Appendix A
Literature Review – Technical Appendix

Prepared by Tetra Tech, Inc. for the Wetlands Expert Panel

Final Version, January 2016

Contents

A. How Wetlands are Currently Represented in the Model

Spatial representation of wetlands

In the Phase 5.3.2 Chesapeake Bay watershed model, forested and emergent non-tidal wetlands are aggregated with into the forest, woodlots and wooded land use (Forest). (EPA 2010). This land use is calculated as the remaining land use after all agricultural, developed, extractive and open water land uses are subtracted from the total acres in each land-river segment. Wetlands are not explicitly mapped or included as a separate land use from forest. Wetlands in the forest land use category only included forested and nontidal emergent wetlands. Tidal wetlands are represented as part of the Chesapeake Bay Water Quality and Sediment Transport Model (WQSTM) (EPA 2010). Additional information on representation of wetlands in the model can be found in Chapter 4 of Chesapeake Bay Phase 5.3 Community Watershed Model documentation.

Forest loading rates

The loading rate for the forest land use is based on the input from atmospheric deposition. Other sources are not considered to contribute to the load (EPA 2010). Numerous existing literature reviews were aggregated to develop a value representative of the exporting loading found in the literature. The export targets for the entire Bay watershed were set at the median loading rates (3.1 lb/ac-yr TN and 0.13 lb/ac-yr TP). Total nitrogen loading rates were adjusted for the proportional change in atmospheric deposition between the land-river segment and the watershed average atmospheric deposition. Total phosphorus was determined not to be highly variable, and the target load is a constant 0.13 lb/ac-yr across the watershed (EPA 2010). Additional information on nutrient loading rates in the model can be found in Chapter 10 of Chesapeake Bay Phase 5.3 Community Watershed Model documentation.

Sediment loading was based on the expected annual average edge of field loading rates data in the National Resources Inventory database. These data are based on average erosion rates from the universal soil loss equation (USLE). The average edge of field loading rate is 0.26 tons/ac-yr (EPA 2010).

Wetlands loading rates

Wetlands are assigned the same loading rates as the forest acres in each land-river segment.

Approach proposed by STAC and the Mid-Atlantic Water Program

The CBP Scientific and Technical Advisory Committee (STAC) and the Mid-Atlantic Water Program have previously attempted to evaluate the effectiveness of wetlands as a BMP. Loading rate reduction methodologies were designed to calculate the load reductions from upland contributing land uses, rather than a load from the wetland itself.

During the April 2007 STAC workshop on quantifying the role of wetlands in achieving nutrient and sediment reductions, a first order kinetic equation was proposed to describe the exponential decline of nutrient and sediment over time related to detention time of runoff in a wetland. The kinetic equation was originally developed by Dr. Tom Jordan from the Smithsonian Environmental Research Center (SERC) and provided in both the STAC Report *Quantifying Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay* and the

2009 *Developing Nitrogen, Phosphorus and Sediment Reduction Efficiencies for Tributary Strategy Practices BMP Assessment: Final Report* by the Mid-Atlantic Water Program at the University of Maryland. The Mid-Atlantic Water Program was tasked with defining BMPs and determining effectiveness estimates that are representative of the overall Bay watershed.

Data have shown that longer detention times improve the nutrient removal efficiency of wetlands. The kinetic equation assumes that wetland detention time is proportional to the ratio of the area of wetland to the area of the watershed. First order kinetics also describe, generally, the finding that the rate of removal is proportional to the concentration, making first order kinetics a practical way to express efficiency as a percentage of the inflow pollutant removed by the wetland.

A first order kinetic equation was developed to represent the removal efficiency of restored wetlands, based on the assumptions that:

- removal is an exponential function of detention time;
- detention time is proportional to the proportion of the watershed that is wetland; and
- there is zero removal when there is no wetland in the watershed

Nonlinear regression was used to fit the model to the removal data in the literature. This yielded the equation:

$$\text{Removal} = 1 - e^{-k(\text{area})}$$

Where:

- Removal: proportion of the input removed by the wetland
- Area: proportion of the watershed area the is wetlands
- k: fitted parameter
  - TN, k=7.90, 95% confidence limits [4.56, 11.2]
  - TP, k=16.4, 95% confidence limits [8.74, 24.0].

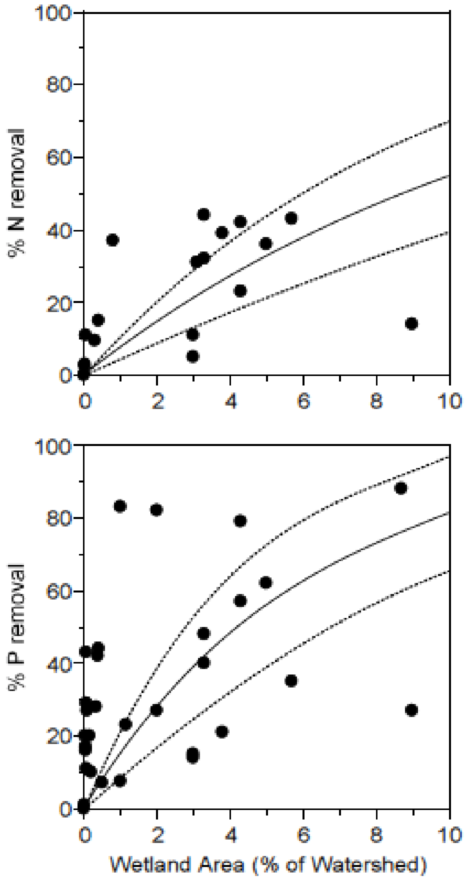

Figure 1. Literature review data points for wetland nutrient removal efficiency based on the wetland area as a proportion of the watershed. Curves indicate non-linear regression fit to data values, with 95% confidence limits. (STAC 2008).

