Chapter 3

Case Study #1: Tidal Wetlands

Coastal wetlands are arguably the Delaware Estuary's most important and characteristic habitat. There are two traits that distinguish this system from others. First, there is a near contiguous border of more than 150,000 hectares of tidal wetlands that fringe Delaware Bay and the lower estuary region. Second, the system has the largest freshwater tidal prism in the world, and the extended salinity gradient leads to a rich diversity of marsh types.

Tidal wetlands are at risk from a variety of climate change impacts, and there is growing concern that hastened wetland loss will translate into lost ecosystem service important for lives and livelihoods. Fifty percent of the original tidal wetlands along the Delaware Estuary have been lost to development and degradation associated with human activities, these losses are continuing today, and much more could be lost by climate change impacts.

3.1 Tidal Wetlands in the Delaware Estuary Watershed

The Delaware Estuary contains diverse tidal wetlands including a variety of types of emergent marshes and forested swamps. Some are flooded regularly by tides and others are irregularly flooded on spring tides or during storms. The most extensive types are marshes dominated by perennial vascular plants. The different marsh communities are mainly delineated by the salinity gradient (Fig. 3-1.) The effects of climate change were examined for the two most ecologically significant wetland types, freshwater tidal marshes and brackish/salt marshes.

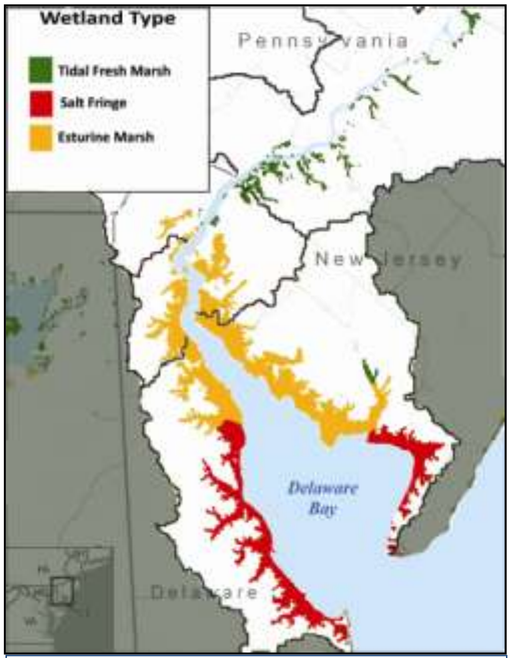


Figure 3-1. Tidal wetlands of the Delaware Estuary (Reed et al. 2008.)

3.1.1. Freshwater Tidal Marshes

Approximately five percent of the original acreage of freshwater tidal marsh remains, amounting to 11,709 hectares based on the latest available 1980s data from the National Wetland Inventory (Appendix G.) Nevertheless, the Delaware Estuary still supports more of this marsh type than any other estuary in the nation. New Jersey contains the greatest percentage, 7302 hectares, and Delaware and Pennsylvania contain 4527 and 380 hectares, respectively.

Freshwater tidal wetlands occur in the upper reaches of large tidal rivers beyond the reach of saltwater. Salinities are less than 0.5 ppt. The characteristic native vegetation species is diverse with dominant species such as wild rice, *Zizania aquatic*, cattails, *Typha* spp., and low marsh species such as arrow-arum, *Peltandria virginica,* pond-lily, *Nuphar lutea*, and pickerelweed, *Pontedaria cordata* (Westervelt et al. 2006). The invasive common reed, *Phragmites australis*, is also abundant, creating dense monotypic stands especially in areas where the natural hydrology has been altered. Freshwater tidal marshes are diurnally flooded and have wide tidal ranges vary from 0.5 to 3 meters (i.e., they are macrotidal.) They contain many rare plant communities and serve as habitat for species such as endangered short-nose sturgeon.

3.1.2. Brackish and Salt Marshes

More than 145,000 hectares of brackish and salt marshes remain in the Delaware Estuary, roughly half in Delaware and half in New Jersey (Appendix G.)   These wetlands extend from Cape Henlopen to New Castle, Delaware, and from Cape May to Salem, New Jersey, forming a near contiguous border around Delaware Bay. Since European settlement, approximately a quarter to half of the brackish and salt water wetlands have been altered or converted for other purposes. Many were diked for agriculture, such as salt hay farming and cattle grazing. Others were impounded to create waterfowl hunting opportunities. As with other areas of the Atlantic coast, vegetated tidal marshes in the Delaware Estuary continue to be lost for various reasons. Between 1998 and 2004 alone, more than one percent of Atlantic coast tidal wetlands were destroyed (Stedman and Dahl 2008.)

Brackish and saltwater wetlands occur in the lower reaches of tidal tributaries and along the open shores of Delaware Bay. Salinities range between 0.5 ppt and 30 ppt. The characteristic native vegetation is less diverse than in freshwater tidal marshes particularly in the regularly flooded low areas of salt marshes due to the need for salinity tolerance. In the low marsh areas smooth cordgrass, *Spartina alterniflora*, is the functional and structural dominant species. In the irregularly flooded high salt marsh, important species include salt hay, *Spartina patens*, Saltgrass, *Distichlis spicata*,and high marsh shrubs such as groundsel tree, *Baccharis halimifolia* and Jesuit's bark, *Iva frutescens* along with the invasive form of common reed, *Phragmites australis*. Most salt marshes of the Delaware Estuary are diurnally flooded with narrower tidal ranges (< 1 m, microtidal) than the freshwater tidal marshes.

3.1.3. Ecological Importance of Tidal Wetlands

Tidal wetlands furnish essential spawning, foraging, and nesting habitat for fish, birds, and other wildlife. They function as the ecosystem's "kidneys," filtering contaminants, nutrients, and suspended sediments, allowing for higher water quality than would otherwise occur. Important finfisheries and shellfisheries are supported by tidal wetlands. They sequester more carbon than any other habitat in the watershed. And importantly, they represent our first line of defense against storm surge and flooding. Acre for acre, tidal wetlands likely provide more ecosystem services than any other habitat type in the watershed.

3.2 Tidal Wetlands – Approach to Assessing Vulnerability and Adaptation Options

The vulnerability of tidal wetlands to climate change and potential adaptation options were assessed by a Wetland Workgroup comprised of wetland scientists and managers from both public and private sectors. Participants included specialists in freshwater tidal marshes and salt marshes. For the purposes of this project, the Wetland Work Group operated as a subgroup under the Climate Adaptation Work Group. Initial tasks completed by the group were to:

- Identify the main physical and chemical environmental factors that are likely to change with changing climate and also affect tidal wetlands (Section 3.3.1.)

- Inventory the main climate change vulnerabilities of tidal wetlands in terms of ecological or physiological consequences (Section 3.3.2.)

- Identify various adaptation options that might be used to lower the vulnerability of tidal wetlands to climate change (Section 3.3.3.)

Following the development of inventories of climate drivers, vulnerabilities, and adaptation options for each of the two marsh types (Section 3.3), the Wetland Work Group then:

- Prepared a survey to rank the relative level of concern for how projected changes in four physical and chemical conditions might impact various indicators of wetland health (Section 3.4),
- Used the survey format to poll experts and rank relative vulnerabilities for the two marsh types (Section 3.5),
- Used the survey to rank various adaptation options for their potential to address the vulnerabilities (Section 3.6),
- Reviewed additional supporting documentation regarding tidal wetland vulnerabilities and adaptation options (Section 3.7),
- Ranked the top vulnerabilities and adaptation options after synthesis of information in Sections 3.5-3.7 (Section 3.8),
- Prepared adaptation recommendations (Section 3.9.)

3.3 Wetland Work Group Inventories

Climate change will affect innumerable direct and indirect ecological interactions, and the Wetland Work Group did not attempt to develop comprehensive lists of climate drivers, vulnerabilities, and adaptation options. The intent of the group was to identify the most important drivers, effects and options that could be fairly analyzed in a short period of time as a first step toward climate adaptation planning.

