An Analysis of Pollutant Removal Performance of Stormwater Wetland Basins in the International BMP Database

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EXECUTIVE SUMMARY

The International Stormwater BMP Database (Database) provides a voluntary repository for information on the pollutant removal performance of stormwater Best Management Practices (BMP). One of the categories in the database is Wetland Basins. Stormwater treatment wetland basins have been of interest as an effective way to reduce the concentration of pollutants in stormwater discharges. However, there is limited information on design criteria for optimum nutrient removal. This study investigated the pollutant removal performance of the wetland basins as it relates to the ratio of the basin's watershed area to the wetland basin area. Parameters included total suspended solids (TSS) and nutrients (Total P, Ortho P, Nitrate-N and Total Kjedahl Nitrogen - TKN.) The data set included inflow and outflow samples from each of the 12 wetland basins in the study. This data was used to calculate a mean pollutant removal for each pollutant for each of the wetland basins.

A sensitivity analysis was performed for all of the pollutants resulting in the exclusion sampling data for Total P and Ortho-P if the inflow values were measured at less than or equal to 0.1 mg/l. Regression analysis showed no statistically significant relationship between mean removal of pollutants with ratio of watershed area to wetland area except for TSS. However, the mean performance for pollutants' removal was at 50%, with total P at 60%, Ortho-P at 65% and Nitrate-N at 54%. TKN had the lowest mean percent removal at 27%. This suggests that regardless of relationship between the wetland area and watershed area, wetlands are effective at the removal of TSS and nutrients on a watershed basis. Suggestions for follow up are expanding the study to include wetland basins outside of the Database and for improvements of data requirements for the Database.

INTRODUCTION:

While the practice has been around for decades, the use of constructed wetlands for stormwater treatment is an increasingly popular choice among stormwater engineers and local government planners. A growing awareness of the impacts of nutrients and sediments on receiving waters and the potential for stormwater treatment wetlands to mitigate these impacts has fueled this interest. Also, there has been a general increase in public awareness of the importance of wetlands ecosystem and an acceptance, and sometimes even desire, for natural landscape in public spaces. Wetlands offer several advantages in that they passively use solar power to operate with little other energy required for operation and maintenance, in some cases they can achieve high levels of treatment, wetlands vegetation provides greenspace and wildlife habitat. (Malaviya and Singh, 2012.)

Typical contaminants of concern in stormwater runoff are total suspended solids (TSS), phosphorus (P) and nitrogen (N). Suspended solids can result in increased sediment load in receiving bodies of water impacting wildlife. Suspended solids can also adversely affect water temperature, light transmittance and dissolved oxygen content. Sediments can have negative effects on the depth of water in lakes and ponds, affect the morphology and hydraulic characteristics of streams and, if applicable, the uses of the water body for recreational, storage and/or water supply uses. (Ellis & Hvitved-Jacobsen, 1996.) TSS is also often a concern indirectly because of the pollutants in the solid phase which are in the suspension. In that case the resulting sediments would also be polluted (Rossi et al, 2013.) This sediment can have direct adverse impacts on the ecology of the waterbody and, if applicable, the uses of the water body for recreational, storage and/or water supply. Phosphorous and Nitrogen can lead to eutrophication in receiving water, especially lakes and ponds that have relatively little flow through them (Ellis & Hvitved-Jacobsen, 1996.) This can lead to low dissolved oxygen levels and create an imbalance in the wildlife habitat.

Stormwater treatment wetland basins have been of interest because they could be an effective way to reduce the concentration of pollutants in stormwater discharges while establishing an ecosystem that can support a wide variety of flora and fauna (Mitsch and Gosselink, 2007.) Examples of regulations that govern the use of constructed wetlands for stormwater treatment include the Denver Urban Drainage and Flood Control District (UDFCD, 2011) and the Chesapeake Preservation Area guidance in Virginia (Virginia Department of Environmental Quality, 2013.) Ideally these wetlands would be planted with a variety of native species. A proper design would provide for a hydroperiod that would support and promote the native species, discourage exotic and/or invasive species, and facilitate the flow management desired (Persson, et. al., 1999.) The primary pollutants of concern that are sought to be treated in these wetland basins are usually nutrients (N, P and TSS). Although on occasion E. coli, metals and some organics are also included as treatment objectives.

Data to support the potential performance of constructed wetlands with design methods is substantially lacking (Mitsch and Gosselink, 2007.)   Carleton, et. al., (2000) compiled data from 39 published studies and analyzed to determine pollutant removal effectiveness with the size of the wetland area. The Carleton study showed exponential relationships between percent removal TSS, Total P, total N, ammonia (NH_3), nitrate (NO_3), total Pb, total Cd, total Cu, and total Zn; and the Wetland area to Watershed area ratio. This would be consistent with the hypothesis showing that increasing the size of the wetlands relative to the watershed would improve the pollutant removal performance.

The International Stormwater BMP Database (http://bmpdatabase.org/) (Database) is a voluntary compilation of information on stormwater best management practices (BMPs) that have been installed at various locations predominately in the continental United States. BMPs are structures or practices designed to decrease the adverse impacts of stormwater discharges. Most typically, these are discharges resulting from changes of land use from their native state for the purpose of development, agriculture or silviculture. The International BMP Database 2016 Summary Statistics (Clary, et. al., 2017) provides information on the range pollutant removal for key BMPs including the stormwater basins. This summary provided a range of median and quartile removal performance for some of the key pollutants including TSS, P and N compounds, as well as some bacteria and metals. However, this summary analysis does not include the properties of the individual wetlands and their watersheds. The summary analysis simply shows the removal data from all the stormwater treatment wetlands in the Database. Clar, et. al. (2004) gives only the median removal value of the pollutants and it dates back to 2004. A recent compilation of percent pollutant removal with a range of performance values was published but with no statistical analysis of the data (Liu, et. al., 2017). Other studies done in Europe (Fisher and Acreman, 2004 and Vymazal, 2006) perform a summary review of wetland removal efficiencies. However, these studies do not include a formal evaluation of pollutant removal performance as it relates to the watershed area and size of the wetlands. Mitsch and Gosselink (2007) cite the Schueler study (1992, not in print) which gives a summary of mean pollute removal efficiencies.

There are some popular design criteria for constructed wetlands. The one that is used most commonly in the Rocky Mountain Region is that of the Denver Urban Drainage and Flood Control District (UDFCD, 2011) with specific criteria based on the size of the watershed. This procedure calculates a Water Quality Capture Volume (WQCV) based on an equation which is third order for the impervious area and multiplied by a drawdown factor. This unit is then multiplied by 0.75 to give a volume of the permanent pool. However, while some general concepts are given for the depth range of the wetlands there is no explicit guidance on the area of the wetland or the permanent pool.

The Virginia Department of Environmental Quality uses The Runoff Reduction Method, which is guidance for implementing The Chesapeake Preservation Act (Battiata, et. al., 2010) and provides for an effective phosphorous removal in wetlands of 75% (Virginia Water Resources Research Center, 2013.) Guidance for constructed wetlands for the Runoff Reduction Method again deals primarily with volume but does stipulate a maximum surcharge depth (depth above normal water level) which does work out to establishing a minimum wetland surface area.

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The BMP Database was sponsored by the Water Environment Research Foundation (WERF), the American Society of Civil Engineers (ASCE)/Environmental and Water Resources Institute (EWRI), the American Public Works Association (APWA), the Federal Highway Administration (FHWA), and U.S. Environmental Protection Agency (USEPA).   The users of the Database are primarily researchers.   The most useful information for a quick overview of BMP performance is the Narrative Overview of BMP Database Study Characteristics (Wright Water Engineers, Inc.

Geosyntec Consultants,2012). However, as will be discussed the information in the Database has severe limitations. The Database has some guidelines as to how the data is to be formatted but there are no requirements how the data is collected or how complete the data is when submitted. The Database has compiled BMP data for a total of over 500 individual BMPs and 30 types of BMPs. These are mostly structural BMPs that range from simple traditional BMPs such as detention basins to more recent innovations such as green roofs.

