Appendix B
Wetland Habitat Benefits and Unintended Consequences Literature Review

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

Final version, March 2016

Contents

A. Wetland Functions and Values

Each Chesapeake Bay Best Management Practice (BMP) Expert Panel is responsible for developing loading or effectiveness estimates for the specific nutrient and sediment reducing technologies and practices they are tasked to address (WQGIT 2015). A previous literature review was conducted to evaluate the effectiveness of wetlands as a BMP (Tetra Tech 2016). The previous literature review for wetlands was conducted to quantify total nitrogen, total phosphorus and sediment removal efficiencies that are representative of the overall Bay watershed.

BMP Expert Panels must also identify any significant ancillary benefits or unintended consequences beyond impacts on nitrogen, phosphorus and sediment loads. This follow-up wetland literature review summarizes literature regarding the habitat functions and values of wetlands in different landscape contexts, including potential unintended consequences to habitat functions and values as a result of various management actions. The value of wetlands to and for habitat is considered, in addition to the pollutant load reductions. This review researches and summarizes existing information to support the Expert Panel's scientific recommendations to protect and promote habitat in the Expert Panel report recommendations. It is important to note that this literature review is not intended to be a fully comprehensive study, but rather to provide an overview of the benefits and/or unintended consequences of wetlands. It does not represent all possible wetland benefits and consequences.

Any identified ancillary benefits or unintended consequences do not change the definitions and loading or effectiveness estimates for nutrient and sediment reducing technologies and practices in the final Expert Panel report. State and local governments may consider both the definitions and effectiveness estimates from the main Panel report, as well as any ancillary benefits or unintended consequences included in this appendix, when deciding which technologies and practices they intend to select, fund and implement within their respective jurisdictions.

B. Literature Review Process

The initial goal of the Wetland Expert Panel was to develop preliminary loading rates for wetland land uses as well as nutrient and sediment removal efficiencies for various wetland types. In 2014 and 2015, literature reviews were conducted to identify literature that provided loading rates and removal efficiencies for nitrogen, phosphorus and sediment. This follow-up wetland literature review summarizes literature regarding the habitat functions and values of wetlands, including ancillary benefits and potential unintended consequences (both positive and negative) to those habitat functions and values. Literature identified during the wetlands BMP efficiency literature review was used as a starting point, followed by a search of published articles, primarily peer-reviewed, using EBSCO, and Google Scholar. Members of the Wetlands Expert Panel were also queried to identify potentially relevant articles; however, the Panel did not provide any new 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*, *restoration*, *habitat*, *value*, *benefits*, *floodplain*, *tidal*, *vegetation*, *animal*, *storage*, *erosion*, *downstream*, *toxics*, *hydrology, carbon sequestration, denitrification,* and *living shorelines* in various combinations to identify potential relevant materials. The term *constructed wetland* was specifically excluded from the search because constructed wetlands are a stormwater treatment BMP and the Panel is interested in identifying benefits and functions of natural or restored wetlands as a land use, not a treatment. This literature review focuses on the benefits of wetlands, but more specifically the benefits of wetlands restoration. Over 130 articles and reports were identified and 73 were determined to be relevant to the habitat benefits of wetlands restoration.

All Bay states have fish and wildlife agencies with additional information on wildlife use of wetland habitats. All States have or are in the process of updating State Wildlife Action Plans which would have recent relevant information on wetland benefits to wildlife.

In addition, the Chesapeake Bay Program released a document *Habitat Requirements for Chesapeake Bay Living Resources* which contains habitat information, including wetlands, for selected species

C. Results of Literature Review

The goal of the literature review was to identify the habitat functions and values of wetlands in different landscape contexts such as fresh and salt water tidal wetlands, floodplains, upland/headwater/depressional wetlands, and restored wetlands. The review includes potential unintended consequences to habitat functions and values as a result of various management actions.

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 Watershed Model (WQGIT 2015). The data source characterization matrix (Table I in the Protocol) was used to assess data appropriateness and influence. Note that this literature review for wetland habitat benefits is more qualitative in nature than the previous literature review for wetland nutrient removal efficiency rates (Tetra Tech 2016). Therefore, there was not a strong focus on the data source characterization topics of *Extent of Replication* and *Data Collection & Analysis Methods* included in the matrix below.

	High Confidence	**Medium Confidence**	**Low Confidence**
Extent of Replication	Clearly documented and well-controlled past work that has since been replicated or strongly supported by the preponderance of other work; recent (< 5-year old) work that was clearly documented and conducted under well-	Clearly documented older (>5-yr old) work that has not yet been replicated or strongly supported by other studies, but which has also not been contraindicated or disputed	Work that was not clearly documented and cannot be reproduced, or older (>5-yr old) work for which results have been contraindicated or disputed by more recent results in peer-reviewed publication or by other

	High Confidence	Medium Confidence	Low Confidence
	controlled conditions and thus conducive to possible future replication		studies that are at least equally well documented and reproducible
Applicability	Purpose/scope of research/publication matches information/data need	Limited application	Does not apply
Study Location	Within Chesapeake Bay	Characteristic of CB, but outside of watershed	Outside of CB watershed and characteristics of study location not representative
Data Collection & Analysis Methods	Approved state or federal methods used; statistically relevant	Other approved protocol and methods; analysis done but lacks significance testing	Methods not documented; insufficient data collected
Conclusions	Scientific method evident; conclusions supported by statistical analysis	Conclusions reasonable but not supported by data; inferences based on data	Inconclusive; insufficient evidence
References	Majority peer-review	Some peer-review	Minimal to none peer-review

Extent of Replication

As aforementioned, this literature review for wetland habitat benefits is more qualitative in nature than the previous literature review for wetland nutrient removal efficiency rates (Tetra Tech 2016). This results in a medium confidence level since there are not necessarily studies that can be replicated. The literature reviewed includes a mixture of peer-reviewed articles as well as informational documents such as literature reviews, fact sheets, and training modules. Most of the articles reviewed are recent. The oldest was published in 1978, while the most recent articles were published in 2015.

Applicability

Many of the studies identified for this literature review did not contain relevant data and were removed from the evaluation. Seventy three of the 131 articles reviewed were determined to be relevant and are included in this summary. 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, three studies using constructed wetlands were identified and used in the analysis. Data applicability can be considered to have a medium level of confidence.

Study Location

The available data were not limited to the Chesapeake Bay watershed, and most of the useful data were derived from studies outside the watershed. Only nine of the 73 relevant articles were within the Chesapeake Bay watershed. Similar soils and hydrology can be generally representative of wetlands even in locations across the country; however some other factors that change with location may be less representative. An example is climate, which can have an impact on the types of benefits a particular wetland offers. Overall, the data are considered to have a medium level of confidence.

Data Collection & Analysis Methods

As mentioned above, this literature review for wetland habitat benefits is more qualitative in nature than the previous literature review for wetland nutrient removal efficiency rates (Tetra Tech 2016). Therefore, specific approved state or federal methods were not typically employed and are not relevant to this literature review.

Conclusions

The conclusions of the reviewed articles have a medium confidence, meaning the presented conclusions are reasonable but not always supported by data. There are often inferences based on data. Some studies did present results based on scientific method; however, other papers were often literature reviews that summarized existing information regarding wetland functions and values.

References

The majority of the relevant resources that are used in this literature review are peer reviewed, but there is a mix of peer reviewed journal articles, papers written by state and federal agencies, papers written by non-profit organizations and papers written by other individuals or organizations. This provides medium confidence (mostly peer review) in the scientific support for the data.

Characterization of Findings

Wetlands are among the most biologically productive ecosystems in the world (NRCS 2014). While wetlands only occupy about five percent of the continental U.S. land surface, up to one-half of all North American bird species feed or nest in wetlands, more than one-third of endangered and threatened species rely on them, and wetlands are home to nearly one-third of our country’s plant species (NRCS 2014). Results of the literature review indicated that both saline and freshwater wetlands provide multiple habitat benefits to mammals, birds, fish, amphibians, and reptiles as well as provide human benefits such as flood reduction, water quality improvement, carbon sequestration, and recreational and educational opportunities.

Of the 14 articles addressing wetlands in the Chesapeake Bay watershed, nine were identified as having potentially relevant data. The remainder did not specifically address ancillary wetland benefits and focused on land uses different than wetlands or nutrient removal rates rather than wetland habitat benefits.

Given the low success rate in identifying Chesapeake Bay-specific information, several studies from outside the watershed were included. When findings specifically from Chesapeake Bay watershed studies are especially relevant, they are called out below. Sixty four 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 because the initial literature search did not identify them as constructed wetlands. When findings from constructed wetlands are highlighted in the following discussion, they are identified as such. The following sections summarize the findings regarding the various ancillary benefits and unintended consequences of wetlands (in addition to nutrient and sediment reduction).