The kinetic equation was developed for wetlands as a BMP (wetlands restoration), rather than wetlands as a land use, since wetlands were not represented as a distinct land use in the Phase 5.3.2 Watershed Model. To use the equation for BMP reporting, the jurisdictions would have been required to submit the ratio of wetland area to watershed area. As a contingency if this information was not reported by a jurisdiction, alternative calculations for the geomorphic regions were developed, based on an assumed proportion of wetlands in the watershed. Wetlands were assumed to be 1, 2, and 4 percent of the watersheds in the Appalachian, Piedmont and Valley, and Coastal Plain geomorphic provinces, respectively. The resulting TN and TP removal efficiencies are described in **Table 1**. If a jurisdiction does not report the geomorphic region of a wetland restoration, a uniform 16.75 percent and 32.18 percent, for TN and TP, respectively are applied.

Table 1. TN and TP removal efficiencies for wetlands by geomorphic province (Simpson and Weammert 2009).

Geomorphic Province	**TN Removal Efficiency**	**TP Removal Efficiency**
Appalachian	7%	12%
Piedmont and Valley	14%	26%

Geomorphic Province	TN Removal Efficiency	TP Removal Efficiency
Coastal Plain	25%	50%

One of the shortcomings of the kinetic equation is that it cannot account for wetlands that are sources of nutrients. Negative removal values (nutrient export) cannot be derived from this equation. During the literature review for development of the equation, any wetlands where only negative removal values were observed were removed from the calculations. In addition, the equation only applies to nitrogen and phosphorus. Due to the lack of data, the relationship between total suspended sediment and wetland area was not determined. A uniform 15 percent removal was approved, based on the average annual removal rates that were available in the literature, plus a margin of safety.

The kinetic equation is unable to account for variations in wetland age, seasonal variation, spatial and temporal variability of flow, landscape position, or type of wetland. These factors will affect the residence time and loadings to a wetland. Craft and Schubauer-Berigan found that floodplain wetlands removed 3 times the nutrients of depressional wetlands on an areal basis (in Simpson and Weamert 2009). The declining phosphorus removal rate over time is also not accounted for in the equation. Nicholas and Higgins found that phosphorus removal declines significantly after about 4 years (in Simpson and Weamert 2009).

The BMP Assessment recommended future refinements to account for seasonal variability, nutrient discharge, hydraulic loading rate, wetland aging, and potential for dissolved P discharge during anaerobic conditions from wetlands with high phosphorus content (Simpson and Weamert 2009).

B. Literature Review Process

The goal of the Wetland Expert Panel was to develop a preliminary loading rate for a wetland land use(s). In 2014, a literature review was conducted to identify literature that provided loading rates or related information for nitrogen, phosphorus and sediment. Literature cited in the STAC report was used as a starting point, followed by a search of published articles, primarily peer-reviewed, using EBSCO, Agricola, and Google Scholar. Members of the Wetlands Expert Panel were also queried to identify potentially relevant articles.

The literature search using the available databases was focused on providing the broadest range of articles about the topic. Search terms were kept general, and included “wetlands” “marsh” “nutrients” “sediment”, “flux” and “loading rate” in various combinations to identify potential relevant materials. The term “constructed wetland” was specifically excluded from the search because constructed wetlands are explicitly a water quality treatment BMP and the Panel is interested in establishing a loading rate for natural or restored wetlands as a land use, not a treatment. Resources were initially parsed into three categories, data from Bay states, data from the United States but outside the Bay watershed, and international studies.

Over 100 articles and reports were originally identified. Following a review of these articles and reports, the Expert Panel indicated an interest in including additional studies in the literature review. A second set of articles was provided by the Expert Panel Coordinator in November 2015.

C. Results of literature review

The goal of the literature review was to determine loading rates. In the absence of actual, explicit loading rates for wetlands, the panel also identified monitoring studies that included event mean concentrations (EMCs) in and out of wetlands, loading in and out of wetlands and annual retention rates that could potentially be used to back-calculate a loading rate. Data that could differentiate major wetland types and hydrologic flow paths were sought. In keeping with the previously identified first-order kinetic equation, the ratio of wetland area to watershed area was also collected, when available.

Data Source Characterization

The weight placed on the literature review findings follows the Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Model (WQGIT, 2014). The data source characterization matrix (Table 1 in the Protocol) was used to assess data appropriateness and influence.

	High Confidence	**Medium Confidence**	**Low Confidence**
Applicability	Definition matches technical specifications	Generally representative	Somewhat representative
Study Location	Very representative of soils and hydrology	Generally representative	Somewhat representative
Variability	Relatively low	Medium	Relatively high
Number of studies	Many	Moderate	Few
Scientific Support	Operational scale research (peer reviewed)	Research scale (peer reviewed)	Not peer reviewed (gray literature)

Applicability

Many of the studies identified for this literature review did not contain relevant data and were removed from the evaluation. There are no technical specifications for natural wetlands, but the Expert Panel did attempt to exclude constructed or wastewater treatment wetlands from the evaluation on the grounds that they do not necessarily represent the normal functioning of a natural wetland. Despite this restriction, a few studies using constructed wetlands were identified and used in the analysis. The data on natural wetlands were very limited, and could not support watershed-wide loading rates or reduction efficiencies on their own. A few studies also provided data based on mesocosms, rather than in-field wetlands. These isolate nutrient processing in a very controlled manner, but do not necessarily represent the full complement of wetland functions. Data applicability can be considered to have a medium level of confidence.

Study Location

The available data was not limited to the Chesapeake Bay watershed, and most of the useful data was derived from studies outside the watershed. Similar soils and hydrology can be generally representative even in locations across the country; however some other factors that change with location may be less representative, such as temperature, which can have a large impact on denitrification rates, one of the key mechanisms for nitrogen removal. Overall, the data can be considered to have medium confidence level.

Variability

The reported results from the scientific literature are highly variable. In many instances this is because each study is evaluating something different, either different types of wetlands or different processes in the wetlands. The inherent variability of local conditions makes it unlikely that there would be low variability in wetland loading or removal rates among wetlands. There is a low to medium confidence level in the variability of the data. Attempts are made below to aggregate data by wetland type and processes, to group similar wetlands and lower variability. This was completed with mixed success.

