wetlands. The total capital cost of a subsurface flow wetland will include earthwork, pipe installation, liner, seeding, overflow tank installation, and washed rock media. (“ Constructed Wetland Systems”).

Collins and Gillies’s (2014) study titled "Constructed Wetland Treatment Of Nitrates: Removal Effectiveness And Cost Efficiency" examined the removal effectiveness and cost efficiency of a 0.2 acre Constructed Wetland (CW) in West Virginia, in reducing nitrogen from nitrate discharges into a surface stream. This CW was a Horizontal Subsurface Flow Wetland. The stream’s water quality was documented before and after the wetland installation to determine the reduction of nitrates. This study evaluates the ability of the CW to reduce stream concentrations of N and gives a cost per Kg N removed, based on streamflow and lifespan. The 0.2 acre CW had a total cost of $29,462 ($147,310 per acre), which included the wetlands design and installation oversight by Canaan Valley Institute; a company hired for the construction process. Also included were materials costs, landowner compensation, and installation bid. It is important to note that the $2,000 under landowner compensation would not be necessary if public land was available. Not included was the costs of ‘researchers’ and farmer involvement in
the decision-making process to site the wetland.” (Collins and Gillies 902). Farmer contribution of organic matter for the wetland was also not included. Annual O and M costs were assumed to be zero. This study also compares this CW cost to other studies, saying that $29,462 is on the lower side of CW costs.

The average N reduction during the growing season, at average flow, was calculated to be 0.14mg/l. This was a 17% reduction from samples previously taken in 2008, before the installation of the wetland. “A representative cost per kilogram of N was computed using the following assumptions: a 15 year CW lifespan with no maintenance costs, a 3% discount rate, and a mean reduction of 80kg of N annually from the low monthly flows base-flow computation.” (Collins and Gillies 904). The cost per Kg of reducing N was estimated at $30.85/kg in 2009 dollars, with a range of $21.65/kg to $60.19/kg. The study then compared this $30.85/kg cost to other forms of Nitrogen removal, such as WWTPs and N fertilizer reductions. Overall, the reduction in N fertilizer application was found to have the lowest cost (via literature review). However, it is unlikely that farmers will willingly reduce their fertilizer application, so the study states that the next best alternative would be a Constructed Wetland. “In summary, we can identify some advantages of a CW treatment system for reducing stream level nitrates: it treats a nitrogen source that alteration of surface land management does not reduce; it consists of only fixed costs which negate future rising per unit costs (as compared with fertilizer reduction BMP costs which rise with crop price increases), and its installation depends upon fewer, but more targeted farmer cooperation efforts....This system can only be cost competitive with other BMPs if it lasts for decades and abates load reductions at the high end of its statistically estimated range.” (Collins and Gillies 906).
Kadlec and Knight (1996) mentions that subsurface-flow constructed wetlands cost about eight times more than surface flow wetlands, mostly due to the cost of gravel fill. Several subsurface flow wetlands were found to have a median cost of $358,000 per hectare (roughly $144,939 per acre) (724-725).

A 1991 article by Reed, titled “Constructed Wetlands for Wastewater Treatment” gave ranges of costs for each general type of wetland (Surface and Subsurface Flow). Reed presented data from 18 subsurface flow wetlands in the U.S. in which the construction cost of one acre varied between $100,000 and $72,222, with a mean value of $87,218 (Reed).

Yu et al. (2015) found Horizontal Subsurface wetlands removed 72.84 and 74.13% of P, while vertical subsurface wetlands were slightly more effective, with a P removal rate of 84.76 and 81.3% (6).

Vymazal’s (2004) study, titled “Removal Of Phosphorus In Constructed Wetlands With Horizontal Sub-Surface Flow In The Czech Republic” stated that Mæehlum and Jenssen (1998) found horizontal subsurface flow wetlands removed as high as 77% TP from ten different systems in Norway (660).

And finally, Chung et al. (2008) found average TP removal efficiencies were between 54 and 68% (87) for subsurface planted wetlands.
3.2 MAUMEE BAY STATE PARK WETLAND

The MBSP wetland is a 3-acre Horizontal Subsurface Flow Wetland, on 9 acres of available land. It was completed in October of 2014. The wetland is located in the Wolf Creek Watershed (WCW), at Berger Ditch, which enters Lake Erie near Maumee Bay State Park. This wetland primarily serves to reduce the amount of E. Coli in the WCW, as well as reducing sediments and total P. This information was taken from an EPA GLRI Grant Proposal conducted by the University of Toledo in April of 2011. The construction cost for the wetland was estimated at $723,380 with post-construction costs of $30,000. This means that the Wetlands’ total construction cost was $753,380. This grant estimate was a bit higher than the actual cost of $735,000. Having a total area of 3 acres means that the MBSP Wetland cost roughly $245,000 per acre, based off of the actual $735,000 cost. There were no land costs for this wetland since it was constructed on public land. There has also been a pump installed at the wetland, however, it is not yet operational. Maintenance costs for the wetland would include replacing the pump when it no longer functions. (University of Toledo USEPA Grant Proposal. “Maumee AOC, Wolf Creek: Passive Treatment Wetland to Improve Nearshore Health and Reduce Nonpoint Source Pollution,” 2011).

The constructed wetland in the WCW reduces TP by 4.52 g/m²/yr., which is a 42% reduction in TP in the WCW. However, P inflow is much lower in the WCW than other watersheds like the Maumee.
Fig. 4: Maumee Bay State Park Wetland

Photo 2: Maumee Bay State Park Wetland

(Courtesy of Dr. Daryl Dwyer and the Dept. of Environmental Sciences, University of Toledo)
3.3 METHODOLOGY

In the following sections, a full BCA for each type of wetland was conducted, to better determine the net benefits of installing each type throughout the Maumee River Watershed.

The MBSP subsurface flow wetland data is one of the references used to conduct the analysis for the wetland treatment systems, along with the other sources studied in the literature review.

As Vymazal (2007) points out, the vertical subsurface flow is the most effective in reducing nutrients; more effective than horizontal subsurface flow and even surface flow wetlands. However, no data was available in terms of cost per acre for a vertical subsurface flow wetland. Therefore, vertical and horizontal subsurface flow wetlands were grouped under simply ‘subsurface flow wetlands’. This is a good topic for future research and is presented in the Future Research section at the end of this paper.

A range of per acre costs were determined for the different types of treatment systems, through literature. For the FWS or surface flow wetlands, the range assumed was $7,000-$30,000 per acre, based on the literature reviewed above (US EPA. "Chapter 7: Capital and Recurring Costs of Constructed Wetlands." and Gachango et al.). The cost range for the subsurface wetlands was assumed to be $72,000-$145,000 per acre, based on the literature provided (Collins and Gillies, Kadlec and Knight, and Reed).

Maintenance costs over the lifetime of the different wetlands were also considered, as well as variation in the lifespan of each system. I assumed a 20-year lifespan for each of the systems, and a 25-year lifespan for the sensitivity analysis. Maintenance costs for the all of the wetlands were considered to be 2% of the total construction cost, from Weiss (2007). The effectiveness of each treatment system is calculated as a range as well. For surface flow
wetlands, the effectiveness was assumed to be between 30 and 50% (Gachango et al.). For subsurface flow wetlands, the P removal effectiveness was assumed to be between 60 and 80% (Vymazal, “Removal Of Nutrients In Various Types Of Constructed Wetlands,” Chung et al., and Yu et al.). Variation in the amount of flow (in cubic feet per second) treated is also included. For the wetlands, it was a range between 2 cfs and 6 cfs per acre.

In order to have a “cfs” comparison, in terms of the amount of flow/ discharge coming down the Maumee River, I used the data from the Ohio Lake Erie Phosphorus Task Force II (see Appendix for table). I converted the discharge in m³/year (in millions) into cubic feet per second. So the mean discharge is 6,266 m³/yr. (millions) coming down the Maumee River (100% of flow). This number is calculated to be 7,012 cubic feet per second, for 100% of the flow in the Maumee River. This 7,012 cubic feet per second was used as a constant. Of course, is it not very feasible to treat 100% of the Maumee River flow in one single treatment system. Therefore, assumptions were made in the variations of percentages of flow that each type of system can treat, explained in the next paragraph.

Variation in the percentage of flow treated was also accounted for. The amount of flow treated is a function of the systems’ P reduction. For example, under the assumption that a wetland can reduce TP by 50%, then to reach a 10% TP reduction, 20% of the flow or discharge would have to be treated. This percentage of flow varies, based on the TP reduction within the wetland. If the TP reduction is greater than 50% in the wetland, for example, then the amount of flow or discharge treated would be lower than 20%. Variations in both of these were considered.

Present Value calculations of the systems’ total cost was then calculated. This formula is the addition of PV of construction cost, plus O&M costs. To “de-annualize” the O&M costs for each system, an annuity formula was used. The formula included each lifespan of 20 and 25
years, and a range of discount rates. A range of 2% to 4% was used regarding the discount rate. According to Boardman et al. (2011), a range of discount rates should be used for the sensitivity analysis in a cost-effectiveness analysis. These Present Value (PV) numbers were then multiplied by the number of acres needed throughout the MRW (via the assumed amount of cfs per acre each system can treat); to get a total one-time cost for reducing TP by 10%, by installing that type of system across the watershed. These total cost numbers for the whole watershed were then divided by the 263,000 Kg removed (to reach a 10% P reduction, 263,000 Kg would have to be removed) to get dollars per Kg removed for the whole watershed, for each type of wetland.