Creation of Animal, Waterfowl, and Fish, and Vegetation Habitat

The literature review resulted in 23 articles on the benefits of wetlands to the habitats of animals, waterfowl, fish, and endangered and threatened species. Most of the articles focused on general animal habitat (17), while five of the articles discussed waterfowl habitat specifically, nine articles discussed fish habitat, and four articles discussed the benefits to endangered and threatened species.

Animal Habitat

Wildlife habitat is an important functional value of all types of wetlands (Amman and Stone 1991; Woodward and Wui 2001). Wildlife use wetlands to varying degrees depending upon the species involved (USEPA undated). Reptiles, amphibians, muskrat, beaver, mink, rabbits, and other small mammals depend on wetlands (Interagency Workgroup on Wetland Restoration, undated). Wetlands serve as the primary habitat for some species that live in wetlands for their entire lives, such as beaver and muskrat, while other species require wetland habitat for only part of their life cycle or during particular seasons when wetlands provide food, water, and cover. Still other species, such as otter, black bear and raccoon use wetlands even less frequently, mostly for feeding.

A literature review completed in 2015 on the connectivity of wetlands to downstream waters indicates that riparian wetlands and non-floodplain wetlands can provide refuge for aquatic insects and other lotic organisms from predators or other environmental stressors (USEPA 2015). This refuge facilitates individual or population survival. Wetlands provide refuge during certain life stages such as breeding, nesting, or nursery sites for frogs, other amphibians, and some reptiles that reside in streams as adults.

In addition to mammals, amphibians, and reptiles, “80% of [the] American breeding bird population and over 50% of protected migratory bird species rely on wetlands” (Mitsch and Gosselink 2007; Interagency Workgroup on Wetland Restoration, undated; NRCS 2014). Diverse wetland types are necessary to support the diversity of bird species. New Zealand’s Greater Wellington Regional Council (2009) indicates that wetlands cover less than 2 percent of New Zealand’s land area, but are home to 22 percent of the native land bird species.

Golladay et al. (1997) tested the hypothesis that regular inundation and drying are important influences on community structure in some seasonal wetlands. Three forested limesink wetlands in southwest Georgia were included in the study and were found to support an abundant invertebrate fauna. Tidal marshes have been found to be some of the most productive ecosystems on earth (Kelly et al. 2011 and Greater Wellington Regional Council 2009) and provide a range of valuable ecosystem services including habitat.

There is a large amount of research on the restoration of agricultural wetlands. Fennessy and Craft (2011) found that agricultural conservation practices increase wetland ecosystem services in the Glaciated Interior Plains in the Upper Mississippi River basin. Eight wetland types were graded low, medium, or high for their relative contribution to animal habitat. No wetland types were graded "low". Riparian and floodplain forests were considered to provide "high" productivity and connectivity for habitat and depression and vernal pool wetlands provided "high" breeding grounds. Wet meadows and seeps provided "medium" plant diversity in terms of animal habitat.

NRCS (2014) provides a summary of the Natural Resources Conservation Service's (NRCS's) Wetlands Reserve Program (WRP) over the last 20 years. The WRP restores wetlands on frequently flooded agricultural land where restoration maximizes habitat for migratory birds and other wildlife and improves water quality. The WRP provides habitat for a wide variety of animals that depend on wetlands.

NRCS established the Migratory Bird Habitat Initiative (MBHI) to increase habitat for migratory birds impacted by the Deepwater Horizon/BP oil spill (NRCS 2014). NRCS worked to increase open water and available food for migrating birds. WRP projects made up a significant portion of the nearly 500,000 acres NRCS enrolled in MBHI, providing more habitat for the over 50 million birds that migrate the Mississippi, Central, and Atlantic flyways each year (NRCS 2014). These WRP restorations can create groups of smaller wetlands that can provide necessary habitat in an agricultural area (Mitsch 1992).

Wetland creation for the purposes of simultaneous nutrient retention and increased species diversity also benefits the biodiversity of agricultural landscapes. Thiere et al. (2009) found that the density of aquatic habitats was increased by at least 30 percent. These results disagree with a study by Jessop et al. (2014) that found that designing wetlands to focus on nutrient reduction may come at the expense of biodiversity (See Negative Impacts section below).

A living shoreline is another type of wetland restoration/creation that is seeing some success. A living shoreline is a sloped, erosion control technique built to protect an embankment that mimics natural habitat and allows for natural coastal processes to remain through the strategic placement of plants, stone, sand fill, and other structural and organic materials (GDNR 2013; Shumway et al. 2012). Living shorelines generally use hard materials, such as oyster shells, to absorb the energy of incoming water to reduce erosion. Living shorelines are included in this literature review because traditional bulkheads may be effective at reducing erosion and upland loss, but they often cause a loss of habitat connectivity to tidal habitat that is essential to shorebirds, fish, and shellfish (GDNR 2013; Shumway et al. 2012). "Through the promotion of native species and habitats, living shorelines can preserve and enhance the ecological integrity of the coastal environment. In general, these environments provide essential water filtration, habitat, and recreational and commercial opportunities…. Oyster reefs, such as those created by living shorelines…, provide up to $100,000/hectare (ha) ($40,500/acre) through water filtration, habitat, bank stabilization, and harvesting potential" (GDNR 2013). Living shoreline implementation occurring along the Delaware River estuary are expected to protect 10 acres of intertidal habitat for every mile of living shoreline (Stutz 2014).

Habitat provided by wetland restoration benefits not only wildlife, but humans as well. Teal and Peterson (2005) feel that the societal benefits of wetland restoration should be measured rather than implied or assumed. Habitat restoration was considered to be a societal benefit in a study of four watersheds [Mississippi River, Delaware Bay, Lower Fox River (Wisconsin), and South Cape Beach Marsh (Massachusetts)].

Waterfowl Habitat

Many birds, including shorebirds and wading birds, feed, nest, and/or raise their young in wetlands (USEPA undated). Migratory waterfowl, including cranes, ducks, geese, swans, and shorebirds move between and use estuarine, riverine, riparian, and non-floodplain wetlands for resting, feeding, breeding, or nesting grounds for at least part of the year (USEPA undated, 2015).

In the Chesapeake Bay Region (a major wintering area for waterfowl), coastal wetlands supported an annual average of nearly 79,000 wintering black ducks from 1950 to 1994 (USEPA undated). Most of these ducks also rely on the depressional wetlands in the upper mid-west and adjacent Canada and interior wetlands in northeastern North America for nesting. Wood ducks are found throughout freshwater deciduous forests of North America. Preferred breeding sites include floodplains, remote ponds, and woodland pools (USEPA 2015). Wetland restoration through the WRP has restored over 530,000 acres in the Mississippi Alluvial Valley, the nation's largest floodplain, which is a critical region for numerous species of waterfowl, including wintering mallards and wood ducks (NRCS 2014).

The U.S. Fish and Wildlife Service (USFWS) also estimates that WRP wetlands in the Prairie Pothole Region of the Dakotas have a potential waterfowl carrying capacity of over 48,000 pairs of ducks per year (NRCS 2014). In addition to the NRCS's WRP, their Conservation Reserve Program (CRP) provides large blocks of restored grasslands and wetlands. The CRP addresses the vital reproductive rates of waterfowl populations in their most important breeding grounds in North America, the prairie pothole wetlands in the upper Midwest. "Wetlands that occur in grasslands tend to attract higher densities of ducks and are considered superior in biological function to those that occur in cropland" (Allen and Vandever 2005).

Nebraska's neighboring Rainwater Basin (RWB) is also an important stop along the Central Flyway. Only 17 percent of the historically greater than 200,000 acres of wetlands in Nebraska's RWB still exist; however, millions of migrating waterfowl continue to stop there each year (NRCS 2014). Wetlands provide wetland-derived food for migrating waterfowl while they are in the RWB.

Webb et al. (2010) conducted a study to determine local (within wetland and immediate watershed) and landscape-scale factors influencing wetland bird abundance and species richness during spring migration at RWB playas. Wetlands were observed to quantify wetland bird use and determine the relative importance of habitat characteristics. Wetland area, vegetation, and water depth were consistently important habitat characteristics to various waterfowl species (Webb et al. 2010). The relationship between duck abundance and wetland area was most evident during times of lower wetland availability, resulting in lower food availability. In general, species richness increased with wetland area. Dense stands of emergent vegetation can limit feeding activity as well as predator detection. Birds tended to look for wetlands with a 50:50 ratio of open water to vegetation. Water depth was negatively correlated with bird abundance. Deep water reduces invertebrate food resource availability for many species of migratory shorebirds.

Fish and Shellfish Habitat

In addition to animals and birds, fish greatly benefit from wetlands. Coastal wetlands serve as important spawning and nursery areas for the young of many recreational and commercial fish and shellfish because they are the most productive of all wetlands and produce so much plant biomass and invertebrate life (Long Island Sound Study 2003; Hamill undated; USEPA undated). "95% of commercially harvested fish/shellfish in the U.S. are wetland dependent" (Mitsch and Gosselink 2007; Interagency Workgroup on Wetland Restoration, undated).