This paper is focused on the BMPs data categorized as stormwater wetlands basins. There is also a category of wetlands channels, but these were not part of the scope of this work. The design of stormwater treatment wetlands varies widely. Figure 1 illustrates a wetland that shows a forebay, a permanent pool and an aquatic bench that is not permanently inundated. Some wetland basins have forebay which ranged from being small to very large relative to the wetland. In some cases there is no forebay. A forebay is a small pond, pool or open water placed immediately upstream of the wetland basin to allow for the settling of solids in order to reduce the sediment load on the wetlands. Excessive sediment in the wetlands can adversely impact the ecology of the wetlands and reduce its effectiveness in removing pollutants. The sediments in the forebay are more easily removed and doing so will not as significantly impact wetland system ecosystem. The absence of a forebay result often in frequent dredging of the planted portion of the wetland Some wetlands have a permanent pool area and others do not.

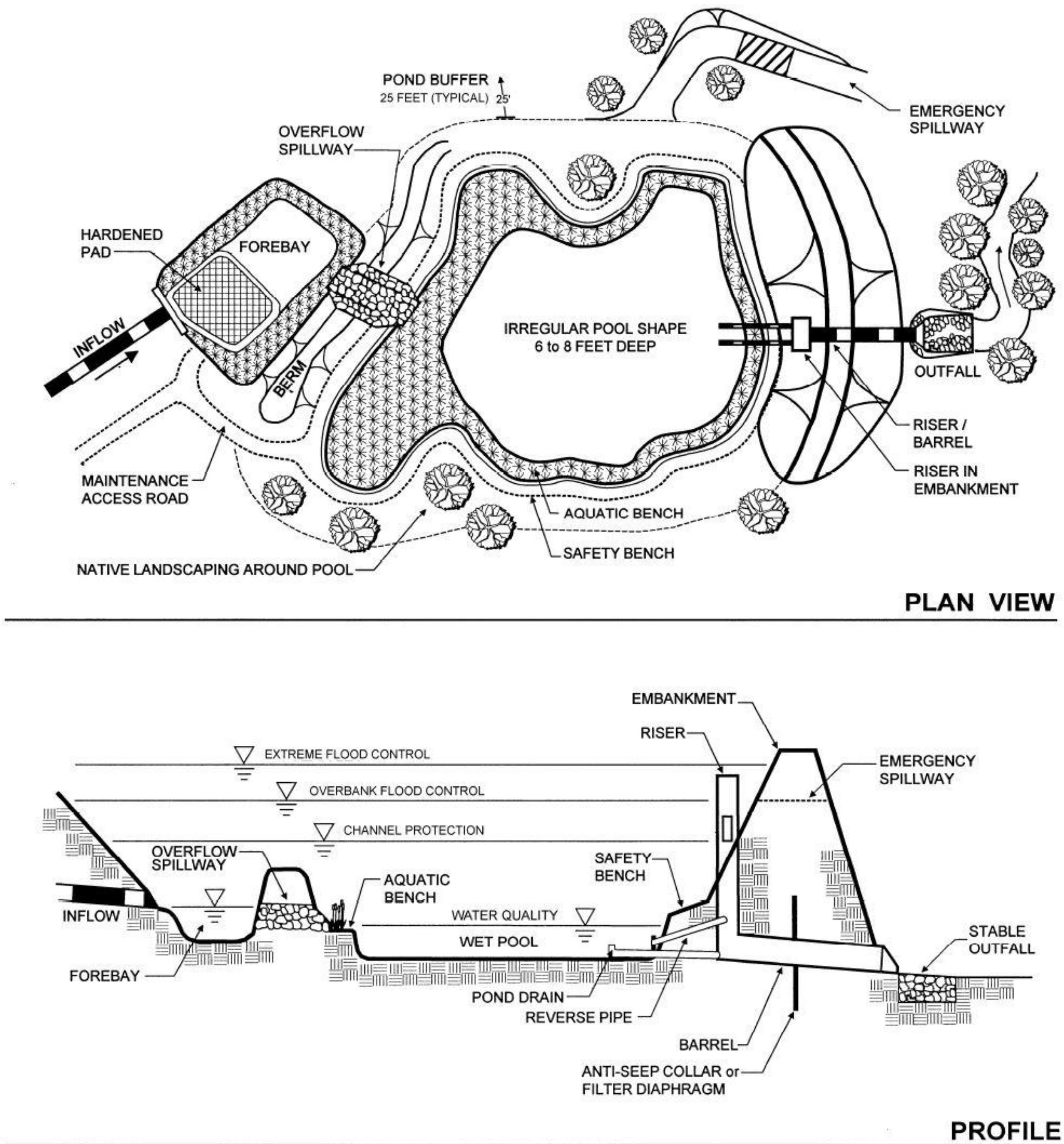

Figure 1. Wetland Sketch from USEPA Stormwater Wet Pond and Wetland Management Guidebook (Center for Watershed Protection, 2009)

It is often assumed that there is correlation between the size of the wetland relative to the watershed area and the pollutant removal efficiency. There are design criteria that often require BMPs, including wetland basins, based on this assumption (VDEQ 2013 and UDFCD 2011.)

However, there is limited published information that validates this assumption as discussed earlier. Wetlands remove pollutants by two primary mechanisms (Vymazal, et. al, 1998). The first mechanism is by the settlement of solids by slowing the flow of the water down. The settlement of solids removes particulate matter, and this usually includes metals and nutrients in the solid phase. So, it would be expected that increasing the surface area of the wetland, relative to the watershed, would allow for more settlement of suspended particles leading to a reduction of TSS and other solid phase pollutants.

The second mechanism for pollutant removal associated with wetlands systems is nutrient uptake by the wetlands plants (Brix, 1997; Greenway, 2003). This activity is normally associated with pollutants entering the system in a soluble state.

However, the chemical and biological activity in a wetland is quite complex. It is dependent on many factors such as:

- The ambient temperature, both immediate and seasonal, affects both biological and chemical activity, plant growth and the resulting nutrient uptake, and the rates of chemical reactions. It also affects the dissolved oxygen in the system which can affect oxidation/reduction reactions.

- The plant species in the wetlands affect the rate of uptake of nutrients and the currents which move through the water. The former would primarily affect nutrients in the dissolved state and the latter in the solid phase but even here there is some interaction.

- The depth of the wetland can increase the mean residence time which can also be a factor in the settlement of solids. It can also affect the resuspension of wetlands and the temperature profile in the water column.

- The amount and type of wildlife in the wetlands is also a factor. Animals can introduce wastes that add to the solids and nutrients in the wetlands.

Those are just a few of the many factors that affect the complicated wetlands ecosystems. So, it is difficult for any type of analysis to reflect all of the aspects of wetland systems that vary from one system to another.

This paper compiled and analyzed several nutrients data in the Database determine if a relationship exists between percent pollutant removal and the size of the wetland relative to the watershed. This information will be of use to designers and regulators in predicting the performance of the treatment efficacy of stormwater treatment wetlands.

HYPOTHESIS:

It is hypothesized that there is a negative correlation between the pollutant removal performance and the WSA:PPA and WSA:TWA ratios. This result is expected because the larger watershed area, relative to the area of the wetlands, would reduce the residence time during which the pollutant removal could occur and/or reduce the area available for settling and other reactions. The hypothesis will be tested by performing linear and exponential regressions of the correlations and calculating the statistical significance of each correlation.

OBJECTIVES:

The objective of this research is to evaluate nutrients and TSS removal performance of individual wetlands basins in the Database and correlate them to the ratio of the size of the watershed to the area of the wetlands basins. This analysis may allow for a better prediction of the pollutant removal effectiveness based on the wetland and watershed characteristics.

METHODOLOGY:

This study evaluated the TSS and nutrients (Total P, Ortho-P, Nitrate-N and TKN) removal efficiency. The data used in this project was gathered from different tables in the Database. A comprehensive excel sheet was developed to consolidate the data. To avoid the potential of transcriber's errors an effort was made by the author to carefully review the compiled spreadsheet. Considerable time and effort was spent on manually cross-checking to eliminate any errors.