It is important to note the total cost numbers for a 10% P reduction for wetlands, was calculated on a per acre cost; versus the sediment pond as dollars per cubic feet.

The analysis including all calculations and assumptions was done in an Excel spreadsheet, over 350 draws. The Excel sheets are available upon request. A breakdown of these assumptions and calculations is detailed in the next section.
3.3.1 CALCULATIONS: ASSUMPTIONS & EXCEL WORK

1. Surface Flow Wetland

   a. MRW Discharge (ft³/Sec) for treating mean flow (average flow of 7,012 cfs between 2007 and 2012 -constant) (Ohio Lake Erie Phosphorus Task Force II)

   b. Range of Construction cost: $7,000-$30,000 per acre (US EPA. "Chapter 7: Capital and Recurring Costs of Constructed Wetlands." and Gachango et al.)

   c. O&M cost: 2% of construction cost range (Weiss)

   d. Percentage of Flow treated (%) Based off of P reduction

   e. Total Discharge treated (ft³/Sec) based off of percentage of Flow treated

   f. Range of flow (cf/s): 2cfs-6cfs per acre (Jackwood)

   g. Range of P reduction effectiveness: 30 – 50% (Gachango et al., etc.)

   h. Discount rate 2, 3, and 4% variations (Boardman et al.)

   i. PV Total Construction Cost per acre (the same as letter b.)

   j. PV O&M calculated using an Annuity Formula (Boardman et al.)

   k. PV Total Cost (PV construction cost + PV O&M cost)

   l. Acres Needed via range of cfs treated per acre

   m. TOTAL Cost for a 10% TP reduction throughout the MRW (one-time cost)

   n. Cost per tonne of P removed for a 10% TP reduction in the whole watershed (263 tonnes removed)

   o. Cost per Kg of P removed (263,000 Kg removed)
2. Subsurface Flow Wetland in general
   a. MRW Discharge (ft³/Sec) for treating mean flow (average flow of 7,012 cfs
      between 2007 and 2012 -constant) (Ohio Lake Erie Phosphorus Task Force II)
   b. Range of Construction costs: $72,000 - $145,000 per acre (Collins and Gillies,
      Kadlec and Knight, and Reed)
   c. O&M cost: 2% of construction cost range (Weiss)
   d. Percentage of Flow treated (%) Based off of P reduction
   e. Total Discharge treated (ft³/Sec) based off of percentage of Flow treated
   f. Range of flow (cf/s): 2cfs-6cfs per acre (Jackwood)
   g. Range of P reduction effectiveness: 60- 80% (Vymazal, “Removal Of Nutrients In
      Various Types Of Constructed Wetlands,” Chung et al., and Yu et al.)
   h. Discount rate 2, 3, and 4% variations (Boardman et al.)
   i. PV Total Construction Cost per acre (the same as letter b.)
   j. PV O&M calculated using an Annuity Formula (Boardman et al.)
   k. PV Total Cost (PV construction cost + PV O&M cost)
   l. Acres Needed via range of cfs treated per acre
   m. TOTAL Cost for a 10% TP reduction throughout the MRW (one-time cost)
   n. Cost per tonne of P removed for a 10% TP reduction in the whole watershed (263
      tonnes removed)
   o. Cost per Kg of P removed (263,000 Kg removed)
### 3.4 RESULTS

Table 3: 20 Year Lifespan Excel Summary Statistics for Wetlands

<table>
<thead>
<tr>
<th>Acres Needed for the whole MRW</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>511 acres</td>
<td>295 acres</td>
</tr>
<tr>
<td>Median</td>
<td>444 acres</td>
<td>258 acres</td>
</tr>
<tr>
<td>Min</td>
<td>234 acres</td>
<td>146 acres</td>
</tr>
<tr>
<td>Max</td>
<td>1,169 acres</td>
<td>584 acres</td>
</tr>
<tr>
<td>St. Dev</td>
<td>218 acres</td>
<td>120 acres</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Cost for a 10% TP Reduction throughout the whole MRW</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$13.03 mill</td>
<td>$40.18 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$10.33 mill</td>
<td>$35.28 mill</td>
</tr>
<tr>
<td>Min</td>
<td>$2.13 mill</td>
<td>$14.12 mill</td>
</tr>
<tr>
<td>Max</td>
<td>$42.04 mill</td>
<td>$110.31 mill</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$8.4 mill</td>
<td>$18.5 mill</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total cost throughout the MRW per kg P removed</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$49</td>
<td>$159</td>
</tr>
<tr>
<td>Median</td>
<td>$42</td>
<td>$136</td>
</tr>
<tr>
<td>Min</td>
<td>$8.00</td>
<td>$59</td>
</tr>
<tr>
<td>Max</td>
<td>$170</td>
<td>$409</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$29</td>
<td>$73</td>
</tr>
</tbody>
</table>
### 3.5 SENSITIVITY ANALYSIS

Table 4: 25 Year Lifespan Excel Summary Statistics for Wetlands

<table>
<thead>
<tr>
<th>Acres Needed for the whole MRW</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>498 acres</td>
<td>296 acres</td>
</tr>
<tr>
<td>Median</td>
<td>417 acres</td>
<td>250 acres</td>
</tr>
<tr>
<td>Min</td>
<td>234 acres</td>
<td>146 acres</td>
</tr>
<tr>
<td>Max</td>
<td>1,169 acres</td>
<td>584 acres</td>
</tr>
<tr>
<td>St. Dev</td>
<td>224 acres</td>
<td>174 acres</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Cost for a 10% TP Reduction throughout the whole MRW</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$12.98 mill</td>
<td>$43.62 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$11.13 mill</td>
<td>$36.73 mill</td>
</tr>
<tr>
<td>Min</td>
<td>$2.44 mill</td>
<td>$16.55 mill</td>
</tr>
<tr>
<td>Max</td>
<td>$40.83 mill</td>
<td>$107.22 mill</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$7.5 mill</td>
<td>$20.4 mill</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total cost throughout the MRW per kg P removed</th>
<th>Surface Flow Wetland</th>
<th>Subsurface Flow Wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$50</td>
<td>$171</td>
</tr>
<tr>
<td>Median</td>
<td>$42</td>
<td>$146</td>
</tr>
<tr>
<td>Min</td>
<td>$9.00</td>
<td>$61</td>
</tr>
<tr>
<td>Max</td>
<td>$170</td>
<td>$408</td>
</tr>
<tr>
<td>St. Dev</td>
<td>$30</td>
<td>$78</td>
</tr>
</tbody>
</table>
3.6 DISCUSSION

Between the two distinct types of wetlands, surface flow wetlands were calculated to be the most cost-effective solution to reduce P loadings by the targeted 10%.

As we can see, with a 20-year lifespan, surface flow wetlands have an average total cost of $13.03 million for a 10% P reduction in the watershed. With the 25-year lifespan, the average total cost of a 10% P reduction is $12.98. The average cost per Kg of P removed if surface flow wetlands were implemented watershed-wide, with a 20-year life, was $49; and $50 with a 25-year life.

From the results, the surface flow wetland has a cost-effectiveness range of $8.00 to $170 per Kg P removed and a mean cost-effectiveness of $49 per Kg, for a 20-year lifespan. Gachango et al. (2015) stated that for the 20-year lifespan scenario of surface flow wetlands, the cost of reducing 1 kg of P ranged between $59.87 and $1,249.50 per kg P retained. My cost per Kg reduction range falls within this range.

Also, according to Trepel (2010), the reduction of 1 kg of P for constructed wetlands in general, range between 71 and 146€ (roughly between $79 and $163). This was comparable to my results, though on the higher end of my surface flow wetland numbers.

Subsurface flow wetlands, on the other hand, are less cost-effective when compared to surface flow wetlands. With a 20-year lifespan, subsurface flow wetlands have an average total cost of $40.18 million, for a 10% P reduction in the watershed. We can clearly see that they are more expensive than surface flow wetlands; due to their higher cost per acre. With the 25-year lifespan, the average total cost of a 10% P reduction is $43.62 million. The average cost per Kg of P removed if subsurface flow wetlands were implemented watershed-wide, with a 20-year life, was $159; and $171 with a 25-year lifespan.
It is interesting to see that, even though surface wetlands are the most cost-effective, the cost-effectiveness ranges of all of the systems (for the whole MRW) overlap. Just as the cost-effectiveness ranges overlap, the total costs of installing each type of system throughout the Maumee watershed, also overlap. This is a good indicator that the cost-effectiveness for each treatment system would depend on the specific site where it is installed in the watershed.

It is also interesting to see that the subsurface flow needs fewer acres than the surface flow wetlands. This is primarily because subsurface flow wetlands are more efficient in their P removal than surface flow wetlands, thus requiring less land to do the same amount of P removal.

Even though surface flow wetlands were the most cost-effective scenario, it is important to note that it may not be efficient or cost-effective to install just one type of system across the whole MRW. As stated above, each installation will be site-specific, and therefore different in terms of size, P reduction, flow treated, etc. Each type of system will be installed where it is the most cost-effective to do so in the watershed, to reach the targeted P reduction.

Especially since subsurface flow wetlands were found to be more efficient in their P removal, as well as needing fewer acres, though more expensive, treating ‘hot spots’ would be a viable option; just like with sediment ponds.
3.7 BENEFITS OF WETLANDS LITERATURE REVIEW

It is also important to consider the extra benefits that wetlands have, such as flood control, improved water quality, and habitat restoration. These additional benefits make wetlands even more cost-effective or feasible to be implemented. The following section details literature that includes these monetized benefits in the wetlands’ scenarios, or individuals’ WTP for such benefits.