Riparian wetlands can also provide feeding habitat for fish during periods of overbank flow (USEPA 2015). Teal and Peterson (2005) link increased fish habitat in restored wetlands to improved fishing as a societal benefit of wetland restoration. Some examples of wetland restoration projects with benefits to fish habitat are described below.

Abt Associates (2014) assessed the potential economic value of long-lasting environmental benefits provided by recent coastal restoration projects: tidal marsh restoration in the San Francisco Bay; eelgrass meadows and oyster reefs restoration in the Seaside Bays of Virginia; and living shorelines in Mobile Bay, Alabama. The projects showed that restoration investment, in terms of initial construction cost, provided a variable return on investment. For every $1 invested in construction costs, the projects each produced between $0.06 and $36 in total long-term ecosystem service benefits. Some, but not all, projects can be expected to demonstrate favorable cost-benefit ratios. Fish populations and diversity showed a positive response to the increased habitat availability and increased range of environmental conditions (primarily salinity). These increased numbers could provide additional forage base for larger game fish of recreational interest (Abt Associates 2014).

Gooseneck Cove in Rhode Island was restored and brought back the natural tidal flow in the marsh, along with native vegetation and improved habitat for striped bass and bluefish (NRCS 2014). Stream restoration projects on floodplain wetlands along Sligo Creek (in the Anacostia watershed within the Chesapeake Bay watershed) have improved habitat conditions so that supported fish populations increased from 2 to 11 native species (Montgomery County and MD DEP 2003).

Endangered and Threatened Species Habitat

NRCS (2014) states that more than one third of all federally listed species depend on wetlands during part of their lifecycle, while the USFWS estimates that up to 43 percent of both federally threatened and endangered species rely directly or indirectly on wetlands for their survival (USEPA undated). "There are more than 40 plant and animal species [in the Long Island Sound] of special concern, threatened, or endangered status that depend on the presence of tidal marshes for one, or many, of their life stages" (Long Island Sound Study 2003). "Conservation and restoration programs provide the habitat these [endangered] creatures need to ensure our wildlife survives into the future" (Hamill undated). Restored wetland habitat can help prevent the listing, and accelerate the recovery, of at-risk species (NRCS 2014). Examples of endangered or threatened species that depend on wetlands for their survival are described below.

Sixty two landowners in Oregon's Willamette River watershed worked together to enroll 7,600 acres into WRP, resulting in improved habitat and Oregon chub survival (NRCS 2014). The Oregon chub was down-listed from Endangered to Threatened. Other species also benefitted, such as the Upper Willamette Spring Chinook salmon, Fender's blue butterfly and Nelson's checkermallow (NRCS 2014).

Wood storks nest in colonies in cypress swamps and are currently listed as a federally endangered species. In 2010, a colony of over 125 wood stork nests, 580 cattle egrets and various other waterfowl were discovered on a WRP project in southwest Georgia (NRCS 2014). Since these restored wetlands are so valuable to these birds, WRP is considered essential to the federal Wood Stork Recovery Action Plan.

WRP helped reverse the federally threatened Louisiana black bear's decline by restoring lost habitat (NRCS 2014). WRP also provides habitat for the bog turtle in eastern states with specific focus in Pennsylvania. This small, semi-aquatic turtle has been listed as a federally threatened species since 1997 (NRCS 2014).

In addition, the federally endangered whooping crane is dependent upon wetland habitat in the Midwest. Conservation efforts, including wetland restoration, have played a critical role in the survival of the whooping crane (NRCS 2014).

Vegetation Habitat

Wetlands are also an important habitat for vegetation. Riparian wetlands provide habitat for aquatic vegetation, emergent vegetation, and phytoplankton (Ducey et al 2015; USEPA 2015). Vegetation species diversity and habitat quality increase rapidly with re-vegetation of a wetland (Abt Associates 2014). Long Island Sound Study (2003) indicates that the primary productivity of wetlands rivals that of rainforests and high yield agricultural fields. Above-ground production of salt marsh angiosperms along the Connecticut coast ranges from 0.13 pounds (lbs)/square feet (ft^2)/year to 0.41 lbs/ft^2/year (Long Island Sound Study 2003).

Tidal salt marshes in the San Francisco Estuary have heterogeneous landscape patterns that support primary productivity and carbon sequestration as well as increased vegetation diversity and habitat for wildlife (Kelly et al. 2011). This indicates that vegetation pattern, in addition to quantity, should be considered when restoring wetlands.

Organic soil amendments in restored wetlands can improve soil properties critical for wetland functioning but the benefits of the treatment and the development of the plant community are highly influenced by initial site conditions (Ballantine et al. 2011). A case study on the restored tidal freshwater Kingman Marsh along the Anacostia River in the Chesapeake Bay watershed indicates that the environmental conditions of urban settings impose constraints in restored wetlands that result in plant communities more like those of urban natural wetlands than those of wetlands in less urbanized watersheds (Baldwin 2004).

Gleason et al. (2008) found that restoration practices improved upland floristic quality and native species richness relative to cropped catchments, but upland floristic quality and native species richness of restored catchments did not approach the full site potential as defined by native prairie catchments. Audet et al. (2015) indicates that high groundwater levels and low nutrient availability are important factors in improving species richness in restored wetlands.

Ho and Richardson (2013) examined floral succession under natural processes following wetland restoration of floodplain and marsh habitats in an urban setting in North Carolina. The most natural wetland succession trajectories occurred in the wettest sites (Low Marsh). Species richness increased by 58 percent in the Low Marsh, while it decreased by 58 percent in the High Marsh. It appears that the frequent inundation of the Low Marshes prevented the establishment of invasive species, while the drier High Marsh was overwhelmed by invasive species. “After the wetland restoration, however, pockets of depressions formed mosaics of micro-environments that gave rise to new habitats and helped diversify plant communities” (Ho and Richardson 2013).

Effect of Wetlands on Flood Control and Water Storage

Peak Flow Reduction

Flood control potential is another important wetland functional value (Amman and Stone 1991). “Small wetlands high in a watershed can reduce and delay flood peaks by temporarily storing water” (Zedler 2003). Non-floodplain wetlands can increase the time for stream discharge to rise and fall in response to a precipitation event due to wetland storage capacity (USEPA 2015). Restored wetlands can help reduce downstream flooding and lessen damaging impacts from floods by providing an area not occupied by homes or farms to spread, slow and store floodwaters (NRCS 2014; Landstudies, Inc 2010; Hunt 1997; Interagency Workgroup on Wetland Restoration undated), and regulate “water movement” (Ducey et al. 2015). Trees and other wetland vegetation also slow flood waters (NRCS 2014).

Streamflow records from 30 gauging stations in watersheds with variable wetland areas were analyzed to assess the influence of wetlands on streamflow (Demissie and Khan 1993). “The floodflow volume to total precipitation ratio decreases by 1.4 percent for an increase of one percent wetland area in the watershed. The decrease in the floodflow volume parameter is significantly lower than for the peakflow parameters” (Demissie and Khan 1993).

A wetland restoration along Grays River in the state of Washington did not show the benefit of peak flow reduction due to wetland restoration (Breithaupt and Khangaonkar 2011). There was little difference found in maximum peak water surface elevations between the pre-restoration and post-restoration analyses.

Bullock and Acreman (2003) presents a database of 439 published statements on the water quantity functions of wetlands from 169 studies worldwide. Emphasis is placed on hydrological functions relating to gross water balance, groundwater recharge, base flow and low flows, flood response and river flow variability. Table 5 in the document lists the number of functional statements for each of the wetland types that were analyzed (floodplains, surface water depressions and slopes, groundwater depressions and slopes, and general wetlands) for these hydrologic functions. Because of the massive amount of wetlands used in this paper, it was not feasible to list the attributes of each individual one. However, a summary of the studies that evaluated flood response shows that the majority of functional statements about wetlands indicated a decrease in the flood peak and flood event volume and an increase in the flood time to peak. The results also indicate that the majority of studies showed that wetlands are an important factor in reducing or delaying floods and increasing flood recession.

Water Storage

"[Riparian wetlands] provide valuable ecosystem services such as floodwater storage…" (Audet et al. 2015). Riparian wetlands and non-floodplain wetlands can be sinks for water by intercepting overland or subsurface flow, if available water storage capacity of the wetlands is not exceeded, which can reduce or attenuate flow to downstream waters and flooding (USEPA 2015). Riparian wetlands can temporarily store water following overbank flow, which then can move back to the stream over time as baseflow. "Both the drained and undrained wetland have the capacity to store water; but because the undrained wetland drains so much more slowly, it stores more water in a given storm event" (Potter 2011).