Number of Studies

The number of studies included in each reference varies from a single study to multiple studies included as part of another literature review. While it is ideal to be able to use data from the original source, rather than an average value already calculated by another literature review, these sources provide relevant data and a cross-section of reasonable or expected values. The current literature review identified a relatively high number of overall data sources from which to derive aggregated literature values, or single study values; however, when the data are broken down into more specific wetland categories, the data for individual categories is sparse in some instances. Despite the large number of studies, there was little consistency in which parameters were studied and great differences in the types of wetlands and hydrologic regimes studied. When taken as a whole, the data provide a medium confidence level, but for individual wetland categories the confidence varies from low to medium.

Scientific Support

All of the relevant resources that are used in this literature review are peer reviewed, but there is a mix of operational and research scale studies, providing medium to high confidence in the scientific support for the data.

Characterization of Findings

Typically, the Chesapeake Bay Program has defined land use loading based on a relatively uniform land use within a catchment; however, results of the literature review indicated that this is not a common approach to how wetlands are represented or evaluated. Wetlands are not generally a uniform land use at the watershed scale and more often are representative of a small area in the watershed, making isolation of a loading rate for wetlands difficult. Most often, the loading from a wetland is in the context of the surrounding land uses.

Of the 42 articles addressing wetlands in the Chesapeake Bay watershed, 13 were identified as having potentially relevant data. The remainder did not specifically address nutrient or sediment loading rates or reduction efficiencies. A number of these studies looked at the nutrient concentrations in wetland soils, watershed-wide loading rates, and floodplain sediment accumulation rates, but these data could not be extrapolated to wetland nutrient and sediment loading rates or removal efficiencies.

Given the low success rate in identifying Chesapeake Bay-specific data, calculations of loading rates and reduction efficiencies include numerous studies from outside the watershed. When findings specifically from Chesapeake Bay watershed studies are especially relevant, they are called out below. Thirty seven relevant articles were identified that addressed wetlands outside the Chesapeake Bay watershed.

Although during the beginning stages of the literature review articles addressing evaluations of constructed/treatment wetlands were excluded from the literature search, a few of these articles have now been included, either because the initial literature search did not identify them as constructed wetlands or because an expert panel member identified the article as relevant. In many cases, there is a more significant body of research on constructed wetlands because they are specifically designed to remove nutrients and sediment. However, the degree to which their function can be compared to natural wetlands is unclear. When findings from constructed wetlands are highlighted in the following discussion, they are identified as such.

Wetland Loading Rates

Only two studies were identified that attempted to define the loading rate for a wetland area independent of the surrounding land uses. Baker et al. (2014) evaluated Barnegat Bay-Little Egg Harbor HUC14 watersheds and determined the export concentration for forest and wetlands combined was 1.17 mg/L for total nitrogen and 0.021 mg/L for total phosphorus. Similarly, Dodd et al. (1992) created nutrient budgets for the Albemarle-Pamlico Sound area, forest and wetlands were again considered as having the same loading rate, which Dodd et al. determined to be 2.07 lb/ac/yr for total nitrogen and 0.12 lb/ac/yr for total phosphorus. Neither study separated the loading from forest and wetland areas into distinct categories. No other studies were identified that provided a loading rate for wetlands as a uniform land use.

One study by Harrison et al. (2011) calculated the surface water and groundwater concentrations of TN and TP within the wetlands, however, the export rates were not calculated. The wetlands, located near Baltimore, MD were two restored relic oxbow wetlands in an urban area and two reference forested floodplain wetlands. Across the restored oxbow wetlands, the groundwater concentrations for TN and TP, respectively, were 0.72 mg/l and 11.5 μg/L. The average at the forested floodplain wetlands were 0.37 mg/L and 114.7 μg/L for TN and TP, respectively. Surface water nutrient concentrations measured within the oxbow wetlands averaged 0.6 mg/L for TN and 24 μg/L for TP.

Denver et al. (2014) provided groundwater nitrate as nitrogen values for depressional wetlands in an agricultural setting. The two natural wetlands in the study had a mean value of 0.055 mg/L NO3-N. The prior-converted cropland had a mean concentration of 7.4 mg/L, and the restored wetlands had a mean value of 1.9 mg/L.

Restored and Natural Wetland Reduction Efficiencies

The majority of studies identified represented wetlands as a BMP, calculating the load reduction from the concentration entering the wetland from upstream land uses. The following discussion summarizes the results. Articles containing data on constructed wetlands were analyzed separately. Twenty five studies with TN, TP or TSS wetland load reduction efficiencies were identified. Of these, five had study sites within the Chesapeake Bay watershed, in Prince George's County, MD and Queen Anne's County, MD. A few studies also provided data from Austria, Australia, Canada, Hungary, and Spain. The remaining studies focused on wetlands throughout the United States, including in Florida, Georgia, Louisiana, North Carolina, and Ohio.

Several studies included aggregated literature review data values and provided a range of reduction efficiencies. When a range of values was provided, these data were not used in the calculation of a mean efficiency value, but are taken into account in providing the range of values.

Eighteen studies contained TN load reduction efficiencies for studies of natural or restored wetlands (excluding constructed wetlands). The mean from the studies that provided values instead of ranges of values is a reduction of 42%. The reduction efficiencies ranged from -8% to 97%. Studies that included value ranges had reductions from -8-450 %. When only the studies with data in the Chesapeake Bay watershed are used, the mean TN efficiency is 22%, with a range of -8-89%.

A few studies also evaluated ammonia and nitrite reductions. One study in Maryland with field data found that the wetlands were a source of ammonium with an increase of 7%, and a range of -21 – 8%. The mean NH4-N reduction was 33% with a range of -49-96%. Noe and Hupp (2007) evaluated a bottomland hardwood forest in Maryland, and found nitrite reductions were only 3%, with a range of 29-33% from event-based monitoring.