The compiled spreadsheet included data from all of the wetland basins for which there was information on the surface area of the permanent pool, the surface area of the wetland and the size of the watershed. Some of the basins had precipitation data, however this data was severely limited and was not used in the final analysis.

Because of the limited number of wetlands that had separately listed forebays, it was decided to combine the areas of the forebays and the permanent pool area into one surface area for each wetland basin. So, when the wetland basin permanent pool area and the total wetland area are discussed they included the areas of forebays when present. In addition, because of the limited data for the volume of the wetland there was no attempt to correlate that removal efficiency to volume of the wetland. This is unfortunate because the mean residence time would have been a possible significant factor for removal efficiency of the wetlands. However, in most cases the permanent pool volume is not a primary design criterion, if it is one at all. The design requirements in the Urban Drainage and Flood Control District (UDFCD, 2011) and the Virginia Runoff Reduction (Virginia Department of Environmental Quality, 2013) method are surface area of the wetland and temporary storage volume above the permanent wetland area. These two specifically address constructed wetlands as a water quality BMP. The volume above the permanent pool and drawdown time (which ends up setting a minimum surface area) are also the regulatory design requirements for stormwater treatment wetlands in Manhattan, Illinois (Village Ordinance 6-2B-4-6: Site Runoff Storage Facility Design Requirements H.2.) and Romeoville, Illinois (Village Ordinance § 160.035 Site Runoff Storage Facility Design Requirements I.2.). In those two regulations they are referred to as naturalized systems to avoid confusion with regulatory wetlands. These regulations are not explicitly referred to as a water quality BMP but are encouraged for that reason. The use of constructed wetlands as stormwater BMPSs are often favored by developers in north central U.S. for reasons of soil management because it allows for the backfilling of excess topsoil into the clay borrow areas. The downside constructed wetlands as BMPs is that in urban and suburban areas the natural and native plantings are not favored by the adjacent homeowners.

The data compiled for this project included inlet and outlet concentrations for each wetland basin for each parameter and sampling event. The mean percent removal for each parameter for each wetland basin was first calculated using two methods. The first method used was to sum the inflow values for each parameter, sum the outflow values for each parameter and use of the ratio of those two sums to calculate an average percent removal for each parameter. The second method was to calculate the percent removal each event for each parameter, sum those percent removals and obtain a mean. Only positive removal values were included in this average. The two methods yielded different results and it was apparent that a few events with large removal quantities could skew the overall average of the percentage removal. Therefore the second method was used in the final analysis.

This study included the nutrients for which there were a sufficient number of wetland basins with data on the pollutants to do an analysis. The parameters included in the analysis are total Kjedahl nitrogen (TKN), nitrate nitrogen (NO3-N), total phosphorous (Total P), ortho phosphorous (Ortho P), and total suspended solids (TSS).

We conducted correlation analysis involving watershed area (WSA) and its ratios with the permanent pool area (PPA) and the total wetland area (TWA) of the receiving wetlands system. The data for the ratios of the watershed area to the permanent pool area of the wetlands (WSA:PPA); and the watershed area to the total wetland area (WSA:TWA) were correlated, plotted and statistically analyzed.

Sensitivity analysis

During the initial analysis of the data, it was observed that with low inflow concentrations, there was often little removal measured or many cases where the outflow concentrations exceeded the inflow concentrations.

Sensitivity analysis was then performed to test if low input values of the various pollutants in the database may be biasing the results and influencing the pollutant removal performance. The objective of the sensitivity analysis was to determine if some low inlet values were disproportionately lowering the mean removal rates.

For the sensitivity analysis all of the data for each pollutant was first included and then reanalyzed removing samples with low inflow concentrations. 0.1 ppm increments were used except that the first step for both Total P and Orth P was 0.05 ppm. The results of the sensitivity analysis are shown in Table 1.

The percent positive removal samples were calculated by totaling all samples remaining that showed a positive removal and then dividing by the total number of samples remaining. That is an indication of the breadth of the effectiveness of the pollutant removal. When there are relatively more samples with a negative removal rate (outlet concentration is higher than the inlet concentration) then the mean positive removal rate is less significant because it reflects fewer of the samples.

The site mean positive removal was calculated by adding up the positive removal percentages for the pollutant for each site and dividing by the total number of positive removal samples for that pollutant for the site. The range of means is reported in Table 1. The mean positive for removal for a pollutant was calculated by adding up the mean positive removal percentages for each site and dividing by the total number of sites with a positive removal percentage. This is an indication of the overall removal performance by the wetlands for the pollutant.

For Total P the percent of samples showing a positive removal ranged from 69% to 86% when inflow concentrations equal or below 0.1 ppm were excluded. The mean positive removal increased from 50% to 60% and the lowest positive removal value increased from 19% to 36%. This cutoff excluded 38% of the samples from the analysis. The statistical analysis was then conducted while removing all data <=0.1 ppm Total P.

The results for Ortho P with a less than or equal to 0.1 ppm elimination were even more significant with an increase in the mean from 25% to 68% percent. However, that also excluded 75% of the samples for Ortho P. The statistical analysis was then conducted while removing all data <=0.1 ppm for Ortho P.

The reasons for the breaks in Total P and Ortho P performance are not clear. The issue with Total P may be a resuspension of the solids portion of the Total P that this outweighs the inflow concentration. It is also possible that stormwater wetlands are not as effective in reducing low inflow concentrations of Total P. The more marked effect for Ortho P leads to the latter. It would seem to indicate that there is a baseline release of P from the system without regard to the lower inflow values. Another detailed analysis of performance based on low inflow concentration would be a good topic for further study.

For TSS, NO_3-N and TKN there was no significant improvement in performance at a given break. Therefore, all of the data were retained for those pollutants, but the statistical analysis and results presented in upcoming sections eliminate the values of less than or equal to 0.1 ppm for both Total P and Ortho P. Further discussion of Table 1 is included in the Results section

Table 1: Summary of Data for Sensitivity Analysis

		Total Samples	Total Sites w/data	Sites with Positive Removal Samples	Total Positive Removal Samples	Percent Samples Excluded	Percent Positive Removal Samples	Site Positive Removal Means Range	Mean Positive Removal
Total P	All Data	153	11	11	106	0%	69%	19%-77%	50%
	<=0.05 excluded	132	11	11	101	14%	77%	23%-76%	53%
	<= 0.1 excluded	95	11	11	82	38%	86%	36%-77%	60%
	<= 0.2 excluded	51	10	10	45	67%	88%	47%-93%	70%
	<= 0.3 excluded	47	10	10	42	69%	89%	47%-93%	72%
Ortho P	All Data	102	7	5	26	0%	25%	34%-92%	62%
	<=0.05 excluded	77	7	5	21	25%	27%	40%-94%	66%
	<=0.1 excluded	25	6	5	17	75%	68%	36%-94%	65%
NO3-	All Data	101	9	9	75	0%	74%	7%-70%	54%
	<=0.1 excluded	95	9	9	73	6%	77%	7%-74%	56%
	<=0.2 excluded	82	9	9	63	19%	77%	10%-98%	53%
	<=0.3 excluded	61	7	7	49	40%	80%	32%-86%	65%
	<=0.4 excluded	50	7	7	40	50%	80%	16%-89%	68%
	<=0.5 excluded	35	6	5	29	65%	83%	18%-98%	70%
TKN	All Data	43	7	5	24	0%	56%	27%-63%	52%
	<=0.3 excluded	42	7	5	23	2%	55%	27%-63%	52%
	<=0.5 excluded	35	7	5	23	19%	66%	27%-63%	52%
TSS	All Data	143	11	10	126	0%	88%	53%-97%	75%
	<=10 excluded	132	11	10	119	8%	90%	53%-97%	75%
	<=20 excluded	120	11	10	110	16%	92%	53%-97%	77%

The final master spreadsheet included basins with complete information for the analysis from 12 sites (Table 2). These were located as follows: Deer Park, TX; Harris, TX (3); Houston, TX; Mays Chapel, MD; Queen Anne, MD; Prince George, MD; Vancouver, WA (2); Portland, OR; and Orlando, FL. These only represent sub-tropical (with Maryland bordering on the northern end of the range) and Mediterranean climates. There were no basins with sufficient data in cold weather or arid climates. This is unfortunate because there is increasing interest in these facilities in colder and drier climates.