Because of their low topographic position relative to uplands, wetlands store and slowly release surface water, rain, snowmelt, groundwater and flood waters (USEPA undated). A one-acre wetland typically stores about one million gallons of water (NRCS 2014). Trees and other wetland vegetation also impede the movement of flood waters and distribute them more slowly over floodplains. This combined water storage and slowing action lowers flood heights and helps reduce floods. Hunt (1997) supports the use of a natural storage approach to reduce flood damages by restoring the Upper Mississippi River basin's natural hydrology. WRP projects in Minnesota's Red River Valley, which is part of the Upper Mississippi River basin, are helping slow and store floodwaters (NRCS 2014). WRP wetlands in the prairie pothole wetlands of the region have a water storage capacity of over 23,000 acre-feet, which covers 46,000 acres, or an area the size of Washington, D.C., in six inches of water (NRCS 2014).

Gleason et al. (2007) conducted a study to develop and apply approaches to quantify changes in ecosystem services resulting from wetland restoration activities in the Prairie Pothole area of the upper Mustinka watershed in Minnesota. In a 110,145 acre watershed area, the watershed-wide water storage was found to be 458,151 acre-feet. Gleason et al. (2007) found that in a 130,368 acre watershed, a 25 percent restoration of the previously farmed and drained prairie pothole wetlands resulted in a watershed-wide water storage increase of 27-32 percent and a 50 percent restoration of the wetlands resulted in an increased water storage of 53-63 percent.

Another study of a 3.2 acre restored wetland receiving unregulated inflows from a 34.6 acre agricultural watershed in Kent Island, Maryland in the Chesapeake Bay watershed, had a water storage net gain of 127 m^3 (Jordan et al. 2003).

Storm Abatement

"Wetlands act as a giant sponge, helping to control water flow and water quality. Their plants slow the flow of water off the land so that, in times of flood, more can be absorbed into the soil" (Greater Wellington Regional Council 2009). The services provided by wetlands include protection against floods (Woodward and Wui 2001; Teal and Peterson 2005) and in general, restoration of a wetland increases local evapotranspiration losses, leading to an effect on downstream flood levels, particularly in dry regions (Potter 2011; Bullock and Acreman 2003).

Floodplain wetlands reduce flooding by absorbing and slowing floodwaters. Headwater wetlands are more unpredictable; although wetland vegetation impedes flow, the saturated subsurface has no available pore space to absorb water and therefore quickens surface flow. Downstream flood risk is likely to be reduced by maintenance of intact forests and upland wetlands (Brauman et al. 2007).

Costanza et al. (2013) used a regression model for 34 major U.S. hurricanes (including storms impacting the Chesapeake Bay watershed) since 1980. A loss of wetlands in the model resulted in an increase in storm damage. The ability of wetlands to control erosion is so valuable that some states, such as Florida, are restoring wetlands in coastal areas to buffer the storm surges from hurricanes and tropical storms by dissipating wave energy before it impacts roads, houses, and other man-made structures (USEPA undated).

Hunt (1997) and Hey and Philippi (1995) discuss the use of a natural storage approach to reduce flood damages by restoring the Upper Mississippi River basin's natural hydrology and wetlands. The watershed area in the Upper Mississippi River basin is 733,591 square miles (mi^2) (Mitsch and Gosselink 2000) and would need seven percent of the watershed area as wetlands for successful flood control.

Aquifer Recharge

While many wetlands help to reduce floods and water flow during storm events, they are also useful during times of dry weather and low flow. Some wetlands maintain stream flow during dry periods; others replenish groundwater (USEPA undated). Wetlands allow water to be absorbed into the soil providing groundwater recharge (NRCS 2014). Non-floodplain wetlands can contribute to groundwater recharge under low water table conditions, which ultimately contributes to baseflow (USEPA 2015).

Pollutant Reduction and Water Quality Improvement

As aforementioned, Tetra Tech (2016) already completed a previous literature review to evaluate the effectiveness of wetlands as a BMP. That literature review focused on the effectiveness of wetlands at removing nitrogen, phosphorus, and sediment. This current literature review briefly discusses nutrient and sediment removal, but focuses on the reduction of toxic pollutants, denitrification, and carbon sequestration with regard to water quality improvement and pollutant reduction.

Services provided by constructed and restored wetlands, in conjunction with ecologically sound watershed practices, can remove contaminants from water (Zedler 2003; Woodward and Wui 2001; Hunt 1997). Wetlands improve water quality by intercepting surface runoff and removing or retaining nutrients, pesticides, and metals, processing organic wastes, and reducing suspended sediments before they reach open water (USEPA 2015, NRCS 2014, USEPA undated). Without wetlands, these pollutants can clog waterways and affect fish and amphibian egg development. Wetlands also reduce environmental problems, such as algal blooms, dead zones, and fish kills, that are generally associated with excess nutrient loadings. The capacity of wetlands to function as a water purifier is limited. Too much surface runoff carrying pollutants can degrade wetlands and the societal services they provide.

Ecological restoration is becoming regarded as a major strategy for increasing the provision of ecosystem services as well as reversing biodiversity losses (Bullock et al. 2011). Bullock et al. (2011) show that restoration projects can be effective in enhancing both, but that conflicts can arise, especially if single services are targeted in isolation. “Soil properties related to water quality in restored wetlands were <50% of reference values after 55 years” (Bullock et al. 2011).

Marton et al. (2015) consider controls on biogeochemical functions that influence water quality, and estimate changes in ecosystem service delivery that would occur if these wetlands were lost. They specifically estimated that the loss of over 9 million acres of prairie pothole wetlands in the Midwest has resulted in an increase of between 5 million and 140 million tons of sediment entering surface waters per year.

Mitsch and Gosselink (2000) estimate that for general water quality improvement in Illinois, a 146 mi^2 watershed would need 1 to 5 percent of the area to be wetlands. “Based on research done at the Des Plaines River Wetlands Demonstration Project, a conservative hydraulic loading rate, yet one sufficient to accomplish substantial improvement in water quality, would be 0.083 cubic feet per second per acre” (Hey and Philippi 1995). Using this hydraulic loading rate, the area necessary to provide essential flood control and water quality improvement at the same time in the Mississippi River at Thebes, Illinois can be calculated. If the mean annual flood flow were to be treated, assuming the same loading rate, about 6 million acres of wetlands (1.3% of the watershed) would be needed. Approximately 13 million acres of wetlands (2.9% of the watershed) would be needed to treat a 100-year flood.

Downstream Effects on Sedimentation

An important function of wetlands is the stabilization of sediment, which reduces erosion (Woodward and Wui 2001). Wetlands also improve downstream water quality by exporting water after sediment has been retained (Marton et al. 2015). Wetland soils and plants help to break down pollutants and trap sediments (Greater Wellington Regional Council 2009).

Mitsch (1992) presents case studies of riparian wetland systems that were evaluated for their role in controlling nonpoint source pollution. The natural riparian cypress swamp had a retention of 0.092 lbs/ft^2 (3 percent removal efficiency) during a flood event. Constructed riparian wetlands (with a pump) in the Des Plaines River had annual retentions of 0.159 to 0.163 lbs/ft^2 (90 and 88 percent removal efficiency, respectively) with a high flow influx rate. Annual sediment retention rates with a low flow influx rate ranged from 0.041 lbs/ft^2 (93 percent removal efficiency) to 0.044 lbs/ft^2 (98 percent removal efficiency).

Another study showed that constructed wetlands in the agricultural Glaciated Interior Plains in the Midwest provided 2,387,606 lbs/year sediment retention (Fennessy and Craft 2011).

Downstream Effects on Streambank Erosion

Wetlands also act as buffers that help protect shorelines and streambanks against erosion. Wetland plants stabilize soil with their roots, absorb the energy of waves, and break up the flow of stream or river currents (Interagency Workgroup on Wetland Restoration undated; USEPA undated). Teal and Peterson (2005) include erosion control as a societal benefit of wetland restoration.

Mitsch (1992) indicates that "…steeper terrain is often most susceptible to high erosion and hence high contributions of suspended sediments…One approach is to attempt to integrate terraced wetlands into the landscape". Another approach is the installation of a living shoreline, which is currently being used to forestall further erosion of existing wetlands to protect and restore Delaware Bay's tidal wetlands (Stutz 2014).

Denitrification

Wetlands also support denitrification. Several wetland denitrification studies are presented below. Four of the studies provide denitrification rates and four provide removal efficiencies. The denitrification rates and removal efficiencies are presented in Table 1 and discussed in more detail in the following paragraphs. In general, denitrification rates appear to be higher at wetland sites with slower flow and a high water table (Hernandez and Mitsch 2007; McPhillips et al. 2015; McJannet et al. 2011; Mitsch et al. 2012; Knox et al. 2008; Gumiero et al. 2011; and Ator et al. 2013).