Eighteen studies provided NO3 or NO3-N reduction efficiencies that covered a wide variety of wetland field measurements and laboratory analysis. The mean nitrate (NO3) reduction was 38%, with a range of -16-97%, and the mean nitrate-nitrogen (NO3-N) was 56%, with a range of -30-99%. Four studies measured TKN, with a mean reduction of 39%, with a range of -2-79%. Two studies also evaluated total organic nitrogen, with a mean reduction of 34% and a range of -15-71%. While Kovacic et al. (2000) reported that organic nitrogen was exported from constructed wetlands, two other studies provided organic nitrogen reduction efficiencies for natural or restored wetlands (Jordan et al. 2003, and García-García et el. 2009). Jordan et al. (2003) found that in a wet year organic nitrogen was exported from the restored wetland in Queen Anne's County, Maryland, but was removed in a dry year. Jordan et al. (2003) also cited a literature synthesis from Kadlec and Knight 1996 that found the overall organic nitrogen removal efficiency to be 56%. The mean organic nitrogen removal rate from the two studies was 28.7% with a range of -15-71%, substantially lower than the findings from Kadlec and Knight 1996.

Twenty studies contained TP load reduction efficiencies for natural or restored wetlands. TP load reduction efficiencies across studies ranged from -46% to 133%. The mean from the studies that provided values instead of ranges of values is a reduction of 41%. Studies that included value ranges had reductions from -14-133%. When only the studies with data in the Chesapeake Bay watershed are used, the mean TP efficiency is 20%, with a range of -41-81%.

Three studies evaluated phosphate (PO4-P) reductions from natural or restored wetlands. The majority of the data were from one event-based study of a golf course in South Carolina where only reduction ranges were provided. Reductions ranged from 0 to 100%. One study looked at total organic phosphorus (Jordan et al. 2003) and found that the mean removal was 26.4% over two years. In the dry year the wetland removed 61% of TOP, and in the wet year served as a source, with a negative efficiency of -8.3%.

Nine studies contained data on TSS reductions; the average reduction was 31% with a range of -30 to 95%. When only the studies with data in the Chesapeake Bay watershed are used, the mean TSS efficiency is 24%, with a range of -15-68%.

Table 2. Nutrient and sediment reduction efficiencies by wetland and vegetation type.

Wetland Type	**Vegetation Type**	**TN % Reduction** Mean Range (number of data points)	**TP % Reduction**	**TSS % Reduction**	**Sources**
Headwaters/ Depressional	Forest (and unknown)	78% 59-97 (2)	80% 66-94% (2)	--	Ardón et al. 2010; Vellidis et al. 2003
Headwaters/ Depressional	Emergent	20% -8.4-40 (7)	15% -11-59% (11)	28% -30-75% (6)	Kalin et al. (2013); Jordan et al. 2003; Knox et al. 2008; Huang et al. (2011)
Headwater/ Depressional	ALL	33% -8.4-97 (9)	19% -11-94 (13)	28.3% -30-75% (3)	
Floodplain	Forest (incl. mixed and unknown)	38% -8-94 (11)	26% -41-100 (16)	32% -15-95 (7)	Ardón et al. 2010; Jun Xu 2013; Lizotte et al. 2012; Lowrance, et al., 1997; McJannet et al. 2012; Mitsch, 1992; Noe and Hupp, 2007; Olde Venterink et al., 2006; Reddy et al. 1999; Richardson, et al. 2011; Rogers et al. 2009; Shields and Pearce 2010; Tockner et al., 1999

Wetland Type	**Vegetation Type**	**TN % Reduction** Mean Range (number of data points)	**TP % Reduction**	**TSS % Reduction**	**Sources**
Floodplain	Emergent	49% 26-89% (13)	58% 10-100% (8)		Ardón et al. 2010; García-García et al. 2009; Mitsch et al. 2012; Olde Venterink et al., 2006
Floodplain	ALL	44% -8-94 (24)	37% -41-100 (24)	32% -15-95 (7)	
Tidal Fresh	Forest	62% 59-65% (2)	32% -47-89% (4)	--	Ardón et al. 2010; Brantley et al. 2008; Day et al 2006
Tidal Fresh	Emergent	--	--	--	
Tidal Saline	Forest	--	--	--	
Tidal Saline	Emergent	--	0% No range (1)	2% No range (1)	Etheridge et al. 2015
Constructed	Emergent (plus mixed, other and unknown)	32% 11-52% (12)	38% -54-97% (31)	92% 88-98 (4)	Ardón et al. 2010; Dierberg et al. 2002; Kovacic et al. 2000; Mitsch, 1992; Moustafa et al. 2012, Raisin, Mitsch and Croome 1997; Reddy et al., 1999; Reinhardt et al. 2005
All except constructed	Forest, mixed and unknown	47% -8-97 (16)	43% -47-100 (44)	37% -15-95 (8)	
All except constructed	Emergent	39% -8-89 (20)	31% -15-100 (20)	25% -30-75 (7)	

Wetland Type	**Vegetation Type**	**TN % Reduction** Mean Range (number of data points)	**TP % Reduction**	**TSS % Reduction**	**Sources**
All	All	40% -8.4-97 (48)	39% -54-100 (95)	44% -30-98 (19)	
Chesapeake Bay Only	All	22% -8-89 (10)	20% -41-81 (10)	24% -15-68 (8)	Kalin et al. (2013); Jordan et al. 2003; Lowrance, et al., 1997; Noe and Hupp, 2007

Constructed Wetlands Reduction Efficiencies

Nine studies contained information on constructed wetlands removal efficiencies. Constructed wetlands were specifically excluded from the literature search process but a few articles were included unintentionally, or constructed wetland information was included as part of a literature review within an article. The data from studies providing individual data points are presented in Table 2 for comparison; note that two of the studies calculated removal efficiencies from mesocosm sampling, rather than in-field data. Two studies provided a range of removal efficiencies for TN and TP. Across these two studies, constructed wetlands were evaluated in Florida, Illinois, Norway and Appalachian Pennsylvania. The TN reduction range was 3-88%, and the TP reduction range was 21-79%, which are consistent with the ranges derived from the individual data points in other studies, shown in Table 2.