Yang et al. (2008) summarized economic values of constructed wetlands for treating eutrophic water, via a survey of 296 respondents. The study applied the contingent valuation method (CVM) and shadow project approach (SPA) to a 600 m² (0.15 acres) constructed wetland in the Hangzhou Botanical Garden.

The CVM estimated a value of 800,000 yuan ($105,263 US dollars, in 2007 dollars, as conducted in this study) as the total economic value of the wetland for a twenty-year lifespan. But, it was stated that the SPA provided a more accurate representation of the real monetary value of the Botanical Garden wetland. The SPA calculated 23.04 million yuan ($3,031,579 US 2007 dollars) as the total economic value of the wetland in a twenty-year period.

This converts to an average economic value of 66.67 yuan per m² per year by CVM; and 1920 yuan per m² per year by SPA. Converted into a per acre benefit/WTP (as 4,046.86 m² = 1 acre) the CVM was estimated to be 269,804 yuan per acre per year (or $35,500 US dollars per acre per year); the SPA was estimated at 7,796,971 yuan per acre per year (or $1,022,365 US dollars per acre per year). Note that these dollar amounts are also in 2007 dollars, as was used in the study.
Pattison et al. (2011) examined the willingness to pay of 1,980 Manitobans for wetland retention and different levels of restoration, focusing on wetland benefits like flood control and agriculture. The lowest level of wetland improvements is retention that would maintain the existing level of wetlands (1.04 million acres); avoiding a loss of 95,000 acres. The highest level of improvement is 100% restoration, which would be an increase of 407,000 acres (to total 1.35 million acres).

The results showed that the annual WTP ranged from $296 to $326 per household over a five-year period, depending on the level of wetland improvement. Using this range, the PVs (at a 5% discount rate) are $550 to $666 million for a five-year program.

According to the study, “the change in wetland areas for 100% restoration suggests benefits of about $1,352–$1,637 per acre, respectively.” (Pattison et al. 240). However, the study states that the value of wetlands retained is higher ($5,794 per acre) than that associated with restoration ($4,212 per acre for 12.5% restoration; and $1,637 per acre for 100% restoration). In other words, the respondents value retaining wetlands at a higher WTP than restoring wetlands, in this study. The results suggest that full 100% restoration would not pass a BCA; however, a combination of wetland retention and a smaller percentage of restoration would be feasible.

Jenkins et al. (2010) evaluated the value of restoring wetlands through the government's Wetlands Reserve Program in Mississippi, by measuring and monetizing ecosystem services. The three primary services studied were mitigation of greenhouse gasses, nitrogen mitigation, and waterfowl recreation. Social welfare value was found to be between $1435 and $1486/ha/year ($3,545 to $3,670 per acre); with GHG mitigation valued in the range of $171 to $222/ha/year, nitrogen mitigation at $1248/ha/year, and waterfowl recreation at $16/ha/year.
Additionally, Jenkins et al. stated that wetlands have other benefits (floodwater storage, sediment retention, and other wildlife habitat) that were not examined in this study; and thus, “the social value estimated here is a lower bound on the full social value of restoring wetlands.” (1057).

Brander, Florax, and Vermaat (2006) conducted an analysis of over 190 wetland valuation studies and presents a comprehensive meta-analysis of the literature on wetland valuation. The study examines tropical wetlands, various estimates from different valuation methodologies, and a broad range of wetland services or benefits.

The average annual wetland value was found to be just over $2,800 per hectare ($6,916 per acre). The median value, however, was only $150 per ha per year; showing the distribution of the values is skewed (there are a greater number of higher values). The study states that this is because the values vary by location/continent, type of wetland, type of wetland service studied, as well as the valuation method used.

The study collected data for the different variables mentioned. Of particular importance, this source specifically discussed over 25 different studies that valued wetlands restoration for water quality improvements. The previously discussed cost estimates for constructing wetlands in the MRW are based on the wetland's ability to remove P and therefore improve the water quality in the MRW and Lake Erie; specifically, reducing the potential formation of harmful algal blooms. Therefore, papers that focus on the water quality improvements wetlands can provide are most relevant for this study. Brander, Florax, and Vermaat (2006) estimated the average annual WTP is roughly $7,000 per ha per year ($17,290 per acre per year). Therefore, I
assumed $17,000 per acre per year as the maximum, for the range of benefit estimates for the proposed restored wetlands in the MRW.

Woodward and Wui (2001) used 39 different studies to evaluate the value of various wetland services, the returns to scale exhibited in wetland values, and the sources of bias in wetland valuation. They found an average value of $567 per hectare per year (or $1,400 per acre per year). I assumed this much lower $1,400 per acre per year as the minimum, for the range of benefit estimates for the proposed restored wetlands in the MRW.
3.8 ADDED BENEFITS METHODOLOGY

From the literature review, the $B$ range I am assuming for this Benefit Cost Analysis is $1,400 to $17,000 per acre per year (Brander et al.; Woodward and Wui). As with all the random variables in this analysis, I assumed the benefits are drawn from a uniform distribution between these minimum and maximum estimates. The annuity formula was applied, with the two different lifespans of 20 and 25 years, as well as a range of discount rates, for each type of wetland. The PV $C$ that were calculated from the previous sections were subtracted from the wetland’s PV $B$ across the whole MRW, to get PV Net Benefits (NB) of the wetlands, for a 10% P reduction watershed-wide.
3.8.1 CALCULATIONS; ASSUMPTIONS AND EXCEL

For each type of wetland, the Excel calculations were identical:

a. Benefits ($ per acre per year) Range between $1,400 and $17,000 (Woodward and Wui; Brander et al.)

b. Discount rate 2, 3, and 4% variations (Boardman et al.)

c. PV TOTAL SB (annuity formula)

d. Acres Needed (from previous section calculations)

e. PV TOTAL B IN MRW for 10% P reduction

f. PV TOTAL C IN MRW (from previous section calculations)

g. NET BENEFITS ($B - $C)
3.9 BENEFITS RESULTS

Table 5: 20 Year Lifespan Excel Summary Statistics Surface Flow wetlands (PVB, PVC, NB)

<table>
<thead>
<tr>
<th>PV TOTAL B IN MRW for 10% P reduction</th>
<th>PV TOTAL C IN MRW</th>
<th>($B - $C) NET BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$73 mill</td>
<td>Mean $13 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$63 mill</td>
<td>Median $10 mill</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$49.6 mill</td>
<td>Standard Deviation 8.2 mill</td>
</tr>
<tr>
<td>Minimum</td>
<td>$7.57 mill</td>
<td>Minimum $2.62 mill</td>
</tr>
<tr>
<td>Maximum</td>
<td>$280.8 mill</td>
<td>Maximum $46 mill</td>
</tr>
</tbody>
</table>

Table 6: 20 Year Lifespan Excel Summary Statistics Subsurface Flow (PVB, PVC, NB)

<table>
<thead>
<tr>
<th>PV TOTAL B IN MRW for 10% P reduction</th>
<th>PV TOTAL C IN MRW</th>
<th>($B - $C) NET BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$39 mill</td>
<td>Mean $42 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$33.7 mill</td>
<td>Median $34.1 mill</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$27.2 mill</td>
<td>Standard Deviation $19.1 mill</td>
</tr>
<tr>
<td>Minimum</td>
<td>$3.8 mill</td>
<td>Minimum $13.9 mill</td>
</tr>
<tr>
<td>Maximum</td>
<td>$129 mill</td>
<td>Maximum $98 mill</td>
</tr>
</tbody>
</table>
3.10 BENEFITS SENSITIVITY ANALYSIS

Table 7: 25 Year Lifespan Excel Summary Statistics Surface Flow wetlands (PVB, PVC, NB)

<table>
<thead>
<tr>
<th>PV TOTAL B IN MRW for 10% P reduction</th>
<th>PV TOTAL C IN MRW</th>
<th>($B - $C) NET BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$82 mill</td>
<td>Mean $13 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$69.6 mill</td>
<td>Median $10.3 mill</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$58.9 mill</td>
<td>Standard Deviation $8.2 mill</td>
</tr>
<tr>
<td>Minimum</td>
<td>$7.5 mill</td>
<td>Minimum $2.6 mill</td>
</tr>
<tr>
<td>Maximum</td>
<td>$371.9 mill</td>
<td>Maximum $48.2 mill</td>
</tr>
</tbody>
</table>

Table 8: 25 Year Lifespan Excel Summary Statistics Subsurface Flow (PVB, PVC, NB)

<table>
<thead>
<tr>
<th>PV TOTAL B IN MRW for 10% P reduction</th>
<th>PV TOTAL C IN MRW</th>
<th>($B - $C) NET BENEFITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$47 mill</td>
<td>Mean $43 mill</td>
</tr>
<tr>
<td>Median</td>
<td>$38.08 mill</td>
<td>Median $37.97 mill</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$31.6 mill</td>
<td>Standard Deviation $19.2 mill</td>
</tr>
<tr>
<td>Minimum</td>
<td>$5.2 mill</td>
<td>Minimum $15.2 mill</td>
</tr>
<tr>
<td>Maximum</td>
<td>$168.1 mill</td>
<td>Maximum $104.5 mill</td>
</tr>
</tbody>
</table>
3.11 DISCUSSION WITH ADDED BENEFITS

Adding in the benefits of wetlands, such as habitat restoration, improved water quality, etc., makes both types of wetlands even more likely to be implemented. The $NB varied widely, due to the number of variables with ranges. For the surface flow wetlands, out of 350 draws, only ten or so scenarios calculated negative $NB. However, it is important to note that this is entirely dependent on the randomized numbers that Excel chose; since many ranges were used (construction cost, discount rate, etc.). For subsurface flow wetlands, it was a more common occurrence to have negative $NB, as their cost per acre was greater than the benefits range provided.