Table 1. Denitrification rates in wetlands

Wetland Type	Denitrification Rate	Nitrate Removal Efficiency	Source
Low riparian wetland	7.13±0.91 lbs N/acre	NA	Hernandez and Mitsch 2007
High riparian wetland	4.09±0.78 lbs N/acre	NA	Hernandez and Mitsch 2007
Riparian wetland (fast flow rate)	410 to 772 µg N/kg soil/day	NA	McPhillips et al. 2015
Riparian wetland (slow flow rate)	727 to 5,261 µg N/kg soil/day	NA	McPhillips et al. 2015
Floodplain	208 lbs/2 year period in groundwater	NA	McJannet et al. 2011
Floodplain	13,239 lbs/2 year period in soil	NA	McJannet et al. 2011
Forested riparian wetland	61 lbs N/acre/year	NA	Vellidis et al. 2003
Restored agricultural wetland	NA	52%	Jordan et al. 2003
Planted riparian wetlands (flood pulses)	NA	6.6%	Mitsch et al. 2012
Planted riparian wetlands (suppressed flood pulses)	NA	3.1%	Mitsch et al. 2012
Unplanted riparian wetlands (flood pulses)	NA	9.6%	Mitsch et al. 2012
Unplanted riparian wetlands (suppressed flood pulses)	NA	4.2%	Mitsch et al. 2012
Planted and unplanted riparian wetlands (normal river conditions)	NA	2.2%	Mitsch et al. 2012
Reference wetland	NA	27%	Knox et al. 2008

Wetland Type	Denitrification Rate	Nitrate Removal Efficiency	Source
(low flow)			
Channelized wetland (high flow)	NA	3%	Knox et al. 2008
Forested wetlands	NA	39% - 88%	Gumiero et al. 2011

NA = not applicable

Hernandez and Mitsch (2007) measured denitrification in two created riparian wetlands in the Olentangy River Wetland Research Park, Ohio. The highest mean denitrification rates were observed in the permanently flooded low marsh zone (7.13±0.91 lbs N/acre), which were significantly higher than the high marsh area (permanently saturated with standing water only during flood pulses) (4.09±0.78 lbs N/acre).

Denitrification at a pair of agricultural riparian sites in central New York was characterized by different hydrologic regimes (fast and slow) (McPhillips et al. 2015). "Denitrification ranged from 727 to 5,261 µg N/kg soil/day at the slow site…[and]...410 to 772 µg N/kg soil/day at the fast site" (McPhillips et al. 2015). The denitrification rate decreased with groundwater flux at both sites and accounted for only 5 to 12 percent of total nitrate removal at both sites.

Analysis of residence times in a naturally occurring floodplain in Australia showed that the wetland is well mixed; however, the time that water spends in the wetland is short (90 percent of the flow passed through the wetland in less than 6 hours), leaving little time for denitrification to take place (McJannet et al. 2011). The hydraulic loading of the wetland was also shown to be much higher than that recommended for denitrification. Annual retention was 208 lbs/2 year period in groundwater and 13,239 lbs/2 year period in soil (McJannet et al. 2011).

Another example of a restored wetland (forested riparian wetland buffer) receiving water from an agricultural watershed resulted in an average annual denitrification rate of 61 lbs N/acre/year (Vellidis et al. 2003).

Denitrification removal efficiencies were provided in four studies. These removal efficiencies support the idea that denitrification occurs at a higher rate in wetlands with slow flow and more water. A restored wetland receiving unregulated highly variable inflows from an agricultural watershed in the Chesapeake Bay watershed (Kent Island, MD) was effective at removing nitrate via denitrification with a removal efficiency of 52 percent (Jordan et al. 2003).

Mitsch et al. (2012) studied a pair of flow-through created riverine wetlands in the Olentangy River Wetland Research Park, Ohio. The percentage of nitrogen removed due to denitrification in a planted wetland was 6.6 percent during artificial spring pulses and 3.1 percent during suppressed flood pulses. The percentage of nitrogen removed due to denitrification in an unplanted wetland was 9.6 percent during artificial spring pulses and 4.2 percent during suppressed flood pulses. Denitrification was 2.2 percent during normal river pulse conditions for both planted and unplanted wetlands.

Knox et al. (2008) examined benefits to water quality provided by a natural, flow-through wetland and a degraded, channelized wetland located in the flood-irrigation agricultural landscape of the Sierra Nevada foothills of Northern California. Removal efficiency was 27 percent due to denitrification and other processes in a reference wetland (low flow) and 3 percent in a channelized wetland (high flow).

Gumiero et al. (2011) studied the potential capacity of an afforested riparian zone in removing nitrogen from river water in Italy. Denitrification potential indicated that carbon availability was the most limiting factor. The denitrification process is more effective in a riparian zone where topographic and soil conditions are conducive to a high water table for as long as possible. Removal efficiencies in forested wetlands ranged from 39 to 88 percent (Gumiero et al. 2011).

A geographic model describing the spatial variability in the likely effectiveness of depressional wetlands in watershed uplands at mitigating nitrogen transport from nonpoint sources to surface waters was constructed for the Northern Atlantic Coastal Plain, including portions of the Chesapeake Bay watershed (Ator et al. 2013). It was found that natural or restored depressional wetlands in the very flat poorly drained upland and the flat poorly drained lowland would likely have a high potential to mitigate nitrogen transport from nonpoint sources to local streams. The area is extremely flat and is underlain by organic soils with relatively high available water capacity and likely reducing geochemical conditions; "water would move slowly through the low-gradient landscape providing ample opportunity for denitrification" (Ator et al. 2013).

While the above studies found that slow flow and a high water table benefits denitrification, Denver et al. (2014) found that there does not seem to be a direct correlation between wetland water table elevation and wetland nitrate removal rates in current and former depressional wetlands in an agricultural landscape in the Choptank River watershed, Maryland in the Chesapeake Bay watershed. The forested natural wetlands studied had a high potential for denitrification.

Three of the denitrification studies also found that natural wetlands are better for the purposes of denitrification than restored or constructed wetlands (Bruland et al. 2006; Ducey et al. 2015; and Hunter and Faulkner 2001). Four constructed or restored wetland/natural wetland pairs in North Carolina were sampled to determine denitrification potential (Bruland et al. 2006). The constructed and restored wetland soils only experienced a limited range of soil chemical conditions and associated biogeochemical transformations; however, the highly variable distribution of nitrate in the natural wetlands indicated that natural wetland soils experienced wider ranges in nitrate concentrations.

Natural wetlands typically have higher denitrification enzyme activity rates as compared with restored wetlands and prior converted croplands (Ducey et al. 2015). Denitrification potential was not found to be significantly different among restored and natural bottomland hardwood wetlands in summer or spring, but in fall and winter denitrification was highest in the natural mature wetlands and lowest in the wetlands restored without hydrology reestablished (Hunter and Faulkner 2001).

While several studies show flow rate, water table, and natural wetlands to play an important role in denitrification, Wolf et al. (2011) also found microtopography in a wetland to be an important factor. Wolf et al. (2011) investigated three constructed wetlands in the Chesapeake Bay watershed in Loudoun County and Prince William County, Virginia that incorporated microtopography during construction. The study found that microtopography enhances denitrification in these constructed wetlands.

Gilbert et al. (2013) determined that nitrate was removed between the Lower Columbia River and estuary in Oregon and Washington. This was likely due to denitrification, dissimilatory nitrate reduction to ammonium (DNRA), or assimilation by phytoplankton in the freshwater tidal flats or water column.

Toxics Reduction

In addition to nutrient and sediment removal, wetlands can be used to reduce toxic pollutants. The roots in riparian areas can be important in removing pesticides from shallow subsurface flow because the labile organic matter and organic residues that accumulate near roots can increase microbial biomass and activity (USEPA 2015). Pesticides and their metabolites can be mineralized and adsorbed where surface area contact is high and contact time with roots is sufficient. Research shows that "the atrazine load carried by storm water into a tributary of the Mississippi River was almost entirely removed when detained in wetlands. Atrazine settled out of the water and was adsorbed by cattail debris, soil, and sediments after 6 to 30 days" (Kadlec and Alvord 1993, unpublished data cited in Hunt [1997]).

Seelig and DeKeyser (2006) agree that many pesticides and other man-made organic chemicals are degraded in wetland environments; however, they warn that if "the rates of addition exceed the capacity of the wetland to perform chemical transformation, toxic concentrations may result". Toxic concentrations in wetlands could result in deterioration of the wetland biotic system, causing a reduction in function, and elevated chemical concentrations in adjacent aquatic systems due to reduced wetland function (Seelig and DeKeyser 2006).

Carbon Sequestration

The following section discusses the role of wetlands in carbon sequestration, but focuses mainly on "blue carbon", which is the ability of tidal wetlands and seagrass habitats to sequester and store carbon dioxide and other greenhouse gases from the atmosphere, helping to mitigate the effects of climate change (https://www.estuaries.org/bluecarbon, accessed 2/18/2016).

Coastal marine habitats such as tidal salt marshes, mangroves, and seagrass meadows each account for areas 1 percent or less of the dominant terrestrial habitats of forests, grasslands and deserts; however, the carbon stocks in these marine systems are similar to those observed in many of these terrestrial systems (Pidgeon 2009). Tidal wetlands store globally significant amounts of soil carbon and can remove carbon dioxide from the atmosphere at rates three to ten times greater than forests (CEC 2014).