In addition to TN and TP, the studies also provided data on other constituents. Kovacic et al. (2000) evaluated NO3-N, NH4-N, PO4-P, organic N and organic P removal percentages at three adjacent constructed wetlands. The mean NO3 removal efficiency was 35.8% with a range of 14-55%. NH4-N removal was 7.6% with a range of -150% to 75%. One site had an outlier rate of -567%, making it a source; however, in absolute terms, the additional loading was only 3.9 lb/yr. This value was excluded from the mean NH4-N removal efficiency calculation. All three wetlands were sources of organic-N, with no organic-N detected at the inlet and resulting concentrations at the outlets ranging between 0.2 and 0.3 mg/L. Similarly, organic-P was exported from the wetlands at concentrations between 0.03 and 0.04 mg/L. Ortho-P was also exported at higher concentrations than entered the wetlands. Concentrations increases ranged from -24 to -9%, with a mean export increase of 16.7%. During most years all three wetlands removed PO4-P. The mean efficiency was 34.9% with a range of -27 to 90%.

Wetlands as Sources of Nutrients and Sediment

Jordan et al. (2003) found that wetlands in Queen Anne's County, Maryland averaged negative removal for TOP-P, TPO4-P, TP, TON-N, TN, based on weekly composite samples over two years. In the two years that the sites were monitored, there was similar total rainfall in both years, but year 2 rainfall was about twice as much during the summer, allowing for flow over the weir. Jordan et al. notes that “because large net fluxes occur sporadically in different weeks, it is difficult to judge whether the wetland is a long-term source or sink of nutrients or TSS. The chance occurrence of one week with high flux can have a strong influence on the annual net flux. This underscores the importance of using continuous automated sampling to observe the effects of rare but critically important events.” This finding highlights that certain events, such as changes in rainfall pattern or flow, can occur and will influence the overall removal efficiency, despite being relatively infrequent.

Ardón et al. (2010) collected two years of data with weekly samples and 10 storm samples at a restored riverine wetland in Tyrell County, North Carolina. Ardón et al. (2010) indicated confidence that “our sampling covered the range of flows that occurred during the 2 years. We included the storm data in our estimates of nutrient export even though the cumulative storm export did not account for more than 10% of the annual exports for any of the nutrients.” The wetland was a sink of NH4-N in year 1 and a source in year 2. TP changed from a source to a sink between years 1 and 2. It was an overall source of TP over two years, but altered the form of exports from inorganic P to particulate P. Seasonal nutrient flux patterns indicated that NH4-N was mostly released during the fall and winter of both years. TP exports were in the spring, coinciding with high temperatures and the largest inundation area. Overall restoration of the wetland seemed to reduce the NO3-N export to the estuary. DON export was higher after restoration, as was TP mass export. Nitrification was inhibited in the flooded, acidic soils of the restored wetland, as compared to its prior actively drained agricultural state. Reflooding increased export of NH4-N and DON. However, the wetland was very good at eliminating the high NO3-N pulses from upland agricultural field fertilization.

Garcia-Garcia et al. (2009) found that export of NH4-N may be sensitive to slight changes in sediment redox potential, and organic matter content. In a temperate Mediterranean climate (Spain) export was hypothesized to be a result of litter decomposition and mineralization creating NH4-N sources in the wetland-stream complex.

Aldous et al. (2007) measured release of phosphorus on newly flooded restoration wetland in Oregon. The study used mesocosms, rather than in-field data. Soils were flooded on a weekly basis. During the four month experiment, the soils in the mesocosms released 1-9 g P/m2. Net flux continued to be from the soils to the water column throughout the experiment, but after day 62 phosphorus flux was not significantly different from 0. The authors extrapolated the results to the Upper Klamath Lake emergent marsh area, finding that restoration would release 64 tons of phosphorus; however, this one-time release was noted to be preferable to the 21-25 tons of phosphorus released annually under agricultural use.

Rogers et al. (2009) attributed large amounts of sediment export in a degraded wetland in Wisconsin to the erosion of sediment that had accumulated in the low-gradient channel of the wetland and was then eroded during two large storms. Drainage ditches also contributed to the net export of sediment.

Kovacic et al. (2000) analyzed removal rates from three wetlands receiving subsurface tile drainage. The nutrient budgets indicated that the wetlands, created by berming part of the floodplain and rerouting tile drainage lies in Illinois, were consistently sources of organic nitrogen and organic phosphorus, ortho-phosphate, and sources of NH4-N and total phosphorus on a less regular basis. The study found that overall these wetlands were neither a source nor a sink for phosphorus, and remained effective at removing NO3-N.

D. Key processes affecting nutrient/sediment retention

In addition to investigating load reduction efficiencies from wetlands, the literature review also included an evaluation of whether specific processes affecting nutrient and sediment retention in wetlands were identified in the studies. Many studies focused on wetland restoration projects and constructed wetlands, rather than natural wetlands.

Fisher and Acreman (2004) conducted a meta-analysis using studies that collectively evaluated 57 wetlands around the world to identify the important factors affecting nutrient reduction in wetlands. Figure 2 summarizes their findings on the most commonly identified factors affecting nutrient retention or reduction. For both swamps/marshes and riparian zones, sediment oxygen availability and redox potential were cited most commonly. These are strongly linked to the flooding/drying regimes and hydroperiod. Hydraulic loading and retention time were also frequently mentioned in studies of both types of wetlands.