For a 20-year lifespan, for surface flow wetlands, PV $C for a 10% P reduction in the whole MRW, was on average around $13 million. PV $B for a 10% MRW wide P reduction was on average around $73 million. $NB then, were on average around $60 million, making surface flow wetlands efficient, as the benefits outweigh the costs of installing them.

For a 20-year lifespan, for subsurface flow wetlands, PV $C for a 10% P reduction in the whole MRW, was on average around $42 million. PV $B for a 10% MRW wide P reduction was on average around $39 million. $NB then, were on average around $-3 million, making subsurface flow wetlands not efficient, as the costs outweigh the benefits of installing them (on average).

For the sensitivity analysis, a 25-year lifespan was used. For surface flow wetlands, PV $C for a 10% P reduction in the whole MRW, was on average around $13 million. PV $B for a 10% MRW wide P reduction was on average around $82 million. $NB then, were on average around $69 million. With the 25-year lifespan, surface flow wetlands’ benefits outweigh the
costs, again making them efficient with, as expected, higher net benefits if the wetlands have a longer lifespan.

For Subsurface flow wetlands, PV $C for a 10% P reduction in the whole MRW, was on average around $43 million. PV $B for a 10% MRW wide P reduction was on average around $47 million. $NB then, were on average around $4 million. With the 25-year lifespan, subsurface flow wetlands’ benefits outweigh the costs, making them efficient. With the greater lifespan of 25 years, on average, subsurface flow wetlands have positive NB, unlike the negative NB with the 20-year lifespan. Thus, I find robust positive NB for the cheaper surface flow wetlands but less robust positive NB for the more expensive subsurface flow wetlands.

It is important to note that the $B would be much higher if focusing solely on wetlands’ ability to improve water quality of eutrophic water. Most of the literature reviewed in this paper detailed wetland benefits such as flood control, habitat restoration, etc. There are not many studies that describe the WTP for reducing nutrients in waterways, and improving water quality of eutrophic water. (Only Yang et al. details WTP for the improved water quality service of wetlands, in treating eutrophic water). More research in this area is needed. As the literature states, we can see that an individual’s WTP for nutrient reduction or improved water quality would be higher than their WTP for many other benefits such as flood control or habitat restoration. Poor water quality in general, as can be seen from the literature review above, has a higher WTP than other wetland services. Some individuals live near eutrophic water, or enjoy recreational or commercial fishing. Thus, these individuals have a higher WTP to improve the water quality, since it is harming their businesses, property values, etc. Not to mention the possibility of contaminated drinking water, like the situation in Toledo, OH, in 2014. These individuals, specifically, are directly affected by the poor water quality, and thus are willing to
pay to solve the problem. This aspect could make both types of wetlands more likely to be implemented, due to the higher $B$. 
CHAPTER 4: P Removal Structures

INTRODUCTION

While particulate or attached P can be reduced by controlling soil erosion (via BMPs, sediment ponds, etc.), Phosphorous Removal Structures (PRSs) target the dissolved Phosphorous within the water. This is especially important since DRP is 100% readily bioavailable to aid in the formation of algal blooms. Using P Sorbing Materials (PSMs) in P removal structures will reduce dissolved P concentrations in the waterways, thus decreasing the potential for P to contribute to algal blooms.

PRSs are primarily used to treat hot spots of periodic flow containing high DP concentrations, instead of treating constantly flowing water with lower P concentrations. “Targeting these hot spots is much more efficient both from the perspective of thermodynamics and design.” (Penn et al., “Evaluation Of A Universal Flow-Through Model For Predicting And Designing Phosphorus Removal Structures." 354).

When evaluating a potential location to install a PRS, there are three necessary requirements, according to Penn, Chad, et al. (2014). Number one is elevated DP concentrations in runoff. Most PSMs are not able to soak up large amounts of P from low P concentration water for extended periods of time. Number two is hydraulic connectivity. The runoff produced at the site must be able to reach a surface body of water. And finally, flow convergence. Channeling the runoff water into a single point for treatment is necessary for the PSM to be effective in removing P.

A PRS must also be able to conduct water through it at a sufficient rate, in order to treat the majority of flow during average rain events. “The rate at which a PSM can remove P is key
to determining its suitability for a certain type of PRS or situation.” (Penn et al., "Removing Dissolved Phosphorus From Drainage Ditch Water With Phosphorus Sorbing Materials." 273).

Some designs for P removal structures concentrate ditch flow to improve contact with PSMs. With these systems, ditch water is forced through the PSMs; and the PSMs can be eventually removed from the structure when they become saturated with P. It was stated in Penn’s 2007 study, that the removal of P from drainage ditch flow has a greater probability of improving water quality downstream. Also, treating drainage ditch flow at one single point, “has the potential to capture P from an entire catchment, making it a spatially efficient means of treating nonpoint source P pollution.” (Penn et al., "Removing Dissolved Phosphorus From Drainage Ditch Water With Phosphorus Sorbing Materials." 269).

It is important to note, however, that contact between drainage ditch water and PSMs declines as flow increases. When the flow increases, it could bypass the sorbing materials entirely, due to their fixed hydraulic conductivity. When this occurs, the PSMs do not have a chance to absorb all of the Dissolved P, since a percentage of the flow bypass the whole system. In other words, with a greater amount of flow; as from a huge storm event, for example, the PSMs are less effective in removing P.

In terms of PSMs, many different materials including industrial by-products have been studied, each varying in cost and P absorbing effectiveness. PSMs typically contain concentrations of aluminum (Al), iron (Fe), calcium (Ca), or magnesium (Mg). Other materials like alum (aluminum sulfate), gypsum (calcium sulfate), and different types of steel slag were also mentioned (Penn et al., "Removing Dissolved Phosphorus From Drainage Ditch Water With Phosphorus Sorbing Materials." 269). PRSs are generally flexible, as any PSM can be used in the design, through a chemical and physical characterization. “This is especially important since
certain PSMs are only available in narrow geographic regions, and because the chemical characteristics within specific types of PSMs will vary, even within the same source.” (Penn et al., “Evaluation Of A Universal Flow-Through Model For Predicting And Designing Phosphorus Removal Structures.” 354). Through these types of systems (PRSs), we can predict P removal without constant monitoring; making them practical for meeting P removal goals.

Designing and constructing a PRS widely depends on many different factors. As mentioned previously, the rate at which a PSM can remove P is important, in order to determine whether or not it can be used in a certain PRS or situation. This rate of absorption depends on many things: the chemical makeup of the material (this affects sorption capacity, retention, kinetics, etc.), availability of the material (higher transportation costs are incurred if a material is not readily available), cost of the material, particle size of PSM, the pH of the PSM and its environment (or water body), hydraulic conductivity of PSM (amount of flow it can successfully ‘treat’), the temperature of the water, and retention time. “Physical characteristics of the ideal PSM for a specific use usually hinges on the balance between maximum surface area and a particle size distribution that meets other design requirements, such as handling or hydraulic conductivity.” (Penn et al., "Removing Dissolved Phosphorus From Drainage Ditch Water With Phosphorus Sorbing Materials." 273).

The efficiency of a PSM in absorbing P can be defined as either discrete or cumulative. “Discrete efficiency is the amount of P removed per unit of P added to the material. PSM efficiency can also be described in cumulative terms, as either the cumulative percentage of P removed or the mass of P removed per unit mass of material when at the point where the outflow concentration equals the inflow concentration.” (Mcgrath, Penn, and Coale 156). 

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Proper design requires development of a design curve for the PSM used in the structure and is used to determine the two efficiencies of PSMs. A design curve is a description of the relationship between DP loading to the PSM and the percentage of DP removal. A design curve is specific with regard to the retention time and the inflow P concentration (Penn et al., “Phosphorus Removal Structures: A Management Option For Legacy Phosphorus.” 53A). The shape of the curve, of course, varies between PSMs, retention times, and inflow P concentrations.

What to do with the removed PSMs after they are saturated with P, is another factor to consider. Options for disposing of the spent material include using as land filling, such as in construction; and land applying, such as on open fields (Penn et al., "Removing Dissolved Phosphorus From Drainage Ditch Water With Phosphorus Sorbing Materials." 273). Spent PSMs such as lime could potentially be applied to farm fields as fertilizer, as well.
4.1 LITERATURE REVIEW

Oklahoma State University has done numerous studies on different P-absorbing materials, as well as constructed a few PRSs. One PRS was built near a poultry farm in Eastern Oklahoma, using steel slag as the PSM. A design curve was constructed for the site, which determined the appropriate amount of PSM to achieve the desired P removal, at a given retention time, inflow P concentration, and PSM characteristics (chemical and physical).

This P removal structure was constructed at an outlet that drained 3.6 ha (8.9 acres) of a poultry farm in eastern OK, located in the Illinois River Watershed. The PRS contains 40 tons of sieved and treated steel slag and was designed to remove 45 percent of the expected annual DP load (20 lbs.) and handle 16 cfs. This PRS is continually being monitored. (Penn et al., “Evaluation Of A Universal Flow-Through Model For Predicting And Designing Phosphorus Removal Structures.” 349).

Penn and Payne (2015) conducted a follow-up study on this structure. They found that the PRS has removed approximately 67% of all DP, over a 16-month time period. The source states that while the structure is removing P as predicted based on P loading, it has lasted longer than the goal of removing 45% of cumulative DP in one year; which is due to below average rainfall.