3.3.1 Climate Drivers

Four climate drivers were identified as most likely to affect tidal wetlands. These are described below along with an initial orientation to how they might affect wetland status in different areas.

Sea level rise. Sea level rise represents the greatest threat to tidal wetlands in the Delaware Estuary, the habitat situated on the "front lines". Tidal marshes maintain an elevation relative to sea level by the accumulation of dead plant matter and sediment. Whether marshes keep pace with sea level rise or not depends on many factors, such as their productivity, sediment supply from other areas, nutrient loadings, wave and current energies, and the rate of sea level rise. This is a delicate balance, and in any given marsh there typically both areas of erosion and drowning as well as areas where the marsh is expanding.

Until about 4000 years ago, the rate of sea level rise was faster than today (about 3 mm per year), and there was considerably less tidal wetland area along the Mid-Atlantic region because that rate was faster than marshes could keep pace with (Day et al. 2000, Najjar et al. 2000.) Then, the rate of sea level rise slowed to approximately 1 mm per year, which allowed tidal marshes to become established and maintain themselves along protected shorelines. During the last 100 years however, the rate of sea level rise in the Delaware Estuary has increased to 3-4 mm per year (Chapter 2.) During this same period, we began to see losses of tidal marsh (PDE 2008, Stedman and Dahl 2008,) presumably due to a mix of direct human impacts and the increased rate of sea level rise. With current projected rates of sea level rise of up to 10 mm per year or more in the coming century (Chapter 2,) it is plausible to expect there to be far more wetlands lost than gained.

The demise of tidal marshes with respect to sea level rise can occur in many ways. Seaward edge erosion can alter the ratio of shoreline edge to marsh area and increase channel and tidal creek scour (Fig. 3-2.) Another common pattern is drowning of interior areas of marsh, especially when insufficient sediments are delivered through tidal exchange or where plant productivity is low. In such cases, the surface elevation of the marsh falls below the threshold needed to keep pace with sea level rise and the marsh drowns (Reed 1995, Cahoon et al. 1999.)


Figure 3-2. Rapid erosion rates are occurring along the seaward margin of many Delaware Estuary salt marshes, as seen here within the mouth of the Maurice River, NJ.

Sea level rise in the Delaware Estuary is likely to be greater than the global average for many reasons (see Chapter 2.) Another local complication is subsidence, which refers to the sinking of land surfaces. Much of the land in the coastal plain of the Delaware watershed is losing elevation (ref.) Since the land is sinking while sea level is also rising, this creates a higher local "relative rate of sea level rise" (RSLR), which marsh communities must keep pace with.

Tidal flooding can only be tolerated by marsh vegetation to a certain physiological limit, so increases in tidal range associated with rising seas may also affect plant productivity, potentially creating a negative feedback, whereby reduced production compromises the ability to accumulate organic matter and grow vertically. Sparse vegetation traps less sediment. Once the marsh community begins to lose elevation relative to sea level, it can become more susceptible to storm surge erosion that accompanies storm events.

The vulnerability of tidal marshes to sea level rise can be exacerbated by the presence of excess nutrient loadings (Turner et al. 2004.) Recent studies have shown that excess nutrients can promote greater aboveground plant production at the expense of belowground production. Belowground production is important for peat formation (for vertical accretion) since much of the aboveground production decomposes in situ. Tall and leggy marsh plants tend to occur in nutrient-laden areas, and since there is little rhizome structure to hold place these marshes can be highly sensitive to storm surges. The Delaware Estuary has some of the highest concentrations of nutrients compared to other large American estuaries (Sharp et al. 1982, Sharp 1988, 1994,) however this system has not shown the tell-tale signs of eutrophication such as algal blooms, hypoxia, and fish kills. One reason for this is the natural high turbidity which inhibits phytoplankton production in many areas. Although relatively unstudied, the extensive fringing tidal wetlands might also be serving as a nutrient sink. More study is therefore warranted to ascertain whether nutrient loadings compound the vulnerability of tidal wetlands to the effects of sea level rise.

Sediment supply from rivers is also needed for marshes to maintain themselves with sea level rise. In recent decades the supply of sediments entering the estuary from major rivers has been decreasing. Maintenance dredging of the shipping channel removes more sediment each year than is imported from the rivers. It is unclear whether sediment management practices, channel configuration and depth, and changing hydrodynamics associated with sea level rise contribute to sediment deficits for tidal marshes.

Tidal inundation into formerly non-tidal areas can also create opportunities for invasive species, such as *Phragmites australis.* This invasive has been observed colonizing former freshwater forested wetlands following meadow dike breaches (K. Philipp, D. Kreeger, Pers. Commun.)

Salinity. The effects of salt water on tidal marshes are problematic for freshwater tidal marshes and freshwater tidal swamps that cannot tolerate salinities greater than half a part per thousand. Salt water intrusion into freshwater areas can occur in short bursts during storms or over longer time periods with relative sea level rise. In either case, shifting salinity zones will drive shifts in marsh communities.

Not only plants, but animal and microbial communities will be altered by salt intrusion particularly in poorly flushed areas (Weston, 2006; Craft et al., 2008, Weston et al., 2009). As plants with a low salt tolerance become stressed, less productive and die, marsh communities shift to salt-tolerant species.

Conversion to saline conditions can also alter soil types, affect evapotranspiration rates, and alter anaerobic decomposition rates. Typically, carbon dioxide (CO_2) gets reduced to methane (CH_4) in freshwater marshes, and a shift to sulfate (SO_4^{-3}) reduction in salt marshes will increase the rate at which organic matter is decomposed, increasing the loss of carbon stored in marsh soils.

Temperature. Increased temperatures will boost production and decomposition rates, but also lead to reduced soil moisture and increased salinity because of greater evapotranspiration. The associated stress from desiccation and/or salinity could offset the higher productivity. Increased temperatures will also promote the northern migration of southern species.

Precipitation and Storm Events. Changes in precipitation patterns are projected to bring an increase in the frequency of both droughts and heavy precipitation storm events, whereas changes in storm intensity could bring greater threats of storm surge and flooding. Projected increases in cool season precipitation will help to offset increases in salinity during the non-growing times of the season, and during the growing season it may be hotter with no marked change in precipitation (Chapter 2.) Taken together with projected increases in strong storms, it is likely that weather will be more oscillatory with greater abrupt swings in salinity and flooding. In salt marshes, such oscillations are believed to contribute to marsh die-back (browning) (Bason et al. 2007.) Low rainfall periods can lead to oxidation of soils and extremely high soil salt concentrations, detrimental to all but extremely halophytic species. When soils are then suddenly flooded and become reduced, they can become toxic to marsh plants.

In both salt and fresh water wetlands, increased desiccation or flooding can also alter sediment supply and erosion. Productivity may be affected by changes in rainfall. Excessive or abrupt shifts in drought, heat waves, and “unseasonably” wet or cold periods can also overwhelm the physiological tolerance limits of some plants and animals.

In general, an increase in precipitation should offset some negative effects of relative sea level rise and salinity increases on tidal wetlands. Aboveground productivity of salt marsh plants is correlated with precipitation patterns, with greater production occurring in years of high precipitation in wetland areas with relatively high salinity levels (De Leeuw et al. 1990, Gross et al. 1990). However, increased frequency and intensity of storm events will impair tidal wetlands through wind, wave, and surge effects. Such disturbances could also make marshes more susceptible to aggressive, non-native species invasions.

Atmospheric CO_2. Increased atmospheric CO_2 concentrations will affect the composition of wetland plant communities by shifting conditions to be more suitable for plants that fix carbon using a C_3 pathway instead of the C_4 pathway. This is important because the current functional dominant plants of Delaware Bay salt marshes are *Spartina* grasses that are C_4 species. Species that will be favored will be sedges and rushes that are currently more common in brackish and freshwater wetlands. While not being directly harmful to C_4 plants, increased CO_2 concentration will stimulate C_3-species (Curtis et al. 1990, Rozema et al. 1991), helping them better compete with C_4 plants (Curtis et al. 1990, Ehleringer et al. 1991). Potentially, this shift in species could lower productivity since C_4-species are more efficient in fixing C, and overall resilience to disturbance could be reduced since the C_3 species are not as good at conserving water (Chapin et al. 2002).