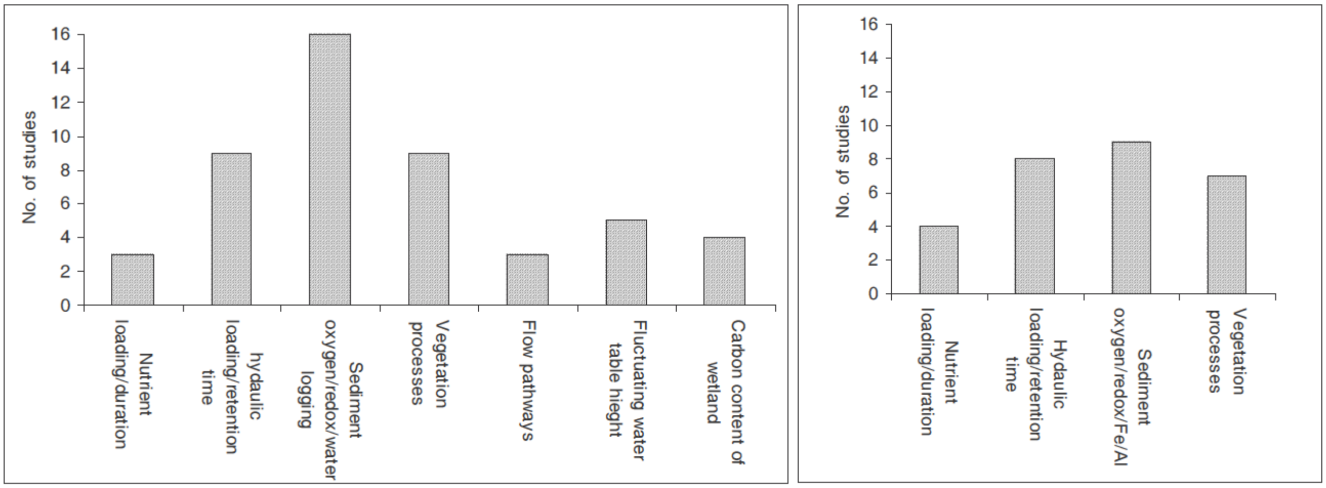

Figure 2. The factors most commonly quoted as being of importance to the nutrient retention or reduction abilities of swamps and marshes (left) and riparian zones (right). From Fisher and Acreman 2004.

Hydroperiod/Hydraulic Loading/Retention Time

Acreman et al. (2007) evaluated the connection between hydrology and wetland restoration across Europe, key issues that were identified included the effect of water level management and the effects of reconnecting rivers to their floodplains and oxbow lakes.

Jordan et al. (2003) linked hydroperiod/retention time to whether a wetland was a source or sink of TN and TP, monitoring a coastal restored wetland in Queen Anne’s County, Maryland over a period of two years. In years with a drying period, wetlands acted as a sink, but in wet years, where a drying period did not occur, the wetland became a source of both TN and TP. The findings for TSS were the opposite, in wet years, the wetland acted as a sink, and in dry years it acted as a source. Wet years tended to have more high flow events. During high flow events the detention time in the wetland was reduced, preventing some of the water from remaining in the wetlands for more than a few hours, reducing the potential for the wetland to remove nutrients and sediment. Kovacic et al. (2003, in Jordan et al. 2003) found that nitrate removal capacity was exceeded in constructed wetlands with unregulated flow during high flow events. Jordan et al. (2003) concluded that removal at the Queen Anne's County site would have been higher with a constant inflow rate rather than variable flows that reduced detention time. Jordan et al. cited the Carleton et al. (2001) conclusion that wetland receiving unregulated inputs from urban or agricultural runoff had overall similar performance as wetland with regulated flows; however, performance was highly variable and possibly related to the variability of inflows. Overall, Jordan et al. found that TN and TP removal rates increased with decreasing hydraulic loading rate and increasing detention time. Similarly, several studies cited in Fisher and Acreman (2004) found that residence time strongly affects denitrification and sediment phosphorus retention.

Mitsch et al. (2012) addressed pulsed flooding of wetlands during a 15-year monitoring study of floodplain diversion wetlands (Olentangy River Wetland Research Park) in Ohio. Although the wetlands did not become a nutrient source on an average basis, in years when the wetlands experienced a spring flood pulse, TN reductions were about half what they were in years when the flood pulse was suppressed or normal river pulse conditions were allowed to occur (25-35% vs 55-60%). Marton, Fennessy and Craft attributed the comparable denitrification rates at natural and restored riparian buffers in a separate Ohio study to the pulsed hydrology in the area, "suggesting that the hydrologic regime was successful in reestablishing N removal via denitrification within 5 years following restoration" (2013).

Seasonality and Temperature

Seasonality (and more generally, temperature) may play a role in nutrient removal. Hernandez and Mitch (2007) found that soil temperature was a significant factor in the denitrification rates in created wetlands at the Olentangy River Wetland Research Park (ORW). Warmer soil temperatures were correlated with higher denitrification rates, although they acknowledge that results have been mixed in other riparian soil studies. Other studies support the observation that denitrification is temperature dependent and can vary accordingly by season (Hunt et al. 1999, Spieles and Mitsch 2000, in Jordan et al. 2003). Mitsch et al. (2005) found that nitrate-nitrogen retention at the Caernarvon, Louisiana wetland was 55 percent by both mass and concentration, while at a comparable wetland at the ORW, the retention was only 35 percent. Mitsch et al. (2005) note that the subtropical climate in southern Louisiana is more conducive to higher denitrification rates and nutrient uptake than the temperate climate of central Ohio, where the ORW is located. The subtropical climate contributes in both higher water temperatures and a longer growing season.

Kovacic et al. (2000) found that in a series of constructed wetlands in an agricultural setting in Illinois, 95 percent of the TN load entering the wetlands was transported in the winter and spring. Although the removal rates for these seasons (26% and 35%, respectively) were much lower than in the summer (95%) and fall (86%), the majority of the loading occurred in the winter and spring, causing these seasons to account for the vast majority of the TN removal (87%). Kovacic et al. noted that other similar wetlands in the Midwest with higher TN removal rates had longer residence times, and were only operational during the warmer growing season, creating higher apparent reduction efficiencies.