Penn’s "Design and Implementation of a Phosphorus Removal Structure" gave a few generalized costs numbers for building PRSs. The cost of a PRS will vary depending on site characteristics, target removal, and PSM characteristics and location. However, after many years of use, the total cost of P removal can be $30 to $100 per pound of P removed ($66.14 to $220.46 per kg removed). According to the study, this cost is low compared to wastewater treatment plants, which usually require $50 to $200 per pound P removed.
Penn and Payne (2014) gave actual cost numbers for the poultry farm PRS that was constructed (Penn and Payne, "1-2-5_Penn Pdf: Using Slag in Phosphorus Removal Structures to Improve Water Quality."). Metal & custom fabrication was listed as $2,677; Slag transportation, sieving, coating was $853; Earthwork for pad & berms was $846; and paint, seed, & erosion mat was $613. The total construction cost for the poultry farm PRS was $4,989. This $4,989 is the (one-time) construction of the PRS as well as the steel slag PSM for year 1. An annual cost of $1,213 to replace the spent PSM is incurred, and the PRS is removing 22lbs of P per year (see the table below).

<table>
<thead>
<tr>
<th>Year</th>
<th>$</th>
<th>P removal (lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,989</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>1,213</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>1,213</td>
<td>22</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>...</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>...</td>
</tr>
</tbody>
</table>
4.2 METHODOLOGY

The OK State sources mentioned in the Introduction and Literature Review sections of this chapter were primarily the ones used in this paper, since no other available sources physically installed a PRS. Future research is needed in the area of P removal structures, and widespread implementation of them.

I used the cost numbers from Penn and Payne (2014) and the poultry farm PRS information, for my analysis. Therefore, I assumed the same amount of flow treated, the same amount of P concentration in the flow, and the same PSM and PSM characteristics. I also assumed the same 45% effectiveness of P removal.

I converted 22 lbs. into Kg for the purpose of keeping every system comparable. 22 lbs. converts into roughly 10 kg (9.97903 kg). So, that means the PRS would have to remove 10 kg of P from an annual dissolved load of 22kg; to be 45% effective.

Again, for a 10% P reduction: 263 tons of P has to be removed, which is 263,000 kg. Just with PRSs installed throughout the MRW, removing roughly 10kgs each, means 26,300 P removal structures would have to be installed.

The annual cost of $1,213 to replace the spend PSM was “de-annualized” over each lifespan (20 and 25 years) using an annuity cost formula, with a range of discount rates. This was then added to the year 1 construction cost of $4,989 to reach PV costs of installing one PRS. This PV cost was then multiplied by the 26,300 PRSs needed to reach a 10% P reduction in the watershed. Costs per Kg of P removed were obtained by dividing this PV total cost for 26,300 PRSs by the required 263,000 Kg to be removed.
4.2.1 CALCULATIONS: ASSUMPTIONS & EXCEL WORK

a. Year 1 construction cost of $4,989 (Penn and Payne)

b. Annual cost to replace PSM of $1,213 (Penn and Payne)

c. 10% P reduction goal; 263,000 kg needs to be removed

d. Each PRS can remove 10 kg of P (Penn and Payne)

e. Discount rate 2, 3, and 4% variations (Boardman et al.)

f. Annuity cost formula for replacing PSM each year

g. PV total cost for 1 PRS over selected lifespan

h. Number of PRSs needed in MRW (26,300 constant)

i. PV total costs for 10% reduction in MRW

j. Cost per kg P removed
4.3 RESULTS

Table 9: 20 Year Lifespan Excel Summary Statistics for PRSs

<table>
<thead>
<tr>
<th>Year 1 construction cost</th>
<th>Annual cost to replace PSMs</th>
<th>kg that need to be reduced</th>
<th>kg removed per PRS</th>
<th>Discount rate</th>
<th>Annuity for annual cost</th>
<th>PV total cost</th>
<th># PRSs needed in MRW</th>
<th>PV total cost throughout the MRW for a 10% P reduction</th>
<th>Cost per kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>2</td>
<td>$19,800</td>
<td>$24,800</td>
<td>26,300</td>
<td>$652.9 mill</td>
<td>$2,500</td>
</tr>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>3</td>
<td>$18,000</td>
<td>$23,000</td>
<td>26,300</td>
<td>$605.8 mill</td>
<td>$2,300</td>
</tr>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>4</td>
<td>$16,500</td>
<td>$21,500</td>
<td>26,300</td>
<td>$564.8 mill</td>
<td>$2,150</td>
</tr>
</tbody>
</table>
### 4.4 SENSITIVITY ANALYSIS

Table 10: 25 Year Lifespan Excel Summary Statistics for PRSs

<table>
<thead>
<tr>
<th>Year 1 construction cost</th>
<th>Annual cost to replace PSMs</th>
<th>kg that need to be reduced</th>
<th>kg removed per PRS</th>
<th>Discount rate</th>
<th>Annuity for annual cost</th>
<th>PV total cost</th>
<th># PRSs needed in MRW</th>
<th>PV total cost throughout the MRW for a 10% P reduction</th>
<th>Cost per kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>2</td>
<td>$23,700</td>
<td>$28,700</td>
<td>26,300</td>
<td>$754.05 mill</td>
<td>$2,900</td>
</tr>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>3</td>
<td>$21,100</td>
<td>$26,100</td>
<td>26,300</td>
<td>$686.7 mill</td>
<td>$2,600</td>
</tr>
<tr>
<td>$4,989</td>
<td>$1,213</td>
<td>263,000</td>
<td>10</td>
<td>4</td>
<td>$19,000</td>
<td>$24,000</td>
<td>26,300</td>
<td>$629.6 mill</td>
<td>$2,390</td>
</tr>
</tbody>
</table>
4.5 DISCUSSION

As we can see, if only PRSs were used to reach a 10% P reduction, it would be very costly. The results show that PRSs are very expensive to install in terms of cost per Kg removed. However, these results are strictly limited due to the assumptions made; as well as the availability of data on the subject. More research is needed in the future about different types of PRSs, their PSMs, different ways to construct them, and with various materials; especially in a watershed-wide scenario. There may be other construction materials that are less costly, as well as other PSMs that could be used.

For the 20-year lifespan, the cost per Kg of P removed ranged from $2,150 to $2,500 over the three different discount rates. For the 25-year lifespan, the range was from $2,390 to $2,900. Compared to the wetlands and sediment ponds so far, the PRSs are the most expensive solution. Again, however, there could be more cost-effective ways of constructing PRSs, as mentioned above.
CHAPTER 5: P CORRECTIVE FEE

INTRODUCTION

Corrective fees aim to correct the effects of a negative externality. Economists prefer corrective fees over any other form of regulation because they can reduce pollution at a lower cost to society (i.e. social cost). With a P fee, there are obvious costs to farmers. They now have to pay more for their fertilizer. The law of demand comes into play, stating that with an increase in price, the quantity purchased, and therefore applied, will decrease. The farmers are losing some of their Consumer Surplus to the corrective fee. There are also costs to the fertilizer manufacturers and suppliers; they are losing Producer Surplus. However, these losses in CS and PS are a transfer payment, dollars transferred to the government as government revenue, and thus not a true social cost of the P corrective fee. Furthermore, the government revenue collected from this fee could be given back to the farmers as a way to offset some or all of their costs.

Again, to the farmers the ‘cost’ of a P corrective fee would be the higher price the farmer pays for fertilizer and, due to the lower amount of fertilizer being applied, any yield reductions. However, the only social cost is any yield reduction as, again, the extra cost for fertilizer is a transfer payment. A few studies have looked at the yield impact of less fertilizer application, noting that soil P has to be taken into account before spreading fertilizer (Beegle and Durst; McKenzie and Middleton).

Since the fee would incentivize farmers to use fertilizer in a more efficient manner, it is likely the fee would also incentivize soil testing. It is likely that farmers are over applying fertilizer as cheap insurance for their crops, given uncertainties in soil P and weather conditions, but there is a certain threshold that is reached for crops, where one more pound of P fertilizer has no effect on yield (Babcock; Iho and Laukkanen). Farmers can more easily know how much P is
already in the soil by doing soil tests. It is a good possibility that a P corrective fee would incentivize farmers to do soil testing, if they aren’t already, in order to use less fertilizer on their fields and only buy exactly how much they need. In the long run, farmers may save time and money by using P fertilizer more effectively, per conducted soil tests, and better application methods.

However, for any P reduction to take place, farmers need to be aware of how their farming decisions impact nutrient runoff. This, and other information (such as how to do soil testing) needs to be provided so that farmers know what they can do to help solve the issue.

One reason a corrective P fee was proposed as a solution, is simply because voluntary measures by farmers are not enough. At the 2016 Toledo Rotary Watershed Conference, Dr. Jeffery Reutter from Ohio Sea Grant and OSU Stone Laboratory essentially agreed that voluntary farming practices are not sufficient on their own to decrease the amount of nutrient runoff required. Most nutrient management programs are voluntary, and most BMPs focus on reducing soil runoff- however, it is known that HABs thrive off of not attached P, but Dissolved P, which most BMPs do not target. Dr, Reutter stated, and I agree, that more targeted incentives for farmers is needed. A P fee is one such incentive. (Reutter).
5.1 LITERATURE REVIEW

Jacob and Casler (1979), talk about how an effluent tax should be set where Marginal Social Costs (MSC) is equal to the Marginal Social Benefits (MSB) of a certain level of pollution reduction. It is noted that a tax can achieve a pollution reduction goal at a lower cost to society, than uniform reduction policies.