The range of impervious areas for the watersheds were reported to be from 19% to 100%. The impervious areas of most of the watersheds were in the range of 35% to 55%. The primary land use was suburban residential, followed by roads. One site was light institutional, and one was rural residential. There was one site with no land use information. There was no attempt made to correlate the impervious cover with the either the inflow into the wetland or the removal efficiency due to the already limited number of data points.

The total range of time over which the sampling events occurred was from 1987 to 2013 with time data not available for one site. The time period of sampling for any individual site was from 2 to 6 years with most sites having a sampling range of 3 to 4 years. Sampling intervals were not regular, sometimes even within sites, but in general ranged from monthly to quarterly. Table 2 gives summary information on each of the wetland basins including surface and watershed areas, and the range of sampling dates.

A mean percent removal was calculated for each of the pollutants considered at each of the sites. The mean values were then plotted against the Watershed area to Total Wetland Area ratio (WSA:TWA) and Watershed Area to Permanent Pool Area ratio (WSA:PPA). The WSA:TWA is the ratio of the watershed compared to the entire area of the wetland system including both intermittently inundated areas and areas that are permanently covered with water. The WSA:PPA is the ratio of the watershed area compared to the Permanent Pool Area that only includes areas that are permanently covered with water.

Table 2: Summary of the data obtained from the Database and used in the data analysis.

Location	WSA	PPA	PPA AS % of WSA	FA	PPA+FA	WSA: (PPA+FA)	TWA	TWA+FA	WSA: (TWA+FA)	Sampling Data Range	Years of Data
	Ha	ha		ha	ha		ha	ha			
Vancouver, WA	5.80	0.15	2.6%	0.06	0.21	27.3	0.26	0.32	18.2	2010-2012	3
Queen Anne, MD	6.48	0.24	3.7%	0.00	0.24	26.7	0.49	0.49	13.3	1987-1989	3
Harris, TX	9.31	3.48	37.4%	0.25	3.73	2.5	3.77	4.01	2.3	2008-2013	6
Vancouver, WA	9.60	0.24	2.5%	0.06	0.30	32.5	0.39	0.45	21.2	2010-2012	3
Portland, OR	10.10	0.17	1.7%	0.00	0.17	58.8	0.25	0.25	40.0	1998-1999	2
Harris, TX	31.28	1.01	3.2%	0.16	1.17	26.7	1.21	1.38	22.7	2009-2013	5
Houston, TX	35.61	15.88	44.6%	0.00	15.88	2.2	6.12	6.12	5.8	2004-2007	4
Mays Chapel, MD	39.46	0.28	0.71%	0.00	0.28	139.3	0.28	0.28	139.3	No Data	
Prince George, MD	40.47	0.40	0.99%	0.00	0.40	100.0	1.62	1.62	25.0	1987-1990	4
Orlando, FL	213.28	5.26	2.5%	0.00	5.26	40.5	5.26	5.26	40.5	1993-1994	2
Harris, TX	439.08	4.05	0.92%	0.30	4.35	101.0	4.62	4.91	89.4	2008-2012	5
Deer Park, TX	463.37	4.01	0.87%	0.53	4.54	102.1	18.91	19.44	23.8	2010-2013	4

WSA = Watershed Area; PPA = Permanent Pool Area; FA = Forebay Area; TWA = Total Wetland Area

RESULTS:

<u>Pollutant Removal Performance of the Wetlands Relative to the Size of the Basin and Watershed</u>

Figures 2 -11 show linear regression graphs of the correlations between the percentage pollutant removal versus WSA:PPA or WSA:TWA for the various parameters analyzed. The exponential relationship curves were not shown as they are visually almost identical to the linear regression lines. Regression lines with discernable negative slope indicate higher performance at lower ratios of watershed area to total wetland area or permanent pool area (so larger wetlands area relative to the watershed area) and lower performance at higher ratios (smaller wetlands relative to the watersheds) which would be consistent with the hypothesis for this study.

However, the graphs for Total P (figures 2 and 3) have a slight positive slope but it has an extremely poor correlation and they are not statistically significant. This lack of correlation does not support the hypothesis and there does not seem to be any relationship between the percent removal of TP with the size of the constructed wetland.

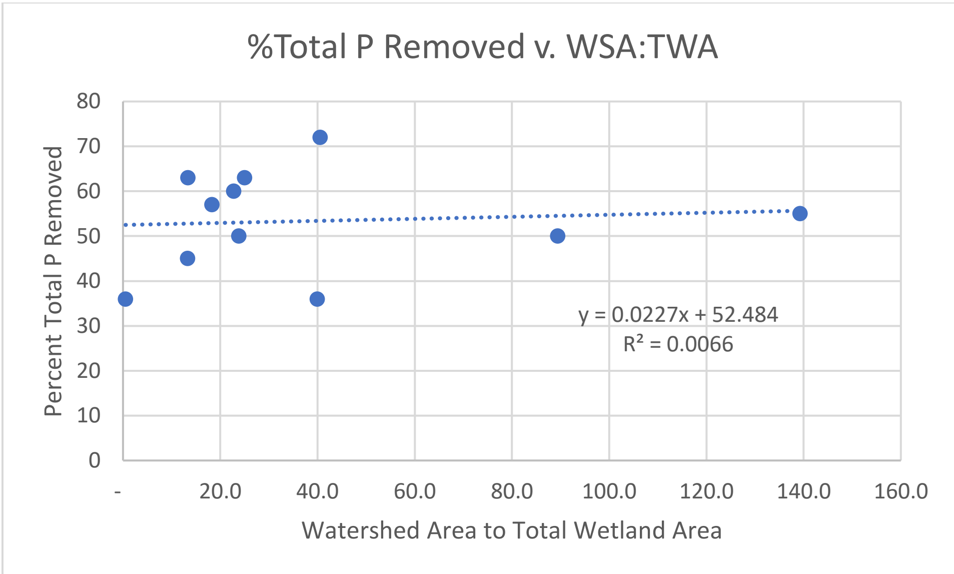

Figure 2. A graph of the percent Total P removed verses the WSA:TWA ratio.

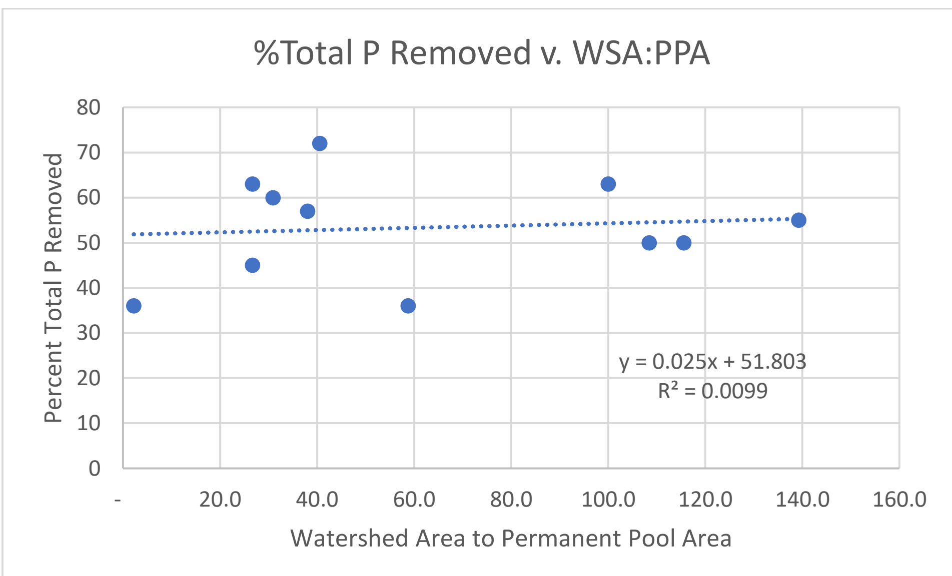

Figure 3. A graph of the percent Total P removed verses the WSA:PPA ratio.