The difference between the coastal marine and terrestrial habitats is the extensive belowground biomass of the dominant wetland vegetation and the capacity of marine habitats for long term carbon sequestration in sediments (Pendleton et al. 2013; Mcleod et al. 2011; Philip Williams & Associates 2009; Pidgeon 2009; Crooks et al. 2011). Inland forests typically store most of their carbon in aboveground biomass such as tree trunks (Pendleton et al. 2013). Vegetated coastal habitats transfer large amounts of carbon to the sediments, contributing about half of the total carbon sequestration in ocean sediments even though they account for less than 2 percent of the ocean surface (Pidgeon 2009; Crooks et al. 2011). This carbon can remain stored in buried sediments for thousands of years.

Wetlands in saline environments have the added advantage of emitting negligible quantities of methane, which is a more potent greenhouse gas than CO_2, whereas methane production in freshwater wetlands partially or wholly negates short-term carbon sequestration benefits (Crooks et al. 2011; Needelman and Hawkes 2012; Chumra 2009).

According to Chumra (2009), tidal marsh soils sequester 1,874 lbs C/acre/year, which is a “substantial rate”. “Each molecule of CO_2 sequestered in soils of tidal salt marshes…probably has greater value than that stored in any other natural ecosystem due to the lack of production of other greenhouse gases” (Chumra 2009). Tidal marshes are the coastal wetland habitat most appealing for greenhouse gas reduction goals due to their high rates of carbon sequestration (averaging 2,000 lbs C/acre/year) (Needelman and Hawkes 2012). This carbon sequestration rate is more than three times greater than the sequestration rates of agricultural lands, grasslands, peatlands, mineral wetlands, and forests, which all have carbon sequestration rates below 450 lbs C/acre/year (Needelman and Hawkes 2012).

Callaway et al. (2012) evaluated the potential for wetland carbon sequestration in the San Francisco Bay. There was little difference in the sequestration rates among natural and restored sites, indicating that a single carbon sequestration rate could be used for crediting tidal wetland restoration projects. The average carbon sequestration rate was 705 lbs C/acre/year (Callaway et al. 2012). A study by Neely (2008) found that carbon sequestration rates did vary between natural and restored wetland soils. Southeastern soils (in North Carolina) have far lower carbon levels than Midwestern soils. Natural wetland carbon levels averaged 124,361 lbs C/acre, while restored wetlands averaged 22,813 lbs C/acre. Average carbon accumulation in restored wetlands was 2,378 lbs C/acre/year (Neely 2008). Ducey et al. (2015) found that wetland restoration, as opposed to no wetlands, resulted in significantly increased levels of carbon sequestration in the North Carolina Coastal Plain.

The Snohomish Estuary in Washington provides a case study for restoration of tidal wetlands and estimates of carbon storage along the northwest coast of the U.S. and southwest coast of Canada (Crooks et al. 2014). This study found that restoring wetland sites shows good potential for high rates of carbon storage. Historic land use change resulted in estimated emissions of 9.9 billion lbs of carbon, of which 6.2 billion lbs of carbon was a result of clearing forested wetland and 3.7 billion lbs from draining soils. Of the 11,846 acres of converted and drained wetlands, 3,343 acres are currently in planning or construction for restoration. These projects are anticipated to rebuild soil carbon stocks of 700 million lbs as wetlands recover to former tidal elevations, and an additional 800 million lbs with sea level rise of 3 feet. Full estuary restoration would rebuild soil carbon stocks of 2.6 billion lbs as marshes build to emergent wetland tidal elevations, and a further 2.6 billion lbs as they accrete with sea level rise of 3 feet (Crooks et al. 2014).

The Blackwater National Wildlife Refuge in the Chesapeake Bay watershed provides another case study on carbon sequestration (Needelman and Hawkes 2012). The USFWS and the U.S.

Army Corps of Engineers has considered a long-term project to use clean dredged material from the Chesapeake Bay shipping channel to restore up to 20,000 acres of tidal marsh at the Blackwater National Wildlife Refuge and surrounding state and private lands. Barges would carry the dredged material to a coastal storage location where it would be slurried and pumped to the refuge. Estimates for restoration sequestration rates range from 8,000 to 19,000 pounds of CO_2/acre/year. The total project could sequester from 165 million to 375 million pounds of CO_2/year (Needelman and Hawkes 2012). Target salinities of the restored marshes have not been established, but methane emissions have been documented from brackish marshes in this region, so a portion of this sequestration would be offset by methane. Methane emissions in brackish wetlands range from 0.5-1.8 ppt (part per trillion) (Needelman and Hawkes 2012).

In the Prairie Pothole Region of the upper Midwest, estimates show that over 90 million pounds of carbon are sequestered or stored in plants on WRP lands (NRCS 2014). On average, it is estimated that every acre of replanted floodplain forest will sequester 5,500 lbs of carbon each year. Conservative estimates show that, WRP easements could account for over 1.2 billion pounds of sequestered carbon annually (NRCS 2014).

Additional Wetland Benefits

Wetland benefits, in addition to the benefits discussed above, include recreation and education such as bird-watching and hunting; community involvement such as counting species of birds, amphibians, reptiles, mammals, insects and plants; outdoor education possibilities such as outdoor classrooms for local schoolchildren; and restoring tribal lands back to historic marsh conditions (NRCS 2014; USEPA undated). Outdoor classrooms provide a place to study vegetative structure, ecological functions, natural ecological processes, biodiversity, and plant-animal interactions.

Additional benefits of wetlands include high biological productivity. Nutrients are transferred to adjacent aquatic systems, which enhances their productivity. Other benefits include aesthetics; hunting and fishing; hiking; natural observation; photography; and canoeing (USEPA undated; Interagency Workgroup on Wetland Restoration undated). Protecting and restoring wetlands can contribute to the economic health, public safety, and quality of life (Wisconsin Wetlands Association undated).

Wetland resources can provide a significant economic benefit as well. Humans use many natural products from wetlands, including mammals and birds, fish and shellfish, and timber (USEPA undated). Various plants such as blueberries, cranberries, mints, and wild rice, are produced in wetlands. Some medicines are also derived from wetland soils and plants. Many of the U.S. fish and shellfish industries harvest wetland-dependent species (e.g., striped bass and brown shrimp). The fish and shellfish that depend on wetlands for food or habitat constitute more than 75 percent of the commercial and 90 percent of the recreational harvest (USEPA undated). Wetlands are also habitats for commercial fur-bearers like muskrat, beaver, otter, and mink, as well as reptiles such as alligators.

"Wetlands are the most productive places on Earth, providing an enormous food source for fish, birds and other animals" (Greater Wellington Regional Council 2009). NRC (1992) discusses wetland value for the food chain. Many mammals, birds, and fish use wetlands as feeding areas.

Understanding of food web alterations as wetlands are reduced is not well studied; however, "the native food web is no doubt essential to the maintenance of community structure" (NRC 1992).

Negative Impacts

The positive impacts of wetlands on habitat identified in this literature review far outweigh the potentially negative impacts, but some negative impacts are discussed below.

Increased Toxics Concentrations

The fact that many pesticides and other man-made organic chemicals (e.g., PCBs, dioxins, PAHs and antibiotics) are degraded in wetland environments is well-documented; however, if the rates of addition exceed the capacity of the wetland to perform chemical transformation, toxic concentrations may result (Seelig and DeKeyser 2006). "The consequences may be twofold: 1) deterioration of the wetland biotic system, causing a reduction in function; and 2) elevated chemical concentrations in adjacent aquatic systems due to reduced wetland function...Losses of surface water impoundment and lowered water tables will result in reduced capacity of wetlands to attenuate and transform man-made organic chemicals" (Seelig and DeKeyser 2006). The role of wetlands as an environmental filter for contaminants is closely connected to the maintenance of natural hydrologic conditions. Therefore, it is important to maintain natural surface water impoundment and water tables to support a wetland's capability to attenuate and transform man-made organic chemicals (Seelig and DeKeyser 2006).

Microbial communities in riparian wetlands and non-floodplain wetlands can also transform elemental mercury to methylmercury before it enters a stream (USEPA 2015). Methylmercury is a particularly toxic and mobile form that bioaccumulates in aquatic food webs. Mercury methylation occurs in the presence of anoxic, saturated soils high in organic matter, mercury-methylating microbes, and mercury from either atmospheric deposition or soils.

Nuisance Species

A second potential negative impact of wetlands is nuisance or invasive species. Four restored depressional freshwater wetlands in western New York were investigated to observe the impact of organic amendments of differing lability on the soil and vegetative development (Ballantine et al. 2011). After 2 years, plant biomass had recovered and reached levels comparable to natural wetlands; however, both native wetlands species and invasive species colonized the sites indicating that the plant community is highly influenced by initial site conditions. Results indicate that site selection for wetland restoration and creation is crucial. It is best to choose sites that are not close to seed sources of invasive species because they are likely to become colonized by those plants.