The two are compared in an analysis of the Fall Creek watershed in New York, consisting of mostly dairy farms. The cost of reducing P discharges from soil erosion, as well as surface runoff, was estimated using a linear programming (LP) model. This study only looked at Soluble P. An estimate was made about what percentage of the total P was soluble, since soluble P is the primary type that contributes to algal bloom production.

To show uniform percentage reductions in P discharges, the model was divided into three parts or three subwatersheds. Each was treated as a ‘farm.’ P discharges were then decreased in increments of 10%, in each of the three subwatersheds. To show the effects of an effluent tax, “a single restriction on P discharge from the entire watershed was introduced, also in increments of 10%.” (Jacob and Casler 309). Under each of the policies, the LP model calculated the “least-cost (or profit-maximizing) rearrangement of production activities to comply with the specified policy.” (Jacob and Casler 310). It was found that the tax policy is less costly than the uniform reduction policy. This is because, with an effluent tax, P discharge reduction can occur in the least-cost place in the whole watershed. In other words, whichever one of the ‘farms’ could decrease their P discharge in the cheapest manner, they would do so.

It was found that the tax policy allows each 10% increment of P reduction to be achieved more efficiently than the uniform reduction policy. Also, all MSCs of the tax is less than all of the MSCs of the uniform policy. However, it is stated that the total cost to farmers with a tax is
much greater than the total cost of a uniform reduction policy. It is also noted that a P tax might not be socially accepted, and therefore not likely to be implemented. If forced between the two policies, farmers would likely choose the uniform reduction policy. An alternative solution is then considered: to cap the amount of discharge and then tax the excess that exceeds this amount. It is mentioned, also, that the tax would have to be high enough to encourage farmers to reduce their pollution, rather than pay the tax.

Lastly, Jacob and Casler did not discuss the possibility of refunding the increased government revenue from the P fee back to the agricultural community. It may be possible that such a tax-and-rebate strategy may lead to the agricultural community preferring it to a uniform reduction policy.

Janssen (2001) combines an ecosystem model with a model of human behavior, to show the relationship between humans and ecosystems. The study describes how farmers’ uncertainty affects a lake, in terms of P pollution. It is stated that a tax policy may or may not be effective, depending on the psychology of the farmer. In cases where the farmers have “high minimum goal of returns from the use of P, leads to a shift to intensive use of phosphorus, higher phosphorus levels in the various components of the ecosystem, and a lower resilience of the overall system.” (Janssen 123). When farmers have a higher level of uncertainty, they tend to use more P, and thus a tax policy will not lead to a significant change in their behavior. In cases where the farmers have a high tolerance for uncertainty and low minimal return targets, “the long-term resilience of the ecosystem can be improved without significantly reducing the returns of the farmers.” (Janssen 123). It is noted, however, that this model is strictly exploratory and more research is needed.
OSU Economist, Brent Sohngen’s "Nutrient Prices and Concentrations in Midwestern Agricultural Watersheds” detailed the impact of nutrient prices on nutrient concentrations on five Midwestern Watersheds: Maumee, Sandusky, Raisin, Scioto and Great Miami. This study found the price elasticity of P ranges from -0.17 to -0.24. This shows that a 10% P price increase will lead to a reduction in P outputs by 1.7% to 2.4%.

It was found that corn prices have a huge effect on P outputs. This is because higher corn prices give farmers an incentive to plant more corn; thus till more acres. With the increase in tilling, more attached P runoff can occur (sediment). Also, a higher flow level/ more rainfall, the higher the P concentrations, since more soil runoff can occur with more rainfall. The study also finds that the amount of P taken up by crops does not significantly reduce P outputs. Soil P is also mentioned to be a significant factor.

With the three Lake Erie watersheds, a policy analysis is conducted (Maumee, Sandusky, and Raisin Rivers). Using data from 2007-2011, the study assessed the implications if the 25% fee was implemented in 2007. Sohngen totals the number of hectares of all three watersheds, amounting to 1,960,842 ha (about 4.8 million acres). A baseline of 18.2 kg P applied per ha was another assumption. The analysis also uses the P nutrient price elasticity, which ranges from -0.23 to -0.29. Given an average elasticity of -0.26, the 25% fee leads to a 6.5% reduction in P loads into Lake Erie (0.25 x 0.26). The price for P was assumed to be a constant $1.96 per kg P. Assuming the farmers’ price elasticity of P demand is -0.25, a 25% fee would reduce P use by 6.25%. Based on this estimated elasticity, P inputs will decrease by 2,229 t yr\(^{-1}\). With a 25% price hike, and 6.25% less P being used, the net cost to farmers is $12 million, or $6 per hectare; $2.43 per acre (as discussed previously, this is a transfer cost). The reduction in nutrient output from the three watersheds was estimated at 210 tons. This means that a 10.6 kg reduction in P
use, equals a 1 kg reduction in P export. Also, the study states that a 6.25% reduction in P use by farmers, would only have a tiny effect on corn and soybean yields, the only true social cost of the program. Specifically cited in Sohngen, et al. (2015), is a 1992 study by Webb et al. that states that reducing P inputs by approximately 33% (from 33 kg/ha to 22 kg/ha) corn yields are reduced by 0.3 percent and has no impact on soybean yields. Further reducing P inputs from 33 kg/ha to 11 kg/ha (a 66% reduction), reduces corn yields by 2.2% and again, there is no impact on soybean yields (Sohngen, et al. 146).

The table below in this study, is on page 146, and gives a breakdown of all calculations/numbers listed above:

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Implications of a 25% increase in nutrient prices on nutrient inputs and outputs in three Lake Erie watersheds, Maumee, Sandusky and Raisin.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn</td>
</tr>
<tr>
<td>Crop Area (ha)</td>
<td>686,295</td>
</tr>
<tr>
<td>Annual phosphorus application (kg P ha⁻¹)</td>
<td>34.1</td>
</tr>
<tr>
<td>Hectares receiving phosphorus (%)</td>
<td>100%</td>
</tr>
<tr>
<td>Annual application (1000 kg)</td>
<td>23,385</td>
</tr>
<tr>
<td>Total cost of phosphorus (millions $)</td>
<td>$45.8</td>
</tr>
<tr>
<td>25% phosphorus usage fee</td>
<td></td>
</tr>
<tr>
<td>Annual phosphorus application (kg P ha⁻¹)</td>
<td>31.9</td>
</tr>
<tr>
<td>Hectares receiving phosphorus (%)</td>
<td>100%</td>
</tr>
<tr>
<td>Annual application (1000 kg)</td>
<td>21,923</td>
</tr>
<tr>
<td>Total cost of phosphorus (millions $)</td>
<td>$53.7</td>
</tr>
<tr>
<td>Reduction in phosphorus application (1000 kg)</td>
<td>$1.46</td>
</tr>
<tr>
<td>Increase in phosphorus cost (millions $)</td>
<td>$7.87</td>
</tr>
<tr>
<td>Reduction in phosphorus cost ($ ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Reduction in phosphorus output from watersheds (1000 kg)</td>
<td>3,236</td>
</tr>
<tr>
<td>Reduction in phosphorus application in tons to achieve a 1 ton reduction in outputs</td>
<td></td>
</tr>
</tbody>
</table>

(Sohngen, Brent, et al. 146).
Additionally, Sohngen described a 135% P usage fee to reduce P loads by 40%, in a 2014 webinar, with a 0.3 price elasticity. Sohngen states that it takes a 9lb reduction in P inputs by farmers to reduce 1 lb. of P that reaches the Lake. The farmland in acres, for the two watersheds used (Maumee and Sandusky), is 4,843,279. Estimated nutrient input in tons is 35,584. Average input was 97lbs per acre in the two watersheds. Then, Sohngen goes into the effects of a 135% fee increase. He states that the nutrient input would decrease by 12,010 tons per year and nutrient output would decrease by 1,311 tons per year. The net cost would be $27,794,373, with a $6 cost per acre of farmland. Sohngen also states that a P corrective fee is more cost-effective than implementing BMPs, which end up costing $14 per acre of farmland (Sohngen et al., “Webinar-The Economics of Water Pollution Control: The Case of Harmful Algal Blooms”).
5.2 METHODOLOGY (MY P CORRECTIVE FEE WORK)

To focus solely on the MRW, I manipulated some of the data Sohngen gathered, as well as used some of the same assumptions as he did in his paper. I followed the format of the study’s table (shown above; specifically, the “total” column, or the totals of all three watersheds combined). Like Sohngen, I assumed that all three watersheds are homogenous, that P had a constant price of $1.96 per kg, and the 18.2 kg P applied per ha (7.4 kg per acre). I used the same 0.26 elasticity for P emissions and then added an additional elasticity of 0.3 for my sensitivity analysis.

I first adjusted the number of hectares from 1,960,842 ha to 1,474,596 ha to focus on solely the MRW, and then converted this number into acres; there are approximately 3.6 million agricultural acres in the MRW. The baseline assumptions remained unchanged from Sohngen’s data, minus the change in the number of acres to only look at the Maumee Watershed. Baseline P emissions in Sohngen’s study (for all three watersheds) was listed as 3,236 (in 1000kg). This number was changed to 2,630,000 to, once again, focus solely on the MRW. According to the 2013 Phosphorous Task Force report, it is known that 2,630,000 kg P is the annual P load from the MRW. For a 10% P reduction, that would mean that 263,000 kg P has to be reduced (0.1 * 2,630,000). Using these assumptions, I calculated the costs for a 10% P reduction in the MRW; with both elasticities of 0.3 and 0.26. The application reduction elasticity was calculated to be 0.29, when the P emissions elasticity was 0.3.