Figure 4 shows the Ortho P relationship between the percent pollutant removal and the WSA:TWA area ratio. It show a very slight negative slope but is not statistically significant. Figure 5 shows the regression for the percent removal versus the WSA:PPA ratio for Ortho P. And while the slope is still negative, steeper and has a higher correlation than the line in Figure

4, it is still not statistically significant. The small sample size that was used for ortho-P analysis may explain the lack of significance.

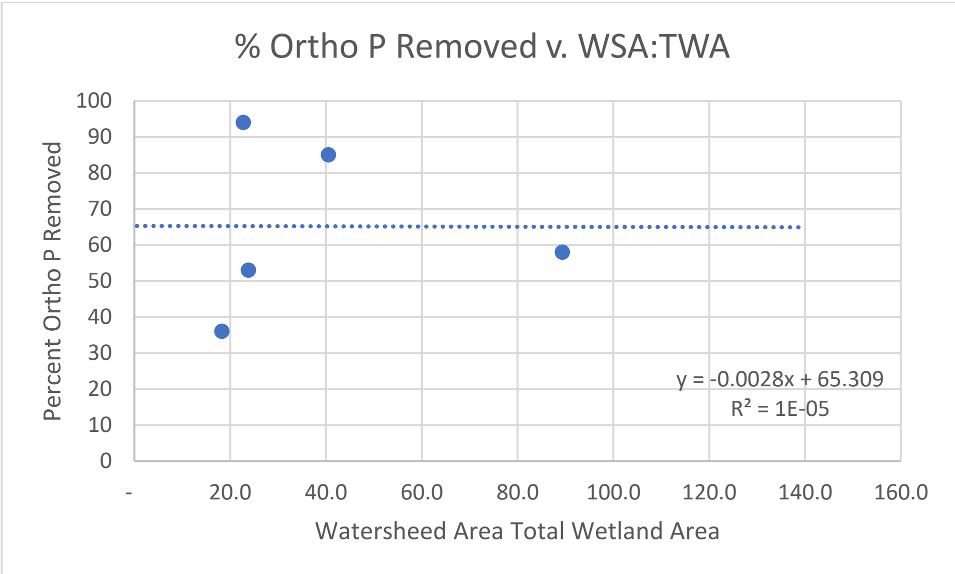

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Figure 4. A graph of the percent Ortho P removed verses the WSA:TWA ratio.

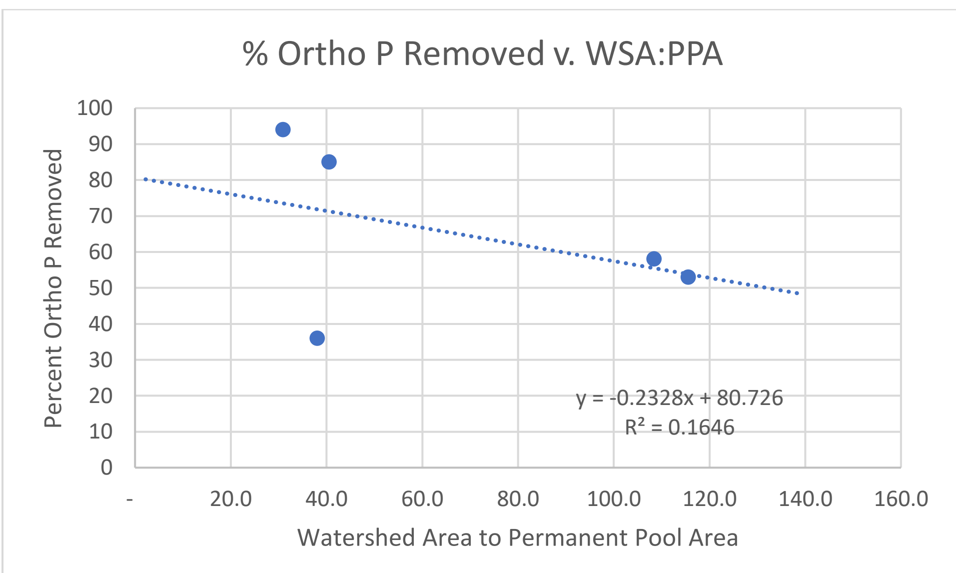

Figure 5. A graph of the percent Ortho P removed verses the WSA:PPA ratio.

Figure 6 shows the linear relationship between the percent removal for nitrates verses the WSA:TWA ratio. The line R^2 is low and is not statistically significant. While there is a point that appears may be an outlier, removing that point from the plot did not make a difference in the statistical analysis. Figure 7 shows the relationship for percent nitrate removal and the WSA:PPA ratio. While it shows a slightly negative slope it once again is not statically significant.

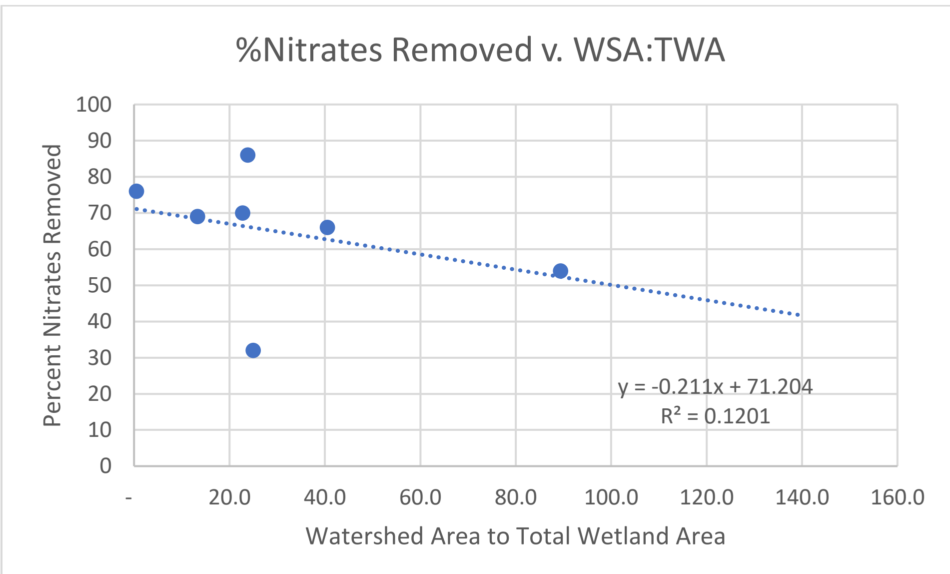

Figure 6. A graph of the percent Nitrates removed verses the WSA:TWA ratio.

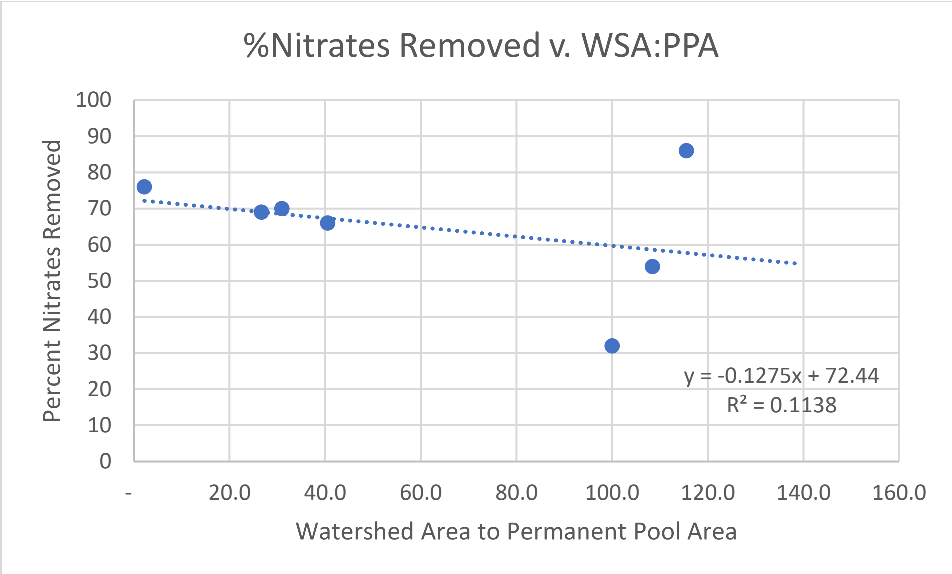

Figure 7. A graph of the percent Nitrates removed verses the WSA:PPA ratio.