Over all plant species, elevated carbon dioxide levels will increase overall productivity of tidal marshes, potentially helping these wetlands accrete faster and keep pace with sea level rise (Langley et al. 2009.) Increasing atmospheric CO_2 will also affect transpiration rates through greater leaf CO_2 exchange over shorter periods of time. Stomates can be opened for shorter periods of time to allow for this exchange, which will cut water loss through these tiny pores thereby helping the plants stave off desiccation stress. Taken together, elevated CO_2 will have both positive and negative effects of tidal marsh ecology and it is difficult to predict net outcomes.

3.3.2 Inventory of Vulnerabilities.

Numerous aspects of tidal wetland health were identified for use in vulnerability assessments. These are briefly described below with an initial orientation to how they might vary between the two wetland types in relation to changes in climate drivers within the Delaware Estuary.

Shifts in Community Species Composition. The presence of various community assemblages of plants and animals is largely determined by the geomorphology, salinity and temperature. As these conditions change in tidal marshes of the Delaware Estuary, the dominant vascular plants will shift along with associated invertebrates. Species that use a C4 photosynthetic pathway will be favored over C3 plants. Invasive species also tend to be effective competitors under disturbed conditions. Shifts in dominant plant species may affect the net ecosystem services furnished by tidal wetlands (Roman and Daiber 1984.)

Desiccation of Marsh Sediments. Wetland condition is obviously sensitive to the wetness of the soil. With rising temperatures and more oscillatory weather (Chapter 2,) sediments in tidal marshes are projected to experience more frequent periods of both dryness and saturation. Frequent alternation of dryness and wetness can affect sediment geochemistry and lead to the formation of free radicals that are toxic to marsh rhizomes, potentially contributing to episodes of marsh dieback.

Change in Habitat Support. The value of tidal marshes as habitat for fish and wildlife is closely tied to the vegetation type, structural integrity and productivity of the vascular plants (Minello and Zimmerman 1983, 1992). Since changes in climate conditions are projected to affect the plants in various ways, their habitat support value will also change.

Productivity. In general, increased temperature and CO_2 will promote greater primary production by vascular plants (Kirwan et al. 2009, Langley et al. 2009) and secondary production by bacteria and animals is expected to follow. However, plant production is sensitive to many factors, such as species composition, salinity, storms, tidal range and nutrient conditions.

Ability of Accretion Rate to Equal RSLR Rate. Tidal marshes must accumulate organic matter and sediments (accretion) at a rate that matches the net change in water level to be sustainable. Local changes in water level in the Delaware Estuary differ from global sea level changes due to many factors (Chapter 2,) and the ecologically meaningful, net change is referred to as the rate of relative sea level rise (RSLR). In many areas of the Estuary, the RSLR appears to exceed the accretion rate of tidal marshes, particularly in the microtidal salt marshes of Delaware Bay and particularly on the New Jersey side of Delaware Bay (Kearney et al. 2002, Kreeger and Titus 2008.) Freshwater tidal marshes of the upper estuary experience macrotidal conditions and are closer to river-derived sediment supplies, and they therefore appear less vulnerable to this factor.

Ability for Landward Migration. With more rapid rises in the sea, the best hope for tidal marshes may be landward migration into suitable natural areas. During landward migration, low marsh species move into high marsh areas, and high marsh species take over upland habitats. Salt marshes also replace brackish and freshwater marshes. Landward migration occurs if there is a gentle slope, suitable sediment, and no barriers. But in the Delaware Estuary, migration is impeded in many areas because of coastal development and hard structures (PDE 2008.) In these areas, community shifts will favor low marsh species until ultimately tidal flooding limits plant survival and marsh areas convert to open water or intertidal mud flats (Section 3.7.2.)

Change of Marsh Area. The total area of tidal wetlands will be determined by the balance of acreage gained through landward migration and lost through conversion to open water or mud flats (Section 3.7.2.) There are likely to be local exceptions where marshes expand seaward, but the expected net change in marsh area is expected to be negative.

Increased Tidal Range. The configuration of the Delaware Estuary is such that tidal amplitude increases in the uppermost areas, ranging from about one meter in Delaware Bay to more than 3 meters in tidal tributaries toward Trenton, New Jersey. Tidal range affects many geomorphological, biogeochemical and ecological processes. As the total tidal volume of the Delaware Estuary increases with sea level, tidal range in the upper estuary is expected to increase, with concomitant effects on marsh ecology.

Ratio of shoreline edge to marsh area. Sea level rise and associated erosion are increasing the area of open water within tidal marshes of the Delaware Bay. Tidal creeks appear to be widening, and interior areas of many marshes are ponding. This trend leads to a net increase in the amount of shoreline edge relative to the total area of vegetated marsh. The ratio of edge to area affects many important marsh functions, such as the usefulness as habitat, productivity, and susceptibility to erosion.

Rate of Channel Scour. As tidal creeks widen within marshes, tidal amplitude increases, and the flushing volume per tide increases with sea level, the hydrodynamic scouring of channel bottoms is expected to also increase. Channel scouring contributes to erosion, potentially producing a positive feedback whereby greater erosion contributes to more open water, tidal flushing and scouring (Day et al. 1998)

Storm surge susceptibility. Storms can have positive and negative effects on tidal marshes. The surge associated with some types of storms can deliver needed sediments that help marshes accrete and keep pace vertically with rising sea level (Reed 1989) On the other hand, storms can be physically damaging and erosive for marshes, and they can decimate freshwater tidal marshes if saltwater accompanies the surge.

Salt Water Intrusion to Fresh Water Habitats. Animals and plants that are adapted to freshwater tidal and brackish conditions are intolerant of rising salinity. Salt stress associated with gradual increases in sea level will slowly but inevitably push these species assemblages further up the estuary and tidal tributaries (see Feature 3.1). The effects of storms can be more sudden if salt water is driven into freshwater areas.

Salt exposure/stress event. Salt marshes are uniquely adapted to seawater exposure, but extreme temperatures and droughts can lead to hypersaline (over 100 psu) conditions on the high marsh. These brines, also called salt pannes, stunt plant growth and can beyond the physical limits of many animals. Although they are a natural feature of salt marshes, changing climate conditions could lead to more hypersaline conditions in more areas, in turn decreasing marsh production and habitat support.

3.3.3 Inventory of Adaptation Options

The Wetland Work Group identified six potential management tactics for helping tidal wetlands adapt to climate change in the Delaware Estuary. Some of these are more applicable to specific marsh types or areas. Some tactics are straightforward restoration activities that double as climate adaptation tactics. Adaptation options are described below along with an initial orientation to how they might address key vulnerabilities by the principal types of wetland habitats.

Watershed flow management. River flows are largely regulated in the upper portions of the Delaware watershed to provide drinking water for people (Chapter 4.) Flows can also be managed to safeguard the public from floods and to ensure sufficient flows to protect environmental health, offset negative impacts of drought, storm surge, and sea level rise in the Estuary. Since freshwater tidal wetlands are vulnerable to storm surge, sea level rise and salinity, flow management represents an adaptation measure for sustaining these habitats.

Strategic retreat. Strategic retreat is defined in different ways. It sometimes refers to the planned relocation of built structures and development from the coast to areas inland, thereby providing a more natural protective buffer to avoid the devastating effects of natural disasters that occur in the coastal zone. For example, the relocation of the Cape Hatteras Lighthouse (Titus et al. 2009a) was a form of strategic retreat. Strategic retreat can also refer to the acceptance that an area will become inundated by open water, and therefore not be developed. In the case of tidal marshes or other natural habitats, one management option is to accept that some areas will not be selected for preservation efforts if they are not deemed appropriate for protective structures to preserve human development.