Kovacic et al. (2000) also found that TP predominantly entered the wetlands in the winter and spring, when removal rates were the lowest. Export of organic P was offset by dissolved P removal, resulting a net effect of the wetlands neither being a source or sink of TP. Winter and early spring pulse flows transported dissolved P out of the wetlands prior to the annual growth of plants in the wetland.

Vegetation

Vegetation can play a role in nutrient removal. Moustafa et al. (2012) conducted an experimental design using mesocosoms with varying hydroperiod, loading rate and vegetation. They found that emergent vegetation was the dominant factor influencing phosphorus flux in a low phosphorus loading rate system in south Florida/Everglades. They conclude that the presence of emergent vegetation "is the most critical for managing large wetland treatment systems receiving low P loadings, while hydrology should be the focus in managing treatment systems receiving high P loadings."

Loading Rates and Concentrations

Brantley et al. (2008) notes that several studies have found that "nutrient removal is inversely related to the loading rate." When loading rates are low, the efficiency of removal is high and when loading rates are high, the overall removal efficiency is lower. In a meta-analysis by Fisher and Acreman (2004), they found that 35 percent of the variation in nitrogen reduction across wetlands was explained by the nitrogen loading; however, there was no significant relationship between inflow nitrogen concentrations and the nutrient reduction. There was insufficient data to conduct a similar analysis on phosphorus (Fisher and Acreman 2004).

Different processes affecting N and P

Fisher and Acreman's meta-analysis found that nitrogen removal is more efficient in conditions conducive to denitrification (anerobic conditions), while phosphorus removal is more efficient under aerobic conditions. Soluble phosphorus transport out of wetlands was noted to increase when wet/water logged conditions were predominant. Nitrogen export increased under conditions of fluctuating water tables, or aerobic and anaerobic sediment zones within close proximity (Fisher and Acreman 2004).

Different Wetland Types

Marton, Fennessy and Craft (2013) found that depressional wetlands in Ohio had twice the phosphorus soil sorption of riparian wetlands, but riparian wetland had significantly higher denitrification rates. Fisher and Acreman (2004) evaluated the efficacy of riparian wetlands versus marshes and swamps for nutrient removal. Overall, riparian wetlands reduced TN and TP more frequently than the swamps and marshes. However, riparian wetlands were also found to be more likely to increase ammonium-N and soluble P loading than marshes and swamps. Fisher and Acreman suggest that soluble nutrients in marshes and swamps are less easily exported into adjacent waters because of slower water movement when compared to riparian wetlands, which are adjacent to flowing water (2004).

E. References

Acreman, M.C., J. Fisher, C.J. Stratford, D.J. Mould, and J.O. Mountford. 2007. Hydrological science and wetland restoration: some case studies from Europe. *Hydrology and Earth System Sciences*. 11(1):158-169.

Aldous, A.R., C.B. Craft, C.J. Stevens, M.J. Barry, and L.B. Bach. 2007. Soil phosphorus release from a restoration wetland, Upper Klamath Lake, Oregon. *Wetlands*. 27(4):1025-1035.

Ardón, M. J.L. Morse, M.W. Doyle, E.S. Bernhardt. 2010. The water quality consequences of restoring wetland hydrology to a large agricultural watershed in the Southeastern Coastal Plain. *Ecosystems*. 13(7):1060-1078.

Baker, R.J., C.M. Wieben, R.G. Lathrop, and R.S. Nicholson. 2014. Concentrations, loads, and yields of total nitrogen and total phosphorus in the Barnegat Bay-Little Egg Harbor watershed, New Jersey, 1989–2011, at multiple spatial scales. *U.S. Geological Survey Scientific Investigations Report 2014–5072*. U.S. Geological Survey. Reston, VA.

Brantley, C.G et al. 2008. Primary production, nutrient dynamics, and accretion of a coastal freshwater forested wetland assimilation system in Louisiana. *Ecological Engineering*. 34:7-22.

Bukaveckas, P.A. and W.N. Isenberg. 2013. Loading, transformation, and retention of nitrogen and phosphorus in the Tidal Freshwater James River (Virginia). *Estuaries and Coasts*. 36:1219-1236.

Day, J.W. et al. 2006. Effects of long-term municipal effluent discharge on the nutrient dynamics, productivity, and benthic community structure of a tidal freshwater forested wetland in Louisiana. *Ecological Engineering*. 27:242-257.

Dierberg, F.E., T.A. DeBusk, S.D. Jackson, M.J. Chimney, and K. Pietro. 2002. Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research*. 36:1409-1422.

Dodd. R.C., G. McMahon, and S. Stichter. 1992. *Watershed Planning in the Albemarle-Pamlico Estuarine System. Report 1 – Annual Average Nutrient Budgets*. North Carolina Department of Environment, Health, and Natural Resources and U.S. Environmental Protection Agency, National Estuary Program.

Etheridge, J. R., F. Birgand, and M. R. Burchell II. 2015. Quantifying nutrient and suspended solids fluxes in a constructed tidal marsh following rainfall: The value of capturing the rapid changes in flow and concentrations. *Ecological Engineering*. 78: 41-52.

Fisher, J. and M.C. Acreman. 2004. Wetland nutrient removal: a review of the evidence. *Hydrology and Earth System Sciences*. 8(4):673-685.

García-García, V., R. Gómez, M.R. Vidal-Abarca, and M.L. Suárez. 2009. Nitrogen retention in natural Mediterranean wetland-streams affected by agricultural runoff. *Hydrology and Earth System Sciences*. 13:2359-2371.

Harrison, M.D., P.M. Groffman, P.M. Mayer, S.S. Kaushal, and T.A. Newcomer. 2011. Denitrification in alluvial wetlands in an urban landscape. *Journal of Environmental Quality*. 40:634-646.

Hernandez, M and W.J. Mitch. 2007. Denitrification in created riverine wetlands: Influence of hydrology and season. *Ecological Engineering*. 30(1):78-88.