Figures 8 and 9 show the linear regressions for the percent TKN removal verses the WSA:TWA and WSA:PPA ratios respectively. Both show a slightly positive slope, which would be counter to the hypothesis. But again, the relationships are not statistically significant.

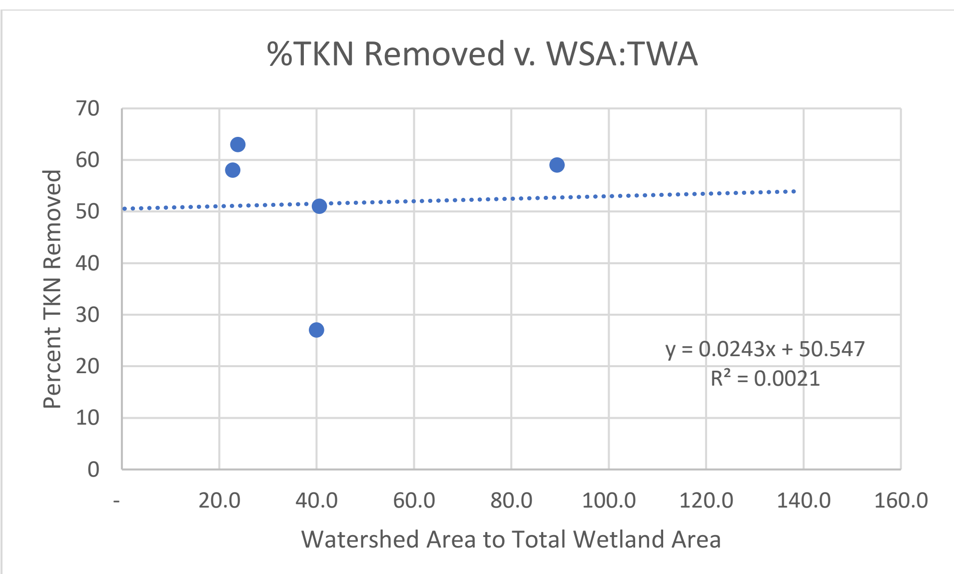

Figure 8. A graph of the percent TKN removed verses the WSA:TWA ratio.

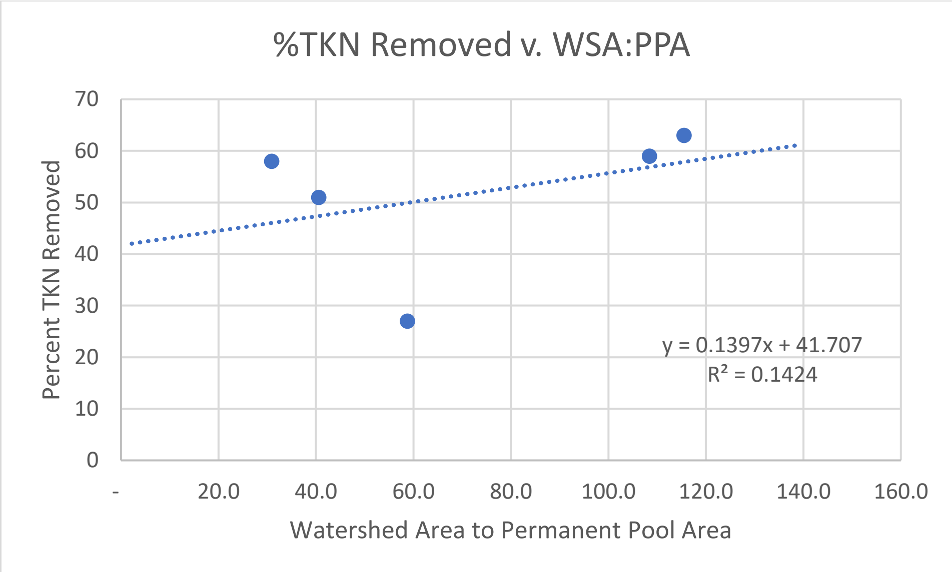

Figure 9. A graph of the percent TKN verses the WSA:PPA ratio.

Figure 10 shows the linear plot of the percent removal for the WSA:TWA ratio and Figure 11 for the WSA:PPA ratio. While both show a negative slope, only the relationship between TSS removal and e WSA:PPA ratio is statistically s significant (Figure 11)

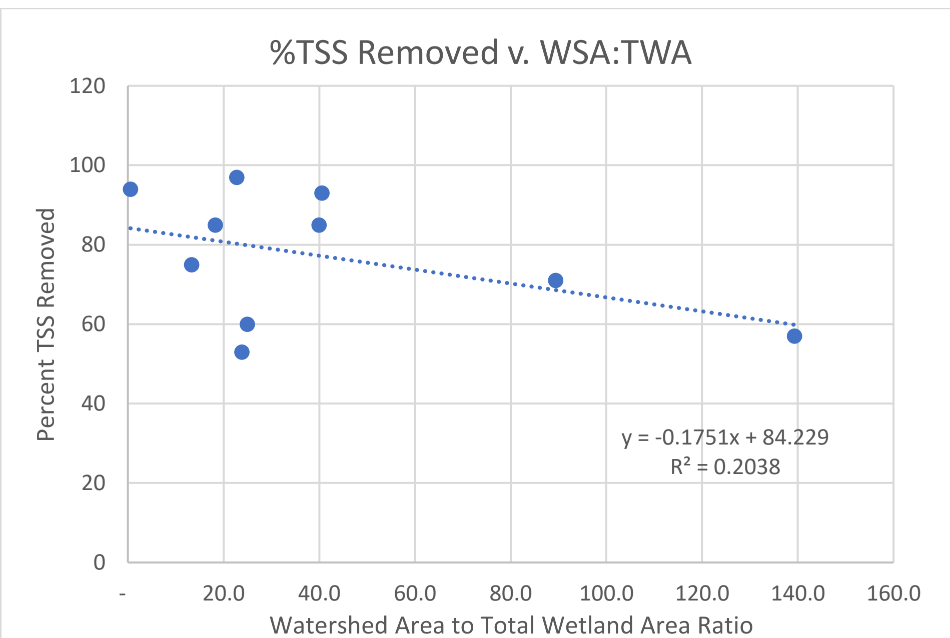

Figure 10. A graph of the percent TSS removed verses the WSA:TWA ratio.

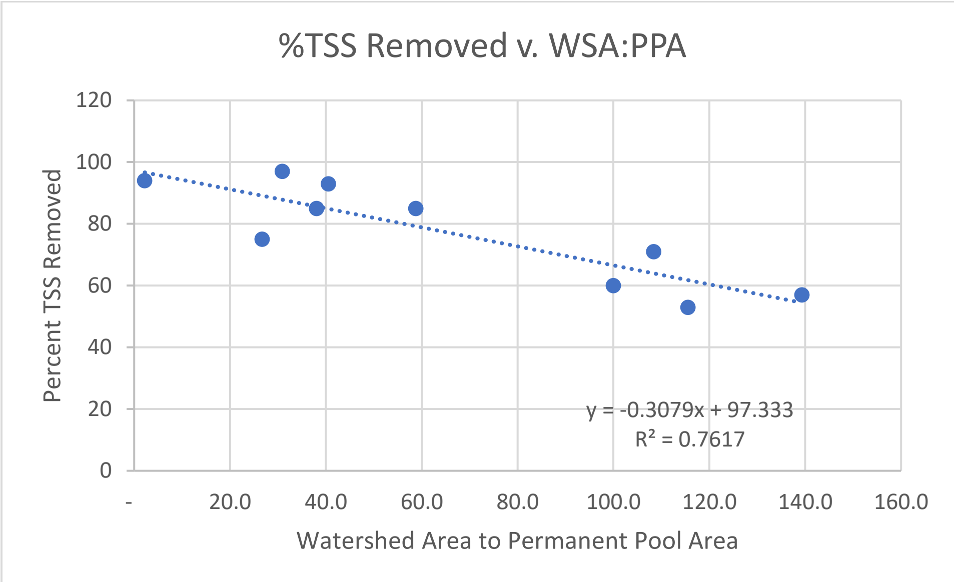

Figure 11. A graph of the percent Total P removed verses the WSA:PPA ratio.