Structure setbacks*.* Structure setbacks prohibit development on land that is expected to erode or be inundated within a given period of time. Structure setbacks can prevent erosion or flood damage as well as allow wetlands to migrate inland as sea level rises. Two counties in Delaware currently prohibit development in the 100-year floodplain along the Delaware River and Delaware Bay (Titus et al. 2009a).

Figure 3-3. A living shoreline being installed along an eroding salt marsh in Delaware Bay.

Creation of buffer lands*.* The creation of buffer lands requires the protection, maintenance, and/or establishment of natural habitat types that lie between developed lands and tidal wetlands. This allows tidal wetlands to migrate inland with less impact to human development.

Living shorelines*.* Living shorelines are natural enhancements to marsh edges that are typically eroding and which provide much greater ecosystem services than traditional structural solutions to erosion such as bulkheads and rip rap. Living shorelines soft armor the marsh edge using natural or degradable materials such as plants, shell, stone, and other organic materials (Fig. 3-3.) Living shorelines typically slow shoreline retreat by augmenting natural stabilization processes.

Building dikes, bulkheads, and tide gates. Dikes are impermeable earthen walls designed to protect areas from flooding or permanent inundation by keeping the area behind them dry. Many areas of the Delaware Estuary that were once tidal wetlands have been diked for other purposes such as waterfowl hunting and salt hay farming. Dikes are usually associated with a drainage system to channel flood water away from vulnerable lands and infrastructure. Due to the long period of sea level rise since many dikes were built around the Delaware Estuary, many diked lands are below mean low water, requiring pumping systems to remove rainwater and seepage (Titus et al. 2009a). According to the Delaware Coastal Program office, no dikes or levees within the State of Delaware are capable of standing up to a one meter rise in sea level.

Bulkheads are walls built in the shallow subtidal or intertidal zone to protect adjacent uplands from erosion by waves and current. Bulkheads hold soils in place but they do not normally extend high enough to protect against storm surge (Titus et al. 2009a). Although bulkheads can be used to protect against erosion, they impair ecological processes and are inferior habitats for fish and wildlife (e.g., Bilkovic and Roggero 2008).

Tide gates are barriers across small creeks or drainage ditches that permit freshwater to exit during ebb tides but prevent tidal waters to enter on flood tides (Titus et al. 2009a). They are effective at permitting low-lying areas just above mean low water to drain without the use of pumps, but they can impede natural ecological processes in areas that were often former tidal wetlands.

3.4 Tidal Wetlands – Survey Methods

Climate change vulnerabilities and potential adaptation options were examined separately for freshwater tidal wetlands and brackish/saltwater wetlands. The Wetland Work Group relied on the initial inventory (Section 3.3) to prepare a survey, which was sent to more than forty wetland scientists and managers in the region.

Survey Monkey™ was used to construct and operate the poll. Each respondent was first asked to rank the relative vulnerability of a particular wetland metric (Section 3.3.2) in response to a particular climate change driver (Section 3.3.1), and this was repeated for each of the two marsh types. Respondents were provided with the most current predictions tailored to our estuary watershed (Chapter 2,) and they were asked to answer the questions to reflect the period from present to 2100 using these best current projections (e.g., for 1 m sea level rise.)

Survey participants were asked to consider all direct and indirect ecological relationships. They were also encouraged to "think outside the box" about adaptation options, and not to limit themselves those consistent with current management practices. Managers currently operate under place-based paradigms for "no net loss," which resist dynamic habitat changes in the coastal landscape. Perspectives on the relative importance of various ecosystem goods and services provided by wetlands might change over time, resulting in concomitant shifts in policies and priorities for flood protection, habitat restoration, strategic retreat, invasive species control, mosquito control, waterfowl management, and fisheries management, as examples. Management paradigms will shift in the future as these perspectives evolve.

Survey respondents were also asked to consider all responses and ratings in comparative fashion across the entire survey. For example, the vulnerability of freshwater tidal marshes to salinity intrusion was compared relative to the potential vulnerability of salt marshes to storms.

Each rating of concern for a specific cause-effect relationship was paired with a query of the respondent's relative level of confidence in the answer, ranging from no confidence to high confidence.

Therefore, respondents with more expertise or knowledge for some situations were permitted to adjust their confidence higher than for situations that they are less familiar with.

Vulnerability rankings were assigned scores from 1-5, and confidence rankings were also scored 1-5 (low to high). These weightings were then multiplied together per respondent to calculate a composite weighting for the vulnerability that integrated concern level and confidence level. Therefore, a respondent who expressed high concern but low confidence for a cause-effect relationship may yield a composite score identical to another respondent who expressed low concern but high confidence. This was one limitation of this risk assessment approach, whereby the net vulnerability could become biased to the low side simply because of a weak understanding by respondents or by insufficient data. For certain purposes, we therefore recommend that raw impact scores may be more useful than composite scores that integrate confidence (both results are provided in Appendix H.)

Not all climate change impacts are expected to impair tidal wetlands, and some positive benefits might occur. In answering questions about ecosystem services, respondents were ask to discern whether the "vulnerability" would lead to a net "positive change," "no net change," "negative change," or "not sure."

Finally, for each cause-effect relationship, respondents were asked to rank the relative effectiveness and feasibility of the adaptation options listed in Section 3.3.3 to offset the vulnerabilities. Respondents were asked to rank both the tactic's effectiveness and feasibility as high, medium or low. Effectiveness and feasibility responses were weighted, averaged among the respondents, and then multiplied together to derive a composite score. Table 3-1 lists the most important vulnerabilities that were identified due to changes in the five physical drivers, along with potential adaptation options.

Table 3-1. Principal climate drivers, tidal wetland vulnerabilities, and adaptation options in the Delaware Estuary that were identified by the Wetland Work Group.

Climate Drivers	Wetland Vulnerabilities	Adaptation Options
Sea Level Rise	• Shifts in Community Species Composition • Ability of Accretion Rate to Equal RSLR Rate • Ability for Landward Migration • Change of Marsh Area • Increased Tidal Range • Ratio of shoreline edge to marsh area • Rate of Channel Scour • Storm surge susceptibility	• Monitor/Research Vulnerability • Beach/marsh nourishment • Elevating homes/structures • Dikes and Bulkheads - short term management or removal • Structure Setbacks; Strategic Retreat • Rebuilding infrastructure • Creation of Buffer Lands • Living Shorelines
Salinity Range Increase	• Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats; Change in Habitat Support • Salt exposure/stress event • Productivity; Invasive Species	• Monitor/Research Vulnerability • Watershed flow management • Salt barrier • Strategic Retreat; • Creation of Buffer Lands
Temperature	• Shifts in Community Species Composition	• Monitor/Research Vulnerability

Change	- Desiccation of Marsh Sediments - Change in Habitat Support - Productivity; Invasive Species	
Precipitation & Storm Events	- Shifts in Community Species Composition - Salt exposure/stress events - Change in Habitat Support - Productivity - Desiccation, flooding or erosion - Sediment supply - Physical impacts by wind, waves and surge	- Monitor/Research Vulnerability - Beach/marsh nourishment - Elevating homes/structures - Dikes and Bulkheads - short term mgmt. or removal to create incentives for landward migration - Structure Setbacks; Strategic Retreat - Rebuilding infrastructure - Prioritize lands to preserve - Living Shorelines
Atmospheric CO_2 increase	- Shifts in Community Species Composition - Productivity	- Monitor/Research Vulnerability - Carbon Trading (acquisition incentives for landward migration)

3.5 Tidal Wetlands – Vulnerability Assessment

The relative vulnerability of the two types of tidal wetlands to changes in climate conditions, as judged by wetland specialists who responded to the survey (Section 3.4) is discussed below in Sections 3.5.1 (Freshwater Tidal Wetlands) and Section 3.5.2 (Brackish/Saltwater Wetlands.) Since there were many different cause-effect results (2 wetland types, 5 climate drivers, 10 wetland outcomes), only example data are shown here for the predicted impacts and associated confidence in the survey rankings. Full survey responses are provided in Appendix H. To summarize the relative differences among wetlands and climate drivers, impact and confidence responses were integrated into a composite vulnerability index, which is shown in Section 3.5.4.