In addition, biological connections are likely to occur between most non-floodplain wetlands and downstream waters through either direct or stepping stone movement of amphibians, invertebrates, reptiles, mammals, and seeds of aquatic plants, including colonization by invasive species (USEPA 2015). There are benefits of wetland connectivity to downstream systems, but isolation can also have important positive effects on the condition and function of downstream waters. Isolation acts to reduce material fluxes between systems. Increased isolation can decrease the spread of invasive species and increase the rate of local adaptation. Therefore, both connectivity and isolation should be considered when examining material fluxes from streams and wetlands. The natural balance between connectivity and isolation should be considered when determining potential biological interactions.

Other Negative Impacts

Jessop et al. (2014) found that designing wetlands to focus on nutrient reduction may come at the expense of biodiversity. “Vectors for biodiversity indicators pointed opposite of those related to nutrient-cycling related services…, suggesting that wetlands with greater habitat value provide lesser nutrient-cycling ecosystem services” (Jessop et al. 2014). Given this tradeoff, it is unrealistic to expect all wetland functions to be maximized. Restoration practitioners should prioritize wetland functions based on local site and watershed context. In addition, where a wetland is needed to reduce pollutants such as nutrients, domination by fewer plant species (i.e., less diversity) may be more efficient at removing the pollutants than a wetland with more diversity.

Callaway et al (2012) evaluated the ability of salt and brackish tidal wetlands to keep pace with sea-level rise through sediment accretion and to estimate the potential for wetland carbon sequestration. Citing others, the study notes that while tidal freshwater wetlands can sequester carbon effectively, methane emissions from these same wetlands can outweigh the benefits of carbon storage and careful management is required.

Mitsch and Gosselink (2007) warned of the potential to increase flows, depending on the location of the wetland, indicating “the location of wetlands in the river basin can complicate the response downstream. For example, detained water in a downstream wetland of one tributary can combine with flows from another tributary to increase the flow peak rather than desynchronize flows.” The usefulness of wetlands in reducing downstream flooding increases with an increase in wetland area; the distance that the wetland is downstream; the size of the flood; the closeness to an upstream wetland; and the lack of other upstream storage such as reservoirs.

D. Conclusions

Most of the articles and studies that were reviewed focused on restored wetlands; however, constructed and natural wetlands were included as well. Results of the literature review indicate that all wetlands are beneficial to mammals, birds, fish, amphibians, and reptiles for providing temporary feeding, breeding, nesting, and rearing areas as well as permanent habitat. Tidal marshes appear to provide more benefits than other wetland types because they are the most productive wetlands and provide much greater carbon sequestration opportunity than freshwater wetlands without the emission of methane gas associated with freshwater wetlands. Natural wetlands with a high water table and slow flow appear to be more successful at denitrification than restored wetlands with those same characteristics; however, restored wetlands still result in greater amounts of denitrification than degraded or no wetlands. The positive habitat benefits of wetlands, including animal habitat, flood reduction, storm abatement, improved water quality, reduced erosion, and groundwater recharge, seem to outweigh the few negative impacts such as increased toxic concentrations and invasive plant and animal species. Many of these negative impacts can be avoided through proper site selection for restored wetlands and attentive management.

E. References

Abt Associates. 2014. *Estimating the Change in Ecosystem Service Values from Coastal Restoration*. Prepared for Center for American Progress and Oxfam America by Abt Associates.

Acreman, M.C., R. Riddington, and D.J. Booker. 2003. *Hydrological impacts of floodplain restoration: a case study of the River Cherwell, UK*. Hydrology and Earth System Sciences, 7(1):75-85.

Allen, A.W. and M.W. Vandever. 2005. The Conservation Reserve Program– Planting for the Future: Proceedings of a National Conference, Fort Collins, Colorado, June 6–9, 2004. Scientific Investigations Report 2005-5145. United States Geological Survey, Biological Resources Discipline, Reston, VA.

Amman, A.P. and A.L. Stone. 1991. *Method for the comparative evaluation of nontidal wetlands in New Hampshire*. NHDES-WRD-1991-3. New Hampshire Department of Environmental Services, Concord, NH.

Ator, S.W., J.M. Denver, A.E. LaMotte, and A.J. Sekellick. 2013. A regional classification of the effectiveness of depressional wetlands at mitigating nitrogen transport to surface waters in the Northern Atlantic Coastal Plain: U.S. Geological Survey Scientific Investigations Report 2012–5266. United States Geological Survey, Reston, VA.

Audet, J., A. Baattrup-Pedersen, H.E. Andersen, P.M. Andersen, C.C. Hoffmann, C. Kjaergaard, and B. Kronvang. 2015. *Environmental controls of plant species richness in riparian wetlands: Implications for restoration*. Basic and Applied Ecology, 16:480-489.

Baldwin, A.H. 2004. *Restoring complex vegetation in urban settings: The case of tidal freshwater marshes*. Urban Ecosystems 7:125-137.

Ballantine, K. and R. Schneider. 2009. *Fifty-five Years of Soil Development in Restored Freshwater Depressional Wetlands*. Ecological Society of American. Ecological Applications19(6):1467-1480.

Ballantine, K., R. Schneider, P. Groffman, and J. Lehmann. 2011. *Soil Properties and Vegetative Development in Four Restored Freshwater Depressional Wetlands*. Soil Science Society of America Journal, 76:1482-1495.

Brauman, K.A., G.C. Daily, T. Ka'eo Duarte, and H.A. Mooney. 2007. *The Natural and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services*. Annu. Rev. Environ. Resour, 32:67-98.

Breithaupt, S. and T. Khangaonkar. 2011. *Effects of Wetland Resotration on Floodplain Hydrodynamics under Extreme Flooding Conditions*. Ecological Restoration, 29(1-2):161-172.

Bullock, A. and M. Acreman. 2003. *The role of wetlands in the hydrological cycle*. Hydrology and Earth System Sciences, 7(3):358-389.

Bullock, J.M., J. Aronson, A.C. Newton, R.F. Pywell, and J.M. Rey-Benayas. 2011. *Restoration of ecosystem services and biodiversity: conflicts and opportunities*. Trends in Ecology and Evolution, 26(10): 541-549.

Callaway, J.C., E.L. Borgnis, R.E. Turner, and C.S. Milan. 2012. *Carbon Sequestration and Sediment Accretion in San Francisco Bay Tidal Wetlands*. Coastal and Esturaine Research Federation. Estuaries and Coasts 35:1163-1181.

CEC (Commission for Environmental Cooperation). 2014. Greenhouse Gas Offset Methodology Criteria for Tidal Wetland Conservation. Montreal, Canada: Commission for Environmental Cooperation. 36 pp.

Chumra, G. 2009. Tidal Marshes. In: Laffoley, D.d'A. and Grimsditch, G. (eds). 2009. The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53 pp.

Costanza, R., O. Perez-Maqueo, M.L Martinez, P. Sutton, S.J. Anderson, and K. Mulder. 2013. *The Value of Coastal Wetlands for Hurricane Protection*. Royal Swedish Academy of Sciences. 37(4):241-248.

Crooks, S., D. Herr, J. Tamelander, D. Laffoley, and J. Vandever. 2011. "Mitigating Climate Change through Restoration and Management of Coastal Wetlands and Near-shore Marine Ecosystems: Challenges and Opportunities." Environment Department Paper 121, World Bank, Washington, DC.

Crooks, S., Rybczyk, J., O'Connell, K., Devier, D.L., Poppe, K., Emmett-Mattox, S. 2014. Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration. Report by Environmental Science Associates, Western Washington University, EarthCorps, and Restore America's Estuaries. February 2014.

Demissie, M. and A. Khan. 1993. *Influence of wetlands on streamflow in Illinois*. Illinois Department of Conservation, Illinois State Water Survey, Champaign, IL.

Denver, J.M., S.W. Ator, M.W. Lang, T.R. Fisher, A.B. Gustafson, R. Fox, J.W. Clune, and G.W. McCarty. 2014. *Nitrate fate and transport through current and former depressional wetlands in an agricultural landscape, Choptank Watershed, Maryland, United States*. Journal of Soil and Water Conservation, 69(1):1-16.

Ducey, T.F., J. O. Miller, M. W. Lang, A. A. Szogi, P. G. Hunt, D. E. Fenstermacher, M. C. Rabenhorst, and G. W. McCarty. 2015. *Soil Physicochemical Conditions, Denitrification Rates, and nosZ Abundance in North Carolina Coastal Plain Restored Wetlands*. Journal of Environmental Quality, 44:1011-1022.

Fennessy, S. and C. Craft. 2011. *Agricultural conservation practices increase wetland ecosystem services in the Glaciated Interior Plains*. Ecological Applications, 21(3):S49-S64.

Georgia Department of Natural Resources. 2013. Living Shorelines along the Georgia Coast: A Summary Report of the First Living Shoreline projects in Georgia. Prepared for Georgia Department of Natural Resources, Coastal Resources Division, Brunswick, GA by Greenworks Enterprises, LLC.