The tables in the next two sections (Results and Sensitivity Analysis) show the calculations for a P fee with a 0.26 elasticity and a 0.3 elasticity. With a 10% P reduction target, and a 0.26 emissions elasticity, a 39% P fee would be required; and with an elasticity of 0.3, a 34% fee is required. The corrective fee amount as a percentage as well as annual dollars, was
calculated for a 10% P reduction watershed wide. An annual per acre cost was also calculated, and over the two lifespans, a range of discount rates were used with the annuity formula. And lastly, cost per Kg removed numbers were calculated.
5.2.1  CALCULATIONS: ASSUMPTIONS & EXCEL WORK

(for both 0.3 and 0.26 elasticities)

a. Corrective Fee amount (%)

b. Dollar cost per year ($)

c. Dollar cost per acre per year ($)

d. TP Reduction amount (10% constant)

e. Discount Rate (range 2-4%)

f. PV annuity Cost

g. Cost per Kg P removed
5.3 RESULTS

Table 11: A 39% P fee with a 0.26 Elasticity Excel Results

<table>
<thead>
<tr>
<th>Maumee (ag acres)</th>
<th>3,642,030</th>
</tr>
</thead>
</table>

**Baseline**

| Annual P application (kg/ acre) | 7.37 |
| Annual Application (1000 kg)    | 26,836 |
| Total cost of P (Millions $)    | 52.6 |

**39% P fee**

| Annual P application (kg/ acre) | 6.65 |
| Annual Application (1000 kg)    | 24,219 |
| Total cost of P (Millions $)    | 65.9 |
| Reduction of P application (1000 kg) | 2,617 |
| Increase in P cost (Millions $) | **13.3** |
| Increase in P cost per acre ($)  | **3.65** |

Baseline P emissions (1000 kg) | 2,630 |
Reduction in P output from watershed with 39% fee (1000 kg) | 267 |
Reduction in P application in tons to achieve 1-ton reduction in output | 9.8 |

Table 12: 20 Year Lifespan Excel Summary Statistics for 39% P corrective fee, 0.26 elasticity

<table>
<thead>
<tr>
<th>Corrective Fee amount (%)</th>
<th>Dollar cost per year</th>
<th>Dollar cost per acre, per year</th>
<th>TP reduction amount (%)</th>
<th>Discount Rate (%)</th>
<th>PV (annuity) cost</th>
<th>Cost per Kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>2%</td>
<td>$217.5 mill</td>
<td>$827</td>
</tr>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>3%</td>
<td>$198 mill</td>
<td>$752</td>
</tr>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>4%</td>
<td>$181 mill</td>
<td>$687</td>
</tr>
</tbody>
</table>
Table 13: 25 Year Lifespan Excel Summary Statistics for 39% P corrective fee, 0.26 elasticity

<table>
<thead>
<tr>
<th>Corrective Fee amount (%)</th>
<th>Dollar cost per year</th>
<th>Dollar cost per acre, per year</th>
<th>TP reduction amount (%)</th>
<th>Discount Rate (%)</th>
<th>PV (annuity) cost</th>
<th>Cost per Kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>2%</td>
<td>$259.7 mill</td>
<td>$987</td>
</tr>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>3%</td>
<td>$231.6 mill</td>
<td>$881</td>
</tr>
<tr>
<td>39%</td>
<td>$13.3 mill</td>
<td>$3.65</td>
<td>10%</td>
<td>4%</td>
<td>$207.8 mill</td>
<td>$790</td>
</tr>
</tbody>
</table>
5.4 SENSITIVITY ANALYSIS

Table 14: A 34% P Fee with a 0.3 Elasticity Excel Results

<table>
<thead>
<tr>
<th>Maumee (ag acres)</th>
<th>3,642,030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td></td>
</tr>
<tr>
<td>Annual P application (kg/ acre)</td>
<td>7.37</td>
</tr>
<tr>
<td>Annual Application (1000 kg)</td>
<td>26,836</td>
</tr>
<tr>
<td>Total cost of P (Millions $)</td>
<td>52.6</td>
</tr>
<tr>
<td><strong>34% P fee</strong></td>
<td></td>
</tr>
<tr>
<td>Annual P application (kg/ acre)</td>
<td>6.64</td>
</tr>
<tr>
<td>Annual Application (1000 kg)</td>
<td>24,190</td>
</tr>
<tr>
<td>Total cost of P (Millions $)</td>
<td>63.62</td>
</tr>
<tr>
<td>Reduction of P application (1000 kg)</td>
<td>2,646</td>
</tr>
<tr>
<td>Increase in P cost (Millions $)</td>
<td><strong>11.02</strong></td>
</tr>
<tr>
<td>Increase in P cost per acre ($)</td>
<td><strong>3.03</strong></td>
</tr>
<tr>
<td>Baseline P emissions (1000 kg)</td>
<td>2,630</td>
</tr>
<tr>
<td>Reduction in P output from watershed with 34% fee (1000 kg)</td>
<td>268</td>
</tr>
<tr>
<td>Reduction in P application in tons to achieve 1-ton reduction in output</td>
<td>9.9</td>
</tr>
</tbody>
</table>

Table 15: 20 Year Lifespan Excel Summary Statistics for 34% P corrective fee, 0.3 elasticity

<table>
<thead>
<tr>
<th>Corrective Fee amount (%)</th>
<th>Dollar cost per year</th>
<th>Dollar cost per acre, per year</th>
<th>TP reduction amount (%)</th>
<th>Discount Rate (%)</th>
<th>PV (annuity) cost</th>
<th>Cost per Kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>2%</td>
<td>$180.2 mill</td>
<td>$685</td>
</tr>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>3%</td>
<td>$164 mill</td>
<td>$623</td>
</tr>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>4%</td>
<td>$149.8 mill</td>
<td>$570</td>
</tr>
</tbody>
</table>
Table 16: 25 Year Lifespan Excel Summary Statistics for 34% P corrective fee, 0.3 elasticity

<table>
<thead>
<tr>
<th>Corrective Fee amount (%)</th>
<th>Dollar cost per year</th>
<th>Dollar cost per acre, per year</th>
<th>TP reduction amount (%)</th>
<th>Discount Rate (%)</th>
<th>PV (annuity) cost</th>
<th>Cost per Kg removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>2%</td>
<td>$215.2 mill</td>
<td>$818</td>
</tr>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>3%</td>
<td>$192 mill</td>
<td>$730</td>
</tr>
<tr>
<td>34%</td>
<td>$11.02 mill</td>
<td>$3.03</td>
<td>10%</td>
<td>4%</td>
<td>$172.2 mill</td>
<td>$655</td>
</tr>
</tbody>
</table>
5.5 DISCUSSION

The P corrective fee would have a $3.03 cost per acre per year, at a 34% fertilizer price increase, with a 0.3 price elasticity. With a 0.26 price elasticity, the fee amount would be 39% and have a $3.65 cost per acre annually. We can see that the results change more due to a change in the price elasticity, rather than a change in lifespan. In other words, a corrective fee responds more to a change in elasticity, rather than a change in lifespan. This solution differs from the natural treatment systems because the fee could be over an infinite lifespan; where wetlands are only effective for 20 or 25 years, and then may become P sources.

With a 10% P reduction target, and with the assumed 0.26 emissions elasticity, a 39% P fee would be required. A 39% fee would decrease P emissions by approximately 10% (10.14%) and reduce P application by slightly less; a reduction of 9.75%. The 39% fee has a ‘cost’ of $13.3 million across the whole MRW, and a per acre cost of $3.65.

With an elasticity of 0.3 instead of 0.26, some interesting changes occur. For a 10% P reduction in emissions, now, a 34% fee is required. Due to the higher elasticity, a lower fee amount is needed to reach the same 10% P emission reduction target. A 34% fee would decrease P emissions by approximately 10% (10.2%) and reduce P application by slightly less; a reduction of 9.86%. The 34% fee has a ‘cost’ of $11.02 million across the whole MRW, and a per acre cost of $3.03. As we can see, the higher elasticity means that farmers react more strongly, and thus a higher fee amount is not necessary to reach a 10% P reduction; with the elasticity change, the fee amount went from 39% to 34%.

It is also important to note that fertilizer prices, historically, have fluctuated. Therefore, any of the P fee amounts proposed here are well within the range of prices historically recorded. In other words, a 34% P fee or even a 39% P fee is not outrageously expensive for farmers; since
prices have been that high without a fee in the past. According to IndexMundi, fertilizer prices peaked in the late 2007 to early 2008-time frame, as can be seen in the photo below:

Photo 3: Historical P Fertilizer prices

![Graph of Triple Superphosphate Monthly Price - US Dollars per Metric Ton.](image)

("Triple Superphosphate Monthly Price - US Dollars per Metric Ton.")

We can clearly see from the graph above, that a 34-39% P fee to reach a 10% P reduction would be entirely feasible as prices have historically been almost three times the current (2016) amount, at one point in time.

Also, there is minimal real social cost with a corrective fee. The cost numbers listed in the tables above would simply be a transfer cost, from the farmers to the government as revenue. The Annuity/ PV cost is simply the revenue generated from the corrective fee, over the identified lifetime and discount rate; and the same can be said for the cost per Kg of P removed numbers.
Therefore, a corrective fee would be the most cost-effective solution to install; however, fees such as this are usually not politically feasible at this time.