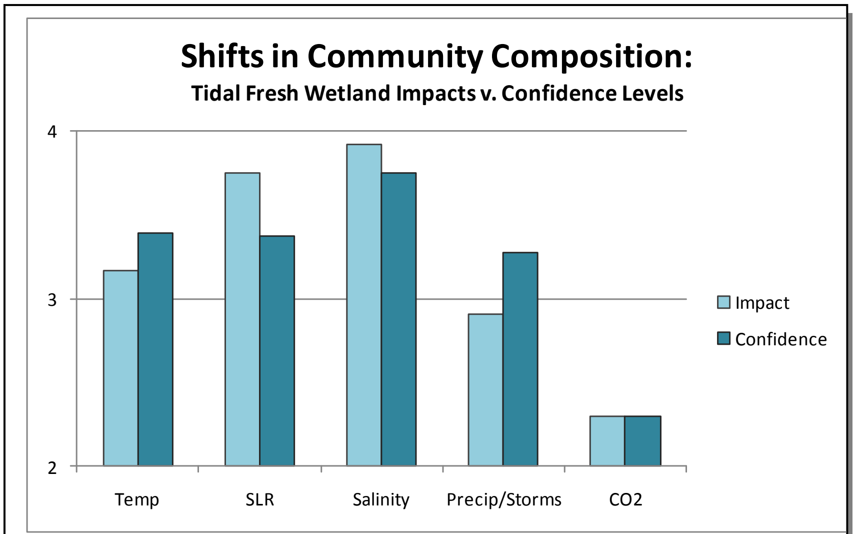


Figure 3-4. Relative levels of concern regarding the potential impact of changing conditions on the **community composition of tidal freshwater wetlands** (light blue) and relative confidence in these projections (dark blue.)

3.5.1 Vulnerability of Freshwater Tidal Wetlands

Estimated impacts varied among the five climate drivers, but the relative importance of the drivers depended on which aspect of freshwater tidal wetland status was examined. The vulnerability to salinity rise was the topped ranked driver that could affect the plant community composition of freshwater tidal wetlands, followed by sea level rise (see blue bars in Fig. 3-4.) This was because any exposure to saltwater is likely to cause acute stress for plants (and animals) that are adapted to freshwater conditions. Temperature rise and changes in precipitation and storms were regarded with moderate concern, whereas marsh vulnerability to increased levels of carbon dioxide was rated as the least concern for the drivers in the poll. Survey response confidence also varied but was generally high for all drivers except carbon dioxide changes.

Shifts in community composition was one of the top-rated vulnerabilities of freshwater tidal wetlands. Changes in habitat support, landward migration potential, and the net change in marsh area were also viewed as high concerns for survey respondents (see Appendix H for full responses.) Changes in productivity and interactions with invasive species were rated as lowest concerns overall.

In general, tidal freshwater wetlands were viewed as being most vulnerable to salinity rise, followed by sea level rise, followed by storms and precipitation changes, followed by temperature and carbon dioxide changes (Appendix H.) Salt water intrusion into upper estuary areas is expected to squeeze suitable habitat for freshwater tidal wetlands because their landward migration is impeded by the fall line as well as by >85% development in the immediate one kilometer landward (Battelle 2006.) In transitional salinity areas, freshwater tidal marshes will be replaced by brackish marshes, thereby causing major shifts in species composition (e.g., plant, animal and microbial), and likely altering many functions of habitat support for fauna (see also Section 3.7.2.)

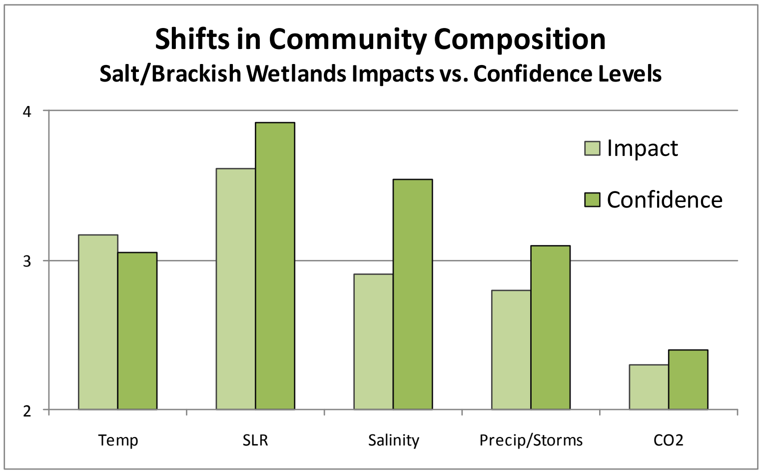


Figure 3-5. Relative levels of concern regarding the potential impact of changing conditions on the **community composition of brackish and saltwater wetlands** (light green) and relative confidence in these projections (dark green.)

3.5.2 Vulnerability of Brackish/Salt Water Wetlands

Sea level rise elicited the greatest concern for brackish and salt marshes out of the various physical and chemical drivers that may change with climate. The greatest vulnerabilities are predicted to be the inability to keep pace with sea level rise through vertical accretion, the inability to migrate landward, shifts in species composition (Fig. 3-5,) loss of suitable marsh area, increased seaward edge erosion, and increased susceptibility to storm surge. Also of high concern was an expected increase in tidal range and a change in the ratio of marsh edge to interior area, both of which are expected to increase with an increasing rate of sea level rise.

Similar to freshwater tidal wetlands, the estimated impacts of changing climate on brackish/salt water wetlands varied among the five climate drivers. Sea level rise clearly elicited the most concern. However, brackish/salt marshes were regarded as also vulnerable to temperature rise, salinity rise, and changing storm and precipitation conditions. Increased atmospheric CO_2 was not rated as being as important (Fig. 3-5.) Survey response confidence varied, being highest for sea level rise effects and lowest for the effects of carbon dioxide changes.

The most vulnerable of the various wetland responses was deemed to be overall marsh area (see Appendix H for full responses.), followed closely by the landward migration ability, vertical accretion rate, amount of edge erosion, and shifts in community composition (shown in Fig. 3-5). For all these responses, the most significant climate driver was sea level rise. Wetland status metrics that were not rated as much of a concern included the amount of channel scouring, the amplitude of the tidal range, and interactions with invasive species (e.g., see Appendix F.)

Table 3-2. Relative levels of concern regarding the potential impact of changing temperature, sea level, salinity, precipitation/storms and carbon dioxide on the various aspects of the status of tidal freshwater wetlands and brackish/saltwater wetlands in the Delaware Estuary.

	Tidal Fresh	**Tidal Salt/Brackish**
	Temperature Change	
Shifts in Community Species Composition	Med-High	Med-High
Desiccation of Marsh Sediments	Med-Low	Low
Change in Habitat Support	Med-Low	Med-Low
Productivity	Med-Low	Med-High
Invasive Species	Med-Low	Med-Low
	Sea Level Rise	
Shifts in Community Species Composition	High	Highest
Ability of Accretion Rate to Equal RSLR Rate	Med-High	Highest
Ability for Landward Migration	High	Highest
Change of Marsh Area	High	Highest
Increased Tidal Range (Upper River)	Med-High	High
Ratio of shoreline edge to marsh area	Med-High	High
Rate of Channel Scour	Med-High	Med-High
Storm surge susceptibility	High	Highest
Seaward edge erosion	High	Highest
	Salinity Range Increase	
Shifts in Community Species Composition	Highest	Med-High
Salt Water Intrusion to Fresh Water Habitats	Highest	Med-High
Salt exposure/stress event	High	Med-Low
Change in Habitat Support	Highest	Med-Low
Productivity	Med-High	Med-Low
Invasive Species	Med-Low	Med-Low
	Precipitation & Storms	
Shifts in Community Species Composition	Med-High	Med-Low
Salt exposure/stress events	Med-High	Med-Low
Change in Habitat Support	Med-Low	Med-Low
Productivity	Med-Low	Med-Low
Desiccation, flooding or erosion	Med-High	Med-Low
Sediment supply	Med-High	Med-Low
Physical impacts by wind, waves and surge	Med-High	Med-High
	Atmospheric Carbon Dioxide	
Shifts in Community Species Composition	Low	Low
Productivity	Low	Low

5.5.3 Comparison of Tidal Wetland Vulnerabilities

Composite vulnerability indices for freshwater tidal wetlands and brackish/saltwater wetlands were contrasted among various responses that might result from each of the five climate drivers. Since most responses were not applicable between the two wetland types, only one example is shown in Figure 3-6.