Huang, J.C., W.J. Mitsch, and D.L. Johnson. 2011. Estimating biogeochemical and biotic interactions between a stream channel and a created riparian wetland: A medium scale physical model. *Ecological Engineering*. 37(7):1035-1049.

Jordan, T.E., D.F. Whigham, K.H. Hofmockel, and M.A. Pittek. 2003. Nutrient and sediment removal by a restored wetland receiving agricultural runoff. *Journal of Environmental Quality*. 32:1534-1547.

Jun Xu, Y. 2013. Transport and retention of nitrogen, phosphorus and carbon in North America's largest river swamp basin, the Atchafalaya River Basin. *Water*. 5:379-393.

Kalin. L., M.M. Hantush, S. Isik, A. Yucekaya and T. Jordan. 2013. Nutrient dynamics in flooded wetlands. II: Model application. Journal of Hydrologic Engineering. 18(12):1724-1738.

Knox, A.K., R.A. Dahlgren, K.W. Tate, and E.R. Atwill. 2008. Efficacy of natural wetlands to retain nutrient, sediment and microbial pollutants. *Journal of Environmental Quality*. 37:1837-1846.

Kovacic, D.A., M.B. David, L.E. Gentry, K.M. Starks, and R.A. Cooke. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *Journal of Environmental Quality*. 29(4):1262-1274.

Lizotte, Jr., R.E., F.D. Shields, Jr., J.N. Murdock, R. Kröger, and S.S Knight. 2012. Mitigating agrichemicals from an artificial runoff event using a managed riverine wetland. *Science of the Total Environment*. 247-428:373-381.

Lowrance, R. et al. 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. *Environmental Management*. 21(5):687-712.

Marton, J.M., M.S. Fennessy, and C.B. Craft. 2014. USDA conservation practices increase carbon strorage and water quality improvement functions: an example from Ohio. *Restoration Ecology*. 22(1):117-124.

McJannet D., J. Wallace, R. Keen, A. Hawdon, and J. Kemei. 2012. The filtering capacity of a tropical riverine wetland: II. Sediment and nutrient balances. *Hydrological Processes*. 26:53-72.

Mitsch, W.J. 1992. Landscape design and the role of created, restored, and natural riparian wetlands in controlling nonpoint source pollution. *Ecological Engineering*. 1:27-47.

Mitsch, W.J., J.W. Day, L. Zhang, R.R. Lane. 2005. Nitrate-nitrogen retention in wetlands in the Mississippi River Basin. *Ecological Engineering*. 24:267-278.

Mitsch W.J, et al. 2012. Creating wetlands: Primary succession, water quality changes, and self-design over 15 years. *BioScience*. 62(3):237-250.

Moustafa, M.Z., J.R. White, C.C. Coghlan, K.R. Reddy. 2012. Influence of hydropattern and vegetation on phosphorus reduction in a constructed wetland under high and low mass loading rates. *Ecological Engineering*. 42:134-145.

Noe, G.B. and C.R Hupp. 2007. Seasonal variation in nutrient retention during inundation of a short-hydroperiod floodplain. *River Research and Applications*. 23:1088-1101.

Olde Venterink, H. et al. 2006. Importance of sediment deposition and denitrification for nutrient retention in floodplain wetlands. *Applied Vegetation Science*. 9:163-174.

Pärn, J. G. Pinay, Ü. Mander. 2012. Indicators of nutrients transport from agricultural catchments under temperate climate: a review. *Ecological Indicators*. 22:4-15.

Raisin, G.W., D.S. Mitchell, R.L. Croome. 1997. The effectiveness of a small constructed wetland in ameliorating diffuse nutrient loadings from an Australian rural catchment. *Ecological Engineering*. 9:19-35.

Reddy, K.R., R.H. Kadlec, E. Flaig, and P.M. Gale. 1999. Phosphorus retention in streams and wetlands: a review. *Critical Reviews in Environmental Science and Technology*. 29(1):83-146.

Reinhardt, M., G. Gachter, B. Wehrli, and B. Muller. 2005. Phosphorus retention in small constructed wetlands treating agricultural drainage water. *Journal of Environmental Quality*. 34(4):1251-1259.

Richardson, C.J., N.E. Flanagan, M. Ho, and J.W. Pahl. 2011. Integrated stream and wetland restoration: a watershed approach to improved water quality on the landscape. *Ecological Engineering*. 37:25-39.

Rogers, J.S. et al. 2009. Hydrologic and water quality functions of a disturbed wetland in an agricultural setting. *Journal of the American Water Resources Association*. 45(3):628-640.

Shields, Jr. F.D. and Pearce, C.W. 2010. Control of agricultural nonpoint source pollution by natural wetland management. *Journal of Environmental Science and Engineering*. 4(4):62-70.

Simpson, T. and S. Weammert. 2009. *Developing Nitrogen, Phosphorus and Sediment Reduction Efficiencies for Tributary Strategy Practices, BMP Assessment: Final Report*. Mid-Atlantic Water Program, University of Maryland. College Park, MD.

STAC (Scientific and Technical Advisory Committee). 2008. *Quantifying the Role of Wetlands in Achieving Nutrient and Sediment Reductions in Chesapeake Bay*. Publication 08-006. Annapolis, MD.

Tockner, K., D. Pennetzdorfer, N. Reiner, F. Schiemer and J.V. Ward. 1999. Hydrological connectivity, and the exchange of organic matter and nutrients in a dynamic river-floodplain system (Danube, Austria). *Freshwater Biology*. 41:521-535.

USEPA (U.S. Environmental Protection Agency). 2010. *Chesapeake Bay Phase 5.3 Community Watershed Model*. EPA 903S10002 - CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis MD. December 2010

Vellidis, G. R. Lowrance, P. Gay, and R.K. Hubbard. 2003. Nutrient transport in a restored riparian wetland. *Journal of Environmental Quality*. 32:711-726.

WQGIT (Water Quality Goal Implementation Team). 2014. *Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Model*. Chesapeake Bay Program Office.