Gilbert, M. , J. Needoba, C. Koch, A. Barnard, and A. Baptista. 2013. *Nutrient Loading and Transformations in the Columbia River Estuary Determined by High-Resolution In Situ Sensors*. Estuaries and Coasts, 36:708-727.

Gleason, R.A., M.K. Laubhan, and N.H. Euliss. 2008. Ecosystem services derived from wetland conservation practices in the United States Prairie Pothole Region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs: Professional Paper 1745. United States Geological Survey, Reston, VA.

Golladay, S.W., B.W. Taylor, and B.J. Palik.1997. *Invertebrate communities of forested limesink wetlands in southwest Georgia, USA: Habitat use and influence of extended inundation*. Wetlands, 17(3):383-393.

Greater Wellington Regional Council. 2009. A beginner's guide to wetland restoration. Greater Wellington Regional Council, Wellington office, Wellington, New Zealand.

Hamill, P. undated. Your wetland: A guide to wetland restoration. Marlbourough District Council, New Zealand.

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

Hey, D.L., and N.S. Philippi. 1995. Flood Reduction through Wetland Restoration: The Upper Mississippi River Basin as a Case History. Restoration Ecology. 3(1):4-17.

Ho, M. and C.J. Richardson. 2013. *A five year study of floristic succession in a restored urban wetland*. Ecological Engineering, 61P:511-518.

Hunt, C.E. 1997. A Natural Storage Approach for Flood Damage Reduction and Environmental Enhancement. United States Geological Survey, Environmental Management Technical Center, Onalaska, Wisconsin.

Interagency Workgroup on Wetland Restoration. Undated. An Introduction and User's Guide to Wetland Restoration, Creation, and Enhancement. National Oceanic and Atmospheric Administration, Environmental Protection Agency, Army Corps of Engineers, Fish and Wildlife Service, and Natural Resources Conservation Service.

Jessop, J.G. Spyreas, G.E. Pociask, T.J. Benson, M.P. Ward, A.D. Kent, and J.W. Matthews. 2015. *Tradeoffs among ecosystem services in restored wetlands*. Biological Conservation, 191:341-348.

Jordan, T.E., D.F. Whigham, K.H. Hofmockel, and M.A. Pittek. 2003. *Wetlands and Aquatic Processes: Nutrient and Sediment Removal by a Restored Wetland Receiving Agricultural Runoff*. Journal of Environmental Quality, 32:1534-1547.

Kelly, M., K.A. Tuxen, and D. Stralberg. 2011. *Mapping changes to vegetation pattern in a restoring wetland: Finding pattern metrics that are consistent across spatial scale and time*. Ecological Indicators, 11:263-273.

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, 37:1837-1346.

Landstudies, Inc. 2010. Floodplain Restoration. Landstudies, Inc., Lititz, PA.

Linwood H. Pendleton , Ariana E. Sutton-Grier , David R. Gordon , Brian C. Murray , Britta E. Victor , Roger B. Griffis , Jen A.V. Lechuga & Chandra Giri. 2013. *Considering "Coastal Carbon" in Existing U.S. Federal Statutes and Policies.* Coastal Management. 41:5, 439-456

Long Island Sound Study. 2003. Technical support for coastal habitat restoration, Section 1: Tidal Wetlands. Long Island Sound Habitat Restorative Initiative.

Marton, J.M., I.F. Creed, D.B. Lewis, C.R. Lane, N.B. Basu, M.J. Cohen, and C.B. Craft. 2015. *Geographically Isolated Wetlands are Important Biogeochemical Reactors on the Landscape*. BioScience, 65(4): 408-418.

Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger, and B. R. Silliman. 2011. *A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2*. Front Ecol Environ 9(10): 552–560.

McPhillips, L.E., P.M. Groffman, C.L. Goodale, and M.T. Walter. 2015. *Hydrologic and Biogeochemical Drivers of Riparian Denitrification in an Agricultural Watershed*. Water, Air, & Soil Pollution, 226(6):169, 17 pp.

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. and J.G. Gosselink. 2000. *The value of wetlands: importance of scale and landscape setting*. Ecological Economics, 35:25-33.

Mitsch, W.J. and J.G. Gosselink.2007. Values and Valuation of Wetlands, Chapter 11 *in* Wetlands. Van Nostrand Reinhold, New York.

Mitsch, W.J., L. Zhang, K.C. Stefanik, A.M. Nahlik, C.J. Anderson, B. Bernal, M. Hernandez, and K. Song. 2012. *Creating Wetlands: Primary Succession, Water Quality Changes, and Self-Design over 15 Years*. BioScience, 62(3):237-250.

Montgomery County and MDEP (Maryland Department of Environmental Protection). 2003. Montgomery County's Commitment to Anacostia Watershed Restoration, Montgomery County Maryland, Department of Environmental Protection.

Needelman, B.A., and J.E. Hawkes. 2012. Mitigating greenhouse gases through coastal habitat restoration. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore- Adapt-Mitigate: Responding to Climate Change through Coastal Habitat Restoration. Restore America’s Estuaries, Washington, DC, pp. 49-57.

Neely, H. 2008. Restoring Farmland to Wetlands: The Potential for Carbon Credits in Eastern North Carolina. Masters Project. Duke University.

NRC (National Research Council). 1992. Restoration of Aquatic Ecosystems. pp 264-271.

NRCS (Natural Resources Conservation Service). 2014. Restoring America’s Wetlands: A Private Lands Conservation Success Story. Washington, DC.

Philip Williams & Associates. 2009. Greenhouse Gas Mitigation Typology Issues Paper Tidal Wetlands Restoration. San Francisco, CA.

Pidgeon, E. 2009.Carbon Sequestration by Coastal Marine Habitats: Important Missing Sinks. In: Laffoley, D.d’A. and Grimsditch, G. (eds). 2009. The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53 pp.

Potter, K.W. 2011. Estimating Potential Reduction Flood Benefits of Restored Wetlands. University of Wisconsin.

Restore America’s Estuaries. 2016. Coastal Blue Carbon. https://www.estuaries.org/bluecarbon, accessed 2/18/2016

Seelig, B. and S. DeKeyser. 2006. Water Quality and Wetland Function in Northern Prairie Pothole Region. North Dakota State University Extension Service, Fargo, ND.

Shumway, C.A., J.G. Titus, and R. Takacs. 2012. Adapting to Climate Change by Restoring Coastal Habitat. In: B.A. Needelman, J. Benoit, S. Bosak, and C. Lyons (eds.) Restore- Adapt-Mitigate: Responding to Climate Change through Coastal Habitat Restoration. Restore America’s Estuaries, Washington, DC, pp. 33-48.

Stutz, B. 2014. Why Restoring Wetlands Is More Critical Than Ever. Updated July 28, 2014; accessed February 16, 2016.
http://e360.yale.edu/feature/why_restoring_wetlands_is_more_critical_than_ever/2789/

Teal, J.M. and S. Peterson. 2005. *Restoration Benefits in a Watershed Context*. Journal of Coastal Research, 40:132-140.

Tetra Tech, Inc. 2016. Draft Literature Review – Technical Appendix. Prepared by Tetra Tech, Inc. for the Wetlands Expert Panel. U. S. EPA Chesapeake Bay Program Office. Annapolis, MD.

Thiere, G., S. Milenkovski, P-E Lindgren, G. Sahlen, O. Berglund, S.E.B. Weisner. 2009. *Wetland creations in agricultural landscapes: Biodiversity benefits on local and regional scales*. Biological Conservation, 142:964-973.

USEPA (United States Environmental Protection Agency). 2015. Connectivity of Streams & Wetlands to Downstream Waters: A Review & Synthesis of the Scientific Evidence. EPA/600/R-14/475F. Office of Research and Development. Washington, DC.

USEPA (United States 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.

USEPA (United States Environmental Protection Agency). Undated. Wetland Functions and Values. Accessed February 18, 2016: Watershed Academy Web http://www.epa.gov/watertrain

Webb, E.B., L.M. Smith, M.P. Vritska, and T.G. Lagrange. 2010. *Effects of Local and Landscape Variables on Wetland Bird Habitat Use during Migration through the Rainwater Basin*. Journal of Wildlife Management 74(1):109–119.

Wisconsin Wetlands Association. Undated. How Wetalnds Benefir Your Community. Madison, WI.

Wolf, K.L., C. Ahn, and G.B. Noe. 2011. *Microtopography enhances nitrogen cycling and removal in created mitigation wetlands*. Ecological Engineering, 37:1398-1406.

Woodward, R.T. and Y.S. Wui. 2001. *The economic value of wetland services: a meta-analysis*. Ecological Economics, 37: 257-270.

WQGIT (Water Quality Goal Implementation Team). 2015. Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Watershed Model. Chesapeake Bay Program Office.

Zedler, J.B. 2003. *Wetlands at Your Service: Reducing Impacts of Agriculture at the Watershed Scale*. Frontiers in Ecology and the Environment, 1(2):65-72.