Survey respondents rated freshwater tidal wetlands and brackish/saltwater wetlands as similarly vulnerable to temperature and precipitation storms, and atmospheric carbon dioxide effects were considered to be less of a concern for both marsh types. The top two concerns were sea level rise (more for brackish/saltwater wetlands) and salinity rise (more for freshwater tidal wetlands).

The relative vulnerability index (combined impact and confidence) for various cause-effect relationships was compared between freshwater tidal wetlands and brackish/saltwater wetlands (Table 3-2). In general, there was a greater number of moderate to high vulnerabilities for cause-effect scenarios for freshwater tidal marshes than brackish/salt marshes. But the most consistently strong survey responses were for brackish/salt marshes exposed to elevated sea level. All aspects of brackish/saltwater wetlands were viewed as at least moderately vulnerable to sea level rise with six out of the nine metrics being rated the highest vulnerability index. There was comparatively less concern for the effects of other changes in climate conditions on brackish/saltwater wetlands. The Wetland Workgroup noted that these wetland metrics are just examples of the myriad processes and elements of marsh ecology that might be affected by changing climate (e.g., see Feature 3-1.)

Feature 3-1. Marsh Soil Microbes and Sea Level Rise

By Tatjana Prša, Graduate Student, Villanova University

Microbial organisms in marsh soils could be impacted by sea-level rise, therefore changing decomposition rates of organic materials. The marshes ability to keep pace with sea-level rise relies on a fine balance between decomposition rates and accumulation of organic matter in the soils. In freshwater marshes contain predominantly methanogenic and saltwater marshes contain mostly sulfate-reducing bacteria. Studies by Drs. Melanie Vile and Nathaniel Weston of Villanova University, suggest that within three months of saltwater intrusion, sulfate reduction rates increase significantly in freshwater marshes, and saltwater marshes shift towards a more diverse community of microbes. Since the overall rate of decomposition is faster with sulfate-reducing bacteria, freshwater soils would decay organic matter at an accelerated rate, releasing more carbon dioxide speeding up saltwater intrusion. Increased decomposition in freshwater marshes may compromise their ability to keep pace with sea-level rise. These results paint a troubling picture for freshwater marshes that experience saltwater intrusion in the Estuary.

3.5.4 Associated Changes in Ecosystem Services

Survey participants were asked to estimate whether ecosystem services furnished by freshwater tidal wetlands will increase, decrease, or not change in response to each cause-effect relationship (e.g., salinity rise affecting community composition.) An increase in salinity was predicted by more survey takers to have an overall negative effect on ecosystem services (Fig. 3-8.). Comprehensive results for ecosystem service outcomes from other cause-effect relationships are provided in Appendix H. Less than 15% of respondents were uncertain for these cause-effect scenarios.

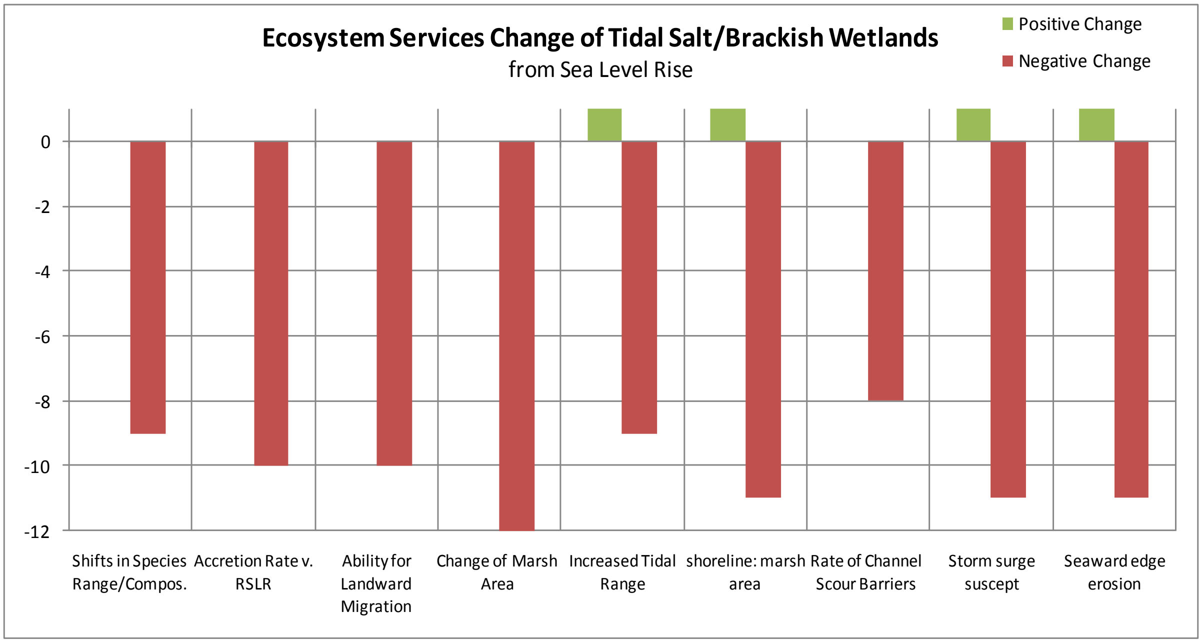


Figure 3-9. Number of survey participants who predicted either net positive or net native changes in ecosystem services by saltwater and brackish wetlands in response to projected rises in sea level by 2100. Survey responses indicating no net change or uncertain change are not shown.

Sea level rise was also viewed by more respondents as likely to cause net decreases in services by freshwater tidal wetlands, however a minority also predicted some positives (Fig. 3-9.) An increase in sea level will have a negative effect on brackish/salt marsh area, and so this was thought to directly reduce ecosystem services through a loss of habitat. See Appendix H for more expected ecosystem service outcomes. Important net losses of services were also predicted for the inability of tidal wetlands to move inland in response to seal level rise and salt water intrusion due to impediments to landward migration, getting squeezed and losing area. Only one positive ecosystem service outcome was predicted by the balance of survey takers, and this was for the effect of elevated carbon dioxide on tidal wetland productivity (Appendix H.)

3.6 Tidal Wetlands - Adaptation Options

Numerous climate adaptation tactics exist that can potentially help address the vulnerabilities of tidal wetlands. As a first effort to prioritize which of these offer the most promise, respondents to the Wetland Work Group survey rated the feasibility and effectiveness of various adaptation tactics that were described in Section 3.3.3 in terms of their ability to offset vulnerabilities of tidal wetlands. Their responses are summarized in Table 3-3 and more detail on the relative effectiveness/feasibility ratings are provided in Appendix H.

Table 3-3. Comparison of the effectiveness and feasibility of various potential adaptation options for addressing the main vulnerability of tidal freshwater wetlands and brackish/saltwater wetlands exposed to changing sea level, salinity, precipitation/storms, and carbon dioxide levels by 2100 in the Delaware Estuary.