A statistical analysis was performed to determine the statistical significance of correlation analysis (Figure 2 through 11.) Both a linear and exponential relationship were examined. The regression analysis was performed in Excel using the LINEST and the LOGEST functions. The LINEST is a simple linear regression analysis. The LOGEST function calculates an exponential curve. The values returned by the LOGEST function were used in the statistical analysis with R^2 and F values presented. Lines were placed on the graphs using the trendline function in the Excel scatter plot.

The results of the statistical analysis are shown in tables 3-6 with the statistically significant values highlighted in yellow. For the regressions, the X values were the WSA:TWA or WSA:PPA as applicable and the Y values were the percent pollutant removal for each pollutant. A P value of less than 0.05 was considered to be statistically significant.

The statistical summary for the linear regression of WSA:PPA ratios for all of the pollutants in the study are presented in Table 3. Of all the parameters, only the TSS relationship was statistically significant. Table 4 shows the statistical summary for the linear relationship for the WSA:TWA ratios for all pollutants and none of the values were statistically significant.

Table 3. Linear regression statistics for percent removal of pollutants verses the WSA:PPA ratio.

WSA:PPA LINEST							
	Slope	**R^2**	**Points**	**F stat**	**DF 1**	**DF 2**	**P value**
Total P	0.0250	0.00993	11	0.0903	**1**	9	**0.771**
Ortho P	-0.233	0.165	5	0.591	**1**	3	**0.498**
NO3-	-0.127	0.114	7	0.642	**1**	5	**0.459**
TKN	0.140	0.142	5	0.498	**1**	3	**0.53**
TSS	-0.308	0.762	10	25.6	**1**	8	**0.00098**

Table 4. Linear regression statistics for percent removal of pollutants verses the WSA:TWA ratio.

WSA:TWA LINEST							
	Slope	**R^2**	**Points**	**F stat**	**DF 1**	**DF 2**	**P value**
Total P	0.0227	0.01	11	0.06	**1**	9	**0.81**
Ortho P	-0.0028	0.000012	5	0.000036	**1**	3	**1.00**
NO3-	-0.2110	0.12	7	0.68	**1**	5	**0.45**
TKN	2.43E-02	0.00210	5	0.006304	**1**	3	**0.94**
TSS	-0.1751	0.20	10	2.05	**1**	8	**0.19**

Table 5 shows the logarithmic relationship for the WSA:PPA ratios for all pollutants and again only the TSS ratio is statistically significant and with a p value very close to the p value for the linear relationship. Figure 6 shows the logarithmic relationship for the WSA:TWA ratio for all pollutants, again showing no statistically significant relationships.

Table 5. Logarithmic regression statistics for percent removal of pollutants verses the WSA:PPA ratio.

WSA:PPA LOGEST						
	R^2	Points	F stat	DF 1	DF 2	P value
Total P	0.621	5	4.92	**1**	3	**0.11**
Ortho P	0.079	5	0.256	**1**	3	**0.65**
NO3-	0.114	7	0.642	**1**	5	**0.46**
TKN	0.104	5	0.349	**1**	3	**0.60**
TSS	0.766	10	26.2	**1**	8	**0.00091**

Table 6. Logarithmic regression statistics for percent removal of pollutants verses the WSA:TWA ratio.

WSA:TWA LOGEST						
	R^2	Points	F stat	DF 1	DF 2	P value
Total P	0.0816981	5	0.267	**1**	3	**0.64**
Ortho P	0.00779	5	0.0236	**1**	3	**0.89**
NO3-	0.152	7	0.899	**1**	5	**0.39**
TKN	0.00307	5	0.00923	**1**	3	**0.93**
TSS	0.196	10	1.95	**1**	8	**0.20**

The y-axis for regressions is percent pollutant removal, and the x-axis is the Watershed Area to Permanent Pool Area (WSA:PPA) and Total Wetland Area (WSA:TWA) respectively.
alpha = 0.05

This analysis seems to indicate that the area of the watershed relative to wetland areas may not be an important factor influencing removal efficiency of nutrients except for TSS. Our hypothesis, which is that there would be a negative correlation between the pollutant removal and the ratio of the size of the watershed to the size of the wetland basis, was supported for TSS removal relationship WSA:PPA, and was rejected for all other parameters.

Mean positive removal for each pollutant is presented into a box whisker plot (Figure 12). The bars on the top and bottom each plot represent the high and low values. The box represents the lower limit of the second quartile and the upper limit of the third quartile. The bar in the middle represents the median and the X represents the mean.

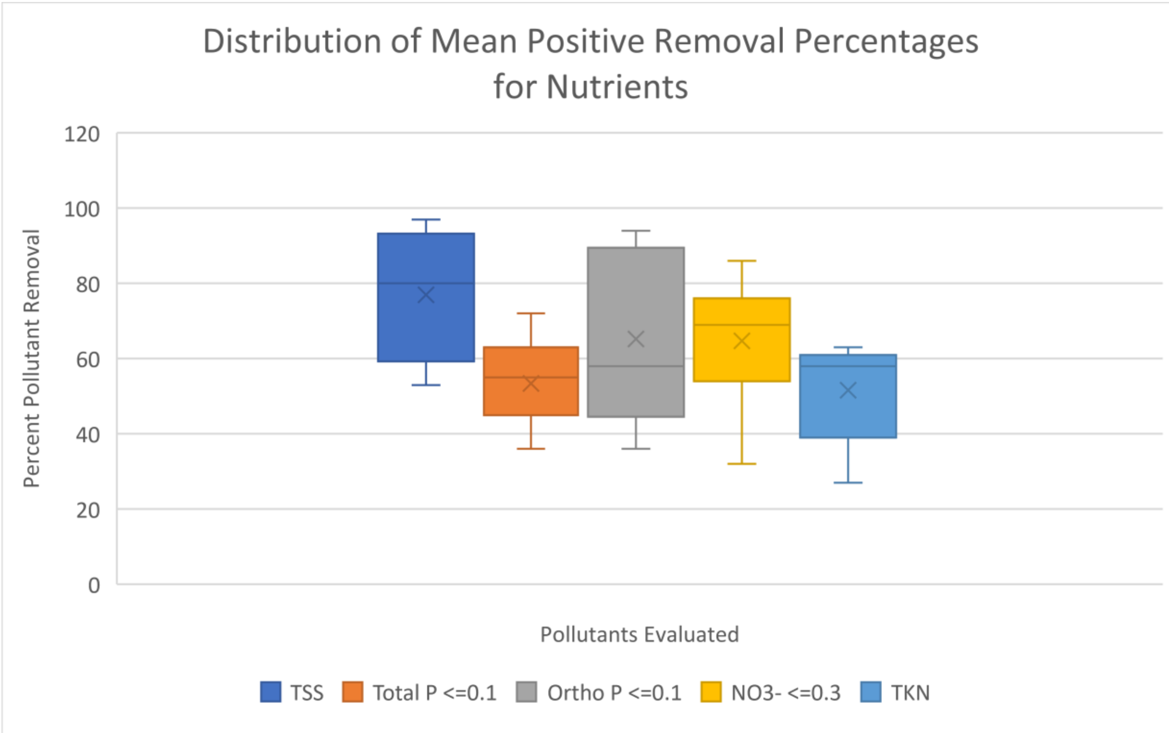

Figure 12. Distribution of mean positive removal percentages for nutrients.

Although we did not find any correlations between the percent nutrient removal and the size of the wetlands to the watershed (except for TSS), the wetlands performed relatively well (Figure 12, Table 1). The mean pollutant removal for the wetlands, when effective, was over 50% and the worst case, TKN still had a low mean percent removal of 27%. In the middle, with the following means, were Total P: 60%, Ortho-P: 65% and Nitrates: 54%. One interesting observation is that while Total P had the most number of sites (11) it had the second lowest range of means, second only to TKN which tied with Ortho P for the fewest number of sites (5.) Ortho-P in fact had the widest range of means.