Nonetheless, there are a couple of ways to make these corrective fees more agreeable. For example, the government could give the revenue back to the farmers as a lump sum. The farmers could then use that money to implement soil erosion measures or other BMPs. Additionally, the revenue could “subsidize” or help farmers invest in the technology to perform soil testing. Another option would be to use that revenue as a double dividend, to install wetlands throughout the watershed. More research in these two areas is needed.
CHAPTER 6: OVERALL RESULTS, DISCUSSIONS, & CONCLUSIONS

In summary, considering a 20-year lifespan (and 25 year), I began by conducting a cost-effectiveness analysis for five different policy options to reduce total phosphorous loadings from the MRW by 10%. Based on my literature review, I estimated the present value total cost to achieve the 10% P reduction. The ranking based on cost-effectiveness analysis is: 1) corrective P fee (minimal social cost; primarily transfer cost), 2) surface flow wetlands (mean PV(C) of $13 million), 3) subsurface flow wetlands (mean PV(C) of $40 million), 4) sediment ponds (mean PV(C) of $172 million), and last 5) P removal structures (mean PV(C) of $606 million).

Therefore, to remove P loadings from the MRW, the results from this paper suggest the two most efficient options are the corrective P fee, followed by the next most effective solution, surface flow wetlands. I find, on average, subsurface flow wetlands, sediment ponds, and P removal structures to be significantly more expensive.

Excluding the P fee for the moment, the results show that across the first four included policy options (sediment ponds, surface flow wetlands, subsurface flow wetlands, and P removal structures), surface flow wetlands were the most cost-effective in each lifespan. Moreover, because wetlands provide benefits to society beyond P reduction, I estimated net benefits to society from the proposed wetlands restoration plans. Out of the two types of wetlands, surface flow wetlands had higher $NB in each lifespan scenario. Based on my literature review, surface flow wetlands robustly lead to positive $NB while subsurface flow wetlands were assumed to have the same benefits per acre, but due to their higher cost per acre, were almost as likely to lead to negative $NB as positive $NB.

Out of the different natural treatment systems considered, the surface flow wetlands were the most cost-effective solution. However, it is important to note that it may not be efficient to
install just one type of natural treatment system across the whole MRW. Each wetland installation will be site-specific, and therefore different in terms of size, P reduction, flow treated, etc. Each type of system/solution will be installed where it is the most efficient to do so in the watershed, to reach the targeted P reduction. In other words, there would likely be a combination of different systems implemented throughout the MRW to reach the targeted 40% TP reduction.

For example, with my assumed costs for each type of natural treatment system, the cheapest sediment ponds are lower cost than the most expensive surface flow wetlands. The same is true for subsurface flow wetlands. Though the minimum cost sediment ponds and subsurface flow wetlands are still more expensive than the mean surface flow wetland cost. Thus, based on my literature review, my conclusion is mostly surface flow wetlands, with possibly some sediment ponds and subsurface flow wetlands were appropriate. Regarding P removal structures, there is little literature available at this time, and the projects are small scale leading to very high-cost estimates due to needing 26,300 of these small scale structures in the MRW to achieve the 10% TP reduction. Thus, at this time my conclusion does not support the use of P removal structures in the MRW.

Since a corrective P fee has minimal social costs and surface flow wetlands are the next most cost-effective solution in P reduction, and regarding all the benefits surface flow wetlands provide to society lead to robust positive net benefits, I conclude the most efficient options are the corrective P fee and restoring on available public land surface flow wetlands in the MRW (future research is needed on potential locations of sites where wetlands could be installed). And finally, subsurface flow wetlands and sediment ponds may be occasionally cost-effective to target sediment and P concentration ‘hot spots’.
One feasible combination of the two most cost-effective solutions presented (the fee and surface flow wetlands) to reach the 40% TP reduction goal, would be to install surface flow wetlands throughout the MRW, to achieve a 20% TP reduction. Then, the other 20% could be obtained by the corrective fee set at 67% up to 77%, depending on the assumed price elasticity of demand.

At a 20% P reduction target and a 0.26 elasticity, a 77% P fee would be required. A 77% fee would reduce P emissions by 20% (20.02%) and P application by slightly less; a reduction of 19.25%. The 77% fee has a ‘cost’ of $22.6 million across the whole MRW, and a per acre cost of $6.20.

At a 20% P reduction target and a 0.3 elasticity, a 67% P fee would be necessary. The 67% fee would reduce P emissions by 20% (20.1%) and P application by slightly less; a reduction of 19.43%. The 77% fee has a ‘cost’ of $18.26 million across the whole MRW, and a per acre cost of $5.01. (See Appendix for tables).

And of course, there could be different combinations of all five systems that were discussed in this paper. It is just a matter of efficiency and site-specific placements throughout the watershed.

Additionally, it’s important to note that there is evidence that surface flow wetlands, as well as the P corrective fee, are more efficient than implementing Best Management Practices (BMPs) across the MRW. A 2016 article by Daniel Kelly, titled “Modeling Lake Erie’s 40 Percent Phosphorus Reduction Target” looked at implementing BMPs stating “$260 million every year would be required to pay for farm bill programs, contributions from farmers, staff time, etc., to get it done.” (Kelly). Over a 20-year lifespan, and a 40% P reduction goal, surface flow wetlands would cost roughly $52 million on average. This cost of $52 million does not
include the added benefits that wetlands have, and yet is still more cost-effective than the annual BMP cost of $260 million, as shown in Kelly’s article. For the corrective fee, the range of transfer costs when scaled to a 40% P reduction, was between $22 million and $62 million per year, depending on the price elasticity. Thus, BMPs were shown to be less cost-effective annually, at $260 million per year, than annual transfer costs of a corrective fee. Additionally, surface flow wetlands over their whole 20-year lifespan ($52 million) were shown to be more cost-effective than annual BMP implementation. This indicates there are more cost-effective solutions to reach the 40% P reduction than solely relying on BMPs to do the job. Furthermore, one solution across the whole watershed is not likely to be the most cost-effective. Each type of solution should be implemented where it is most efficient to do so.
CHAPTER 7: FUTURE RESEARCH NEEDED

Future research is needed to find available public land within the watershed; or possible areas where treatment systems could be installed. Then, out of this amount of available public land, figuring where to put each different type of treatment system, according to the size of available land, location, etc.

Also, more research is needed on the per acre cost of vertical subsurface flow wetlands. In the 2010 study, Vymazal also mentioned that vertical subsurface flow wetlands require less land than the other types of wetland systems. Therefore, vertical subsurface flow wetlands could possibly be cheaper per acre than the other types of wetland systems, as well as have a higher effectiveness. But again, research on this is needed, as no data other than effectiveness is available.

Future research could also investigate the sensitivity of the cost-effectiveness results due to the reduced effectiveness of wetlands and sedimentation ponds in the winter months. In other words, in the winter months since there is ice, not all of the treatment systems will function as well, in reducing phosphorous.

Climate change is another factor to consider. With climate change comes the increased likelihood of severe rainfall, especially, which could bypass most solutions mentioned, such as the natural treatment systems and PRSs. These effects of climate change are in need of further research.

Future research is also needed on where to physically install sediments ponds in the MRW. As stated in Chapter 2, a SWAT model would be beneficial, since it could identify the areas of high sediment. Sediment ponds could, therefore, with this modeling, be installed in sediment ‘hot spots’, and this would render them more cost-effective.
There are not many studies that look at wetland benefits as reducing nutrients in waterways, and improving water quality of eutrophic water. More research in this area is also needed.

Additional research could also identify what to do with the corrective fee revenue. The government could give that money back to the farmers, or for some other environmental solution for the algal bloom problem, such as installing wetlands or other systems mentioned in this paper, where efficient to do so.
REFERENCES


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Jackwood, Ryan. Dept. of Environmental Sciences, University of Toledo. Personal communication. October, 2015.


University of Toledo USEPA Grant Proposal. “Reduction of Sediment and Bacteria Loadings to Public Beaches at Maumee Bay State Park via Enhanced Riparian Habitat.” EPA-R5-GL2012-1. 2012.


APPENDICES:

1. Map of the Maumee River Watershed

2. Data from the 2013 Ohio Lake Erie Phosphorus Task Force II (32)

<table>
<thead>
<tr>
<th></th>
<th>Water Year Total</th>
<th>Spring (March-June)</th>
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<tr>
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<td>Discharge m³/year (millions)</td>
<td>Total Phosphorus (tonnes/year)</td>
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<td>Mean (00-12)</td>
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<td>Mean (07-12)</td>
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3. Photos of the 2014 Algal Bloom on Lake Erie

Satellite image of 2013 intense bloom, which was concentrated in the lake's western basin. (Credit: MODIS/NASA, processed by NOAA/NOS/NCCOS). National Oceanic and Atmospheric Administration, 10 July 2014. Web.

4. Available Public Land in the MRW: GIS Map (50m away from waterway)
5. **20% P reduction target: 77% fee, 0.26 elasticity**

<table>
<thead>
<tr>
<th>Maumee (ag acres)</th>
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<tr>
<td><strong>Baseline</strong></td>
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<tr>
<td>Annual P application (kg/acre)</td>
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<td>Annual Application (1000 kg)</td>
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<td>Total cost of P (Millions $)</td>
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<td><strong>77% P fee</strong></td>
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<td>Reduction in P application in tons to achieve 1-ton reduction in output</td>
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6. **20% P reduction target: 67% P fee, 0.3 elasticity**

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<td>Total cost of P (Millions $)</td>
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<td><strong>67% P fee</strong></td>
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<td>Reduction in P output from watershed with 67% fee</td>
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<tr>
<td>Reduction in P application in tons to achieve 1-ton reduction in output</td>
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