	Tidal Fresh	Tidal Salt/Brackish
	Sea Level Rise	
Beach/marsh nourishment	Med-High	Med-Low
Elevating homes/structures	Med-Low	Med-Low
Dikes, Bulkheads, and Tide Gates	Med-High	Med-High
Structure Setbacks	High	Med-High
Rebuilding infrastructure	Med-High	Med-High
Strategic Retreat	Highest	Highest
Creation of Buffer Lands	Highest	High
Living Shorelines	High	High
	Salinity Range Increase	
Watershed flow management	High	Med-High
Salt barrier	Low	Low
Strategic Retreat	Med-High	Med-High
Creation of Buffer Lands	Med-Low	Med-Low
	Precipitation & Storms	
Beach/marsh nourishment	Low	Med-Low
Elevating homes/structures	Low	Med-Low
Dikes, Bulkheads, and Tide Gates	Med-Low	Med-High
Structure Setbacks	Med-High	Med-High
Rebuilding infrastructure	Med-Low	Med-High
Strategic Retreat	Med-High	Med-High
Creation of Buffer Lands	Med-Low	Med-High
Living Shorelines	Med-High	Med-High
	Atmospheric Carbon Dioxide	
Carbon Trading	Med-High	Med-High

Activities that facilitate the landward migration of tidal marshes were rated as having the greatest promise, especially for addressing the vulnerabilities associated with sea level rise (Table 3-1.) These activities include clearing the path to allow for landward migration of tidal marshes (strategic retreat), structure set-backs, and creation of buffer lands between development and marshes (e.g. forests) to allow for landward migration. These were ranked highest for both freshwater tidal and brackish saltwater wetlands (Table 3-1.) Adaptation options for dealing with sea level rise were ranked higher than tactics for addressing salinity, storms, and carbon dioxide.

To address salinity rise, survey respondents indicated that watershed flow management is the best adaptation option, especially for helping reduce the higher vulnerability of freshwater tidal wetlands to saltwater.

Carbon trading was the only adaptation option identified for offsetting the negative effects on atmospheric CO_2 on both tidal fresh and tidal brackish/salt water wetlands. This was considered a moderate to highly effective and feasible option.

Living shoreline tactics that can help to reduce erosion and enhance ecosystem services were also rated highly for addressing both sea level rise and storms/precipitation. Bulkheads, dikes and tide gates were rated similarly for their effectiveness in decreasing marsh vulnerability. On the other hand, sediment nourishment, the elevation of structures (to allow for more tidal flow,) and creation of salt barriers were given low marks by survey respondents (Table 3-3.)

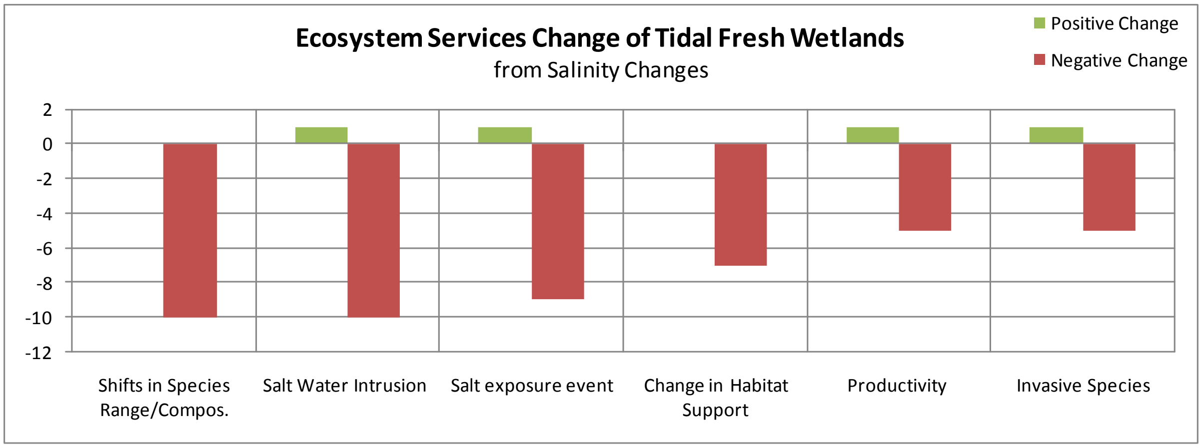


Figure 3-8. Number of survey participants who predicted either net positive or net native changes in ecosystem services by tidal freshwater wetlands in response to projected rises in salinity by 2100. Survey responses indicating no net change or uncertain change are not shown.

3.7.2 Future Changes in Tidal Wetland Ecosystem Services

In support of the Climate Ready Estuaries pilot, EPA awarded a Technical Assistance grant for Industrial Economics (IEc) to more accurately predict climate change impacts on tidal wetlands and corresponding ecosystem services changes in the Delaware Estuary (Appendix G.) Rates of primary production were examined as an example ecosystem service. In addition, the IEc analysis included a comparison of projected outcomes from two different types of wetland restoration efforts at two time periods (2020 and 2050).

Table 3-4. Data used by IEc to forecast future changes in tidal marsh acreage in the Delaware Estuary using the Sea Level Affecting Marsh Model (SLAMM.)

Inputs for SLAMM model
National Wetlands Inventory Data
Sea Level Rise Predictions: IPCC & Titus
Elevation Data
Accretion Rate Data
Tide Gauge Data
Erosion Rate Data

Wetland Acreage. IEc used Version 6 of the Sea Level Affecting Marshes Model (SLAMM) to predicted changes in wetland acreage, transitions of wetland types, and potential wetland migration areas following a similar approach to that used by Craft et al. (2009.) Twenty-three wetland classes were used based on the attributes adopted by the National Wetlands Inventory (NWI). The SLAMM model incorporated data linking various physical factors to marsh change (Table 3-4,) thereby calculating acreage gains and losses in each of the wetland classes (including tidal flats and open water). Therefore, the total acreage remained constant even though there were predicted to be big shifts from some habitat types to others.

Table 3-5. Predicted acreage changes for tidal marshes, open water and tidal flats, scrub-shrub swamps, and other habitats in the Delaware Estuary by 2100 using the Sea Level Affecting Marsh Model (SLAMM, see Appendix G.)

		Marsh	Open Water/Tidal Flats	Scrub-Shrub/Swamp	Other
Upper Estuary	PA	1,717	98	-71	-1197
	NJ	4,468	192	-1,902	-2758
Lower Estuary	PA	-1814	5,821	-500	-3507
	NJ	-930	14,250	-2,661	-10,659
Delaware Bay	PA	-21,331	49,914	6,584	-21,998
	NJ	-24,668	36,254	-7,007	-4,560

Table 3-5 summarizes the net change in the principal habitat categories analyzed with SLAMM. Across the whole estuary, 42,558 hectares of tidal wetland are predicted to be lost, with most being located along the microtidal shorelines and tributaries of the Delaware Bay region. In addition, 50,236 hectares are expected to be lost from adjacent habitats that are more landward, including scrub-shrub swamps, non-tidal wetlands, and uplands. The SLAMM analysis predicts that these losses will translate into a net gain of 106,529 hectares of open water and tidal flat habitat. Outputs from the SLAMM model were

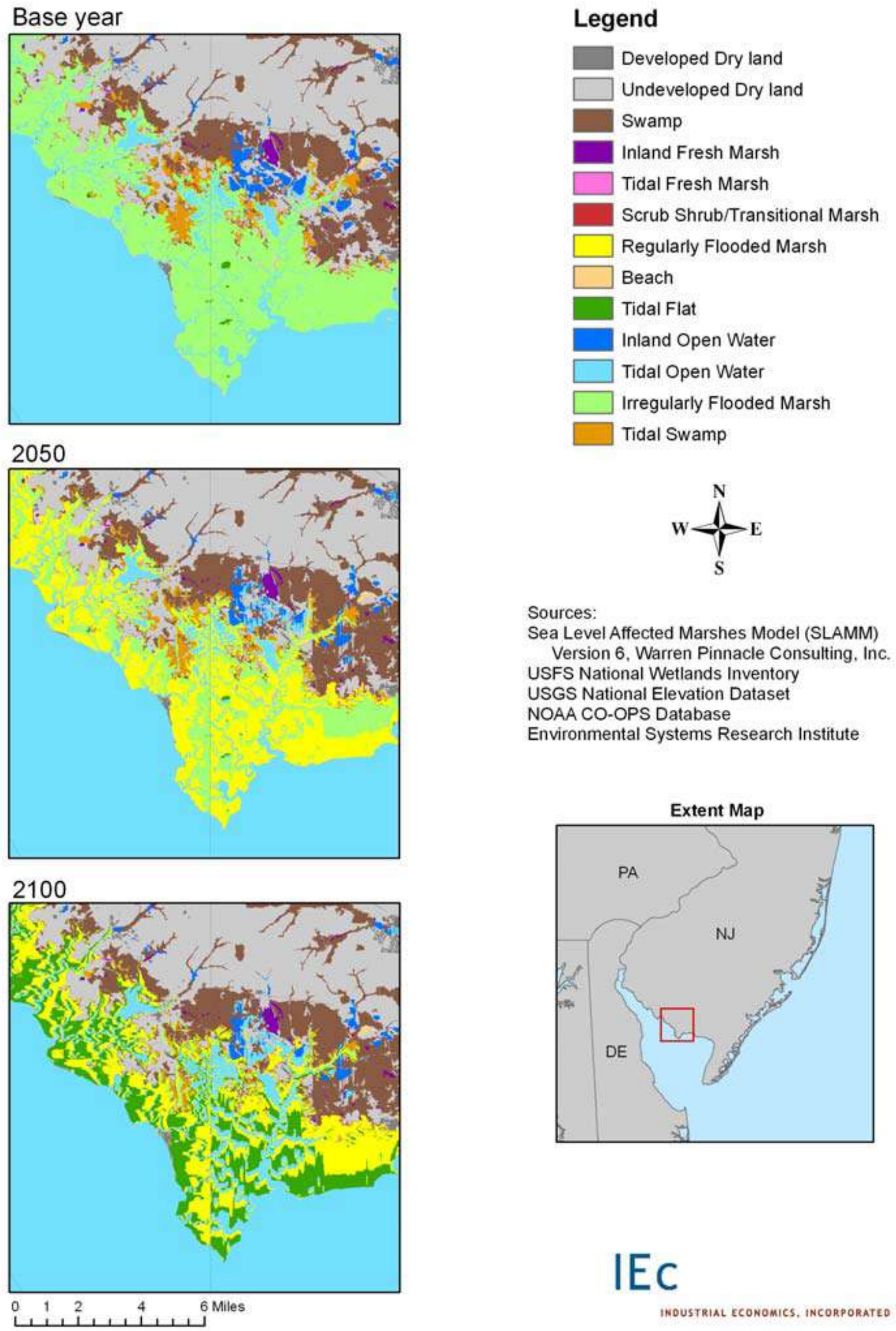


Figure 3-10. The geographical coverage of thirteen habitat types (see legend) in an area of southwest New Jersey at present (1980s NWI data) and as predicted by SLAMM in 2050 and 2100.

put into GIS to show an example of how the various habitat types, including tidal wetlands, are predicted to change between the present and 2100 in southwestern New Jersey (Fig. 3-10.) By 2050, many of the irregularly flooded marshes are expected to turn into regularly flooded mashes. Then at the end of the century, many of these marshes will transition into mudflats or open water as interior areas of marsh begin to break up and tidal creeks widen.

Wetland Services Change. Industrial Economics used the Habitat Equivalency Model (HEA) to predict ecosystem service changes that would accompany the predicted changes in seven habitat categories from the SLAMM model (Table 3-6.) The HEA tool was first developed to access natural resource damages from oil spills and to calculate how much restoration would be needed to offset those damages. For our purposes, HEA considered climate impacts as the 'damage'. HEA compares the losses of habitat and potential gains from restoration (or climate adaptation) activities using a unit of scale called a Discounted Service Acre Year (DSAY). This unit of measure incorporates time, allowing non-linear changes in condition, function, or dollars to be captured using principles of ecological and economic compounding. DSAYs can therefore be used to more effectively promote "no net loss" of wetlands by making it easy to figure out exactly how much loss is occurring and how much restoration is needed at any point in time. HEA analysis can be extended to be used for any ecosystem service. For this study, primary productivity was selected because of the availability of literature on this metric. Specifically, IEc ran HEA analysis on only the "primary production for consumption," meaning the proportion of total production that could be readily consumed by animals.

Table 3-6. Habitat types contrasted for their relative primary production services using Habitat Equivalency Analysis (HEA.)

Habitat Types used in HEA
Regularly Flooded Marsh
Irregularly Flooded Marsh
Tidal Fresh Marsh
Scrub/Shrub Marsh
Tidal Swamps
Tidal Flats
Tidal Open Water

To estimate whether restoration practices might reasonably be used to offset projected losses of wetland acreage and services, IEc used HEA to calculate the total cost of one example restoration tactic if that tactic were to be implemented to preserve all vulnerable tidal wetlands. To do this, living shorelines were considered a preventative measure which could be used to offset future wetland losses through the end of the century. Assuming living shorelines would be installed in 2020, the projected costs (in today's dollars at that date) to armor all tidal wetlands was projected to be $29 billion (Table 3-7; see Appendix G for calculations.) This price tag may seem large, but if effective this restoration option would be used to combat all wetland losses occurring over a 90 year period (by 2100.) In contrast, if wetlands are allowed to degrade with no intervention, by the year 2050 enough wetlands would be lost or severely degraded so that complete restoration would be required to restore acreage if that was deemed necessary. This full restoration option would include costs of fill management, regrading, creation of tidal creeks, and re-vegetation. The cost of the full restoration tactic in is calculated to be $39 billion (in today's dollars at that date; Table 3-7). Therefore, $10 billion (in today's dollars) could be

Table 3-7. Comparison of the habitat equivalency outcomes and associated costs for two adaptation approaches for addressing projected tidal wetland losses: 1) use of living shorelines in 2020 to stem future losses and 2) restoration of lost wetlands in 2050 (see also Appendix G.)

REGION	STATE	DISCOUNTED SERVICE ACRE YEAR LOSS[1]	DISCOUNTED PRIMARY PRODUCTIVITY LOSS (THOUSAND KG)	RESTORATION ACREAGE	ESTIMATED COST OF RESTORATION (BILLION $2009)
Prevention in 2020 (Living Shorelines)					
Lower Estuary	Delaware	-22,950	-2,461	1,832	$ 1.04
	New Jersey	-36,384	-3,902	2,904	$ 1.65
Delaware Bay	Delaware	-239,686	-25,704	19,128	$ 10.9
	New Jersey	-269,223	-28,871	21,485	$ 12.2
TOTAL		**-568,243**	**-60,938**	**45,348**	**$ 25.8**
Restoration in 2050					
Lower Estuary	Delaware	-22,950	-2,461	4,422	$ 1.59
	New Jersey	-36,384	-3,902	7,010	$ 2.52
Delaware Bay	Delaware	-239,686	-25,704	46,178	$ 16.6
	New Jersey	-269,223	-28,871	51,869	$ 18.6
TOTAL		**-568,243**	**-60,938**	**109,478**	**$ 39.3**

saved with early intervention in 2020 using living shorelines compared to full restoration later, in 2050. Preventative wetland measures are not only the cheaper climate adaptation option in terms of implementation costs, but they would also maintain all of the attendant ecosystem services (not valued here) provided by the wetlands that would otherwise be lost in the interim until restoration would hypothetically occur.

The methodology presented in Appendix G promises to help evaluate the trade-offs associated with various adaptation tactics, thereby assisting resource managers in deciding how to best stem losses of wetland acreage and ecosystem services due to climate change. In some cases, strategic retreat or no action might be the realistic scenario. However when adaptation tactics are sought and contrasted to proactively address the effects of climate change, the relative costs and benefits of adaptation options can be contrasted using HEA for different locations and at different installation dates.

3.7.3 Natural Capital of Tidal Wetlands in the Delaware Estuary Watershed

Besides being valued for their primary production (as in Section 3.7.2), tidal wetlands are hot spots for many other ecosystem services (Figure 3-11). The Natural Capital Team identified many of these and assigned the ecosystem goods and services to categories used in the Millennium Ecosystem Assessment (2005.) (Table 3-8.) Generally, tidal wetlands provide flood protection, support fisheries and shellfisheries, sequester carbon, and help to maintain water quality, among others.