DISCUSSION:

Our results, based on this limited dataset that could be used from the Database, do not show a relationship between the size of the wetlands relative to the size of the watershed and the removal performance for nutrients. Our hypothesis was that there would be a negative correlation between the size of the watershed to wetland area ratio and pollutants removed. The results showed that, for this dataset from the Database, this is only true for TSS and only for that ratio with the permanent pool area. There is a limited amount of studies that relate the performance of pollutant removal to the size of the watershed relative to the size of the wetland. A study by Carleton, et. al. (2001) found a correlation between the size of the wetland relative to the size of watershed only when it was plotted logarithmically. Whereas the results of the analysis for this paper found a statistically significant relationship for TSS only for both logarithmic and linear correlations. The Carleton study (2001) was comprehensive reviewing 35 studies from 49 wetlands systems in the US. The larger number of data points may have contributed to the greater number of correlations which were statistically significant. For many of the pollutants in this study the degrees of freedom were low. The Carleton study found an exponential relationship between the pollutant removal of the wetlands and the ratio of the wetlands area to the size of the watershed for TSS and nutrients (Total P, Total N, Nitrates and NH_3), among other pollutants. Carleton's analysis included both positive removal values and negative removal values in its analysis while our study only included positive removal values.

Fisher and Acreman (2004) conducted a very extensive study using data and databases from different continents but limited to N and P related primarily to natural wetlands systems. Their study found that for most sites, as loading relative to the wetland size increased the percent removal decreased on a logarithmic plot. If it is assumed that loading, on average, is related to the size of the watershed this would be consistent with the Carleton study.

TSS removal being correlated with WSA:PPA and not the WSA:TWA raises the question whether the wetland permanent pool area is simply acting as a settling basin without regard the presence of wetlands vegetation? This may not be the case. Kalainesan, et. al (2009) found that TSS concentration from sediment basins were often higher than inflow concentrations in their study suggesting resuspension. The primary mechanism for the settling of solids in sediment basins is the slowing of the flow of the water both giving time for the sediments to settle and reducing the turbulence that kept the solids in suspension. Braskerud (2001) found evidence that wetland vegetation created a resistance to the resuspension of particulates which improved the overall sediment retention in wetlands. The possible contribution of wetlands plants in settling of solids is to act as a large number of baffles. Baffles are objects in the path of flow which diverts the flow around it thereby increasing the path of the flow. This longer flow path would give the sediments more time to settle and also reduces the turbulence created by large inflows which would potentially introduce resuspension.

The fact that this study found a lack of a statistical correlation between the WSA:PPA and WSA:PPA ratios and the percent removal for the nutrients is difficult to explain. As previously discussed the removal of nutrients works through several different mechanisms. Some of those mechanisms indicate better performance is expected with longer residence time.

Ortho P showed a downward trend of percent removal versus the watershed to permanent pool area as expected but it was not statistically significant. However, this was a limited data set with only 5 points possibly explaining the lack of statistical significance. Total P showed a basically flat line with a very minor positive slope for the same type of plot. This is a little puzzling because of the reduction of TSS. Yang and Toor (2018) found that about 1/3 or more of the total P in an urban watershed was filterable meaning that is was particulate and expected to have correlation with the TSS performance. A portion of the total P would most likely be in particulate form and it would be expected to settle and show, some correlation with the reduction of TSS.

The nitrate removal efficiency verses the watershed to wetland area appeared to show a correlation but turned out not to be statistically significant and again the lack of statistical significance may be due to the small number of data points.

There are several possibilities regarding TKN performance. While, as in the case of Total P, it would be expected the solid organic N would settle several possible biochemical mechanisms are at play possibly converting one form of nitrogen to another. "The processes that affect removal and retention of nitrogen during wastewater treatment in constructed wetlands (CWs) are manifold and include NH_3 volatilization, nitrification, denitrification, nitrogen fixation, plant and microbial uptake, mineralization (ammonification), nitrate reduction to ammonium (nitrate-ammonification), anaerobic ammonia oxidation (ANAMMOX), fragmentation, sorption, desorption, burial, and leaching. However, only few processes ultimately remove total nitrogen from the wastewater while most processes just convert nitrogen to its various forms. It is even possible that ammonification is occurring in the wetlands which would reduce the nitrates by converting them to ammonia thereby reducing the nitrates and increasing the TKN" Vymazal (2006). Also, according to Vymazal (2006) the area of nitrogen movement in stormwater treatment wetlands is not as well studied.

The overall pollutant removal means in our analysis ranged from 52% for TKN to 75% for TSS. Mitsch and Gosselink (2007) reported TSS removal at 75% which is consistent with what we found. Our analysis showed TKN removal at 52% as compared to 25% for Total N in Mitsch and Gosselink (2007) but our study excluded the 44% negative removal samples.

Carleton (2001) found similar overall removal performances but no means were given, and the overall range included the negative removal means. Fisher and Acreman (2004) showed 84% positive removal across all phosphorous species with a mean positive removal of 58% and an 80% positive removal for all nitrogen species with a mean positive removal of 67%.

It can be concluded from both this study and the literature that most of the time the constructed stormwater wetlands are very effective in removing TSS and nutrients from stormwater runoff. And used on a watershed wide scale, constructed wetland basins would be an effective means of reducing the pollutant load to the receiving waters. However, the wetlands cannot be relied upon alone to meet specific targets at a specific point when pollutant removal is critical for the protection of the receiving water. The data would indicate that if the watershed has a significant number of wetland basins they would be effective at reducing the load by about 50%. According to our data the wetlands basins have a positive Total P removal 86% of the time. So, if there a large number of wetlands taking the mean removal of 60% for 86% of the wetlands would give 0.60 x 0.86 = 0.52 or 52%. Which is to say that if there are a large number of treatment wetlands in the watershed it could be expected that there would be an approximately 52% reduction of Total P for the watershed as a whole. Of course, this is a major generalization and more specific data to the region and their design methods would improve those estimates dramatically. However, as previously mentioned, very few sites have well-planned monitoring plans after construction is complete and the wetlands have stabilized.

Unlike wastewater discharges, stormwater discharges are subject to swings of discharge rates from long periods of no flow to short bursts of rapid runoff. The more developed the watershed the more severe these swings. Unfortunately, the funding sources for most constructed stormwater treatment wetlands do not include means for reporting the design information of the wetland and/or conducting properly controlled and carefully planned monitoring of their performance.

One main finding of this study that there is a difficulty in establishing a direct correlation between the performance of a wetland based upon its size with limited information that is available from the different public databases. What is required is significantly more intensive sampling and data gathering / reporting about the pollutant loadings and the BMPs.

To obtain the required pollutant loading data, rainfall data at the time of sampling is needed as well as the size of the drainage area and pollutants' concentrations. It would also require the flow rate into the BMP at the time of the sampling. Ideally this would be measured directly at the point source inlet. However, it would more likely need to be estimated from the size of the watershed and runoff characteristics. This would require information about not only the size of the watershed but also the type of ground cover and information on soil classification. This information would need to be used in a computer model such as HEC-HMS (http://www.hec.usace.army.mil/software/hec-hms/) or the EPA Storm Water Management Model (EPA SWMM, https://www.epa.gov/water-research/storm-water-management-model-swmm) to determine the flow rates into the wetland basin. HEC-HMS is a hydrology model and EPA SWMM is a combined hydrology and hydraulics model. Both could be used to calculate the inflow rates, but EPA SWMM could also be used to calculate the hydroperiods and storage volumes in the wetlands basins.

In addition to the surface area, information regarding wetlands basins needs to include bathymetric data so that hydraulic residence times could be calculated. Ideally, this would allow for outflow sampling to be obtained after a known residence time following the inflow sampling. Additional helpful information to make more accurate comparisons would the type and density of the vegetation. Not only is that information not available in the Database, it is not available in most studies involving stormwater treatment BMPs. Much more information is available on wastewater treatment BMPs as typically most, if not all, of required information is required for permit compliance either by the construction permit or the discharge permit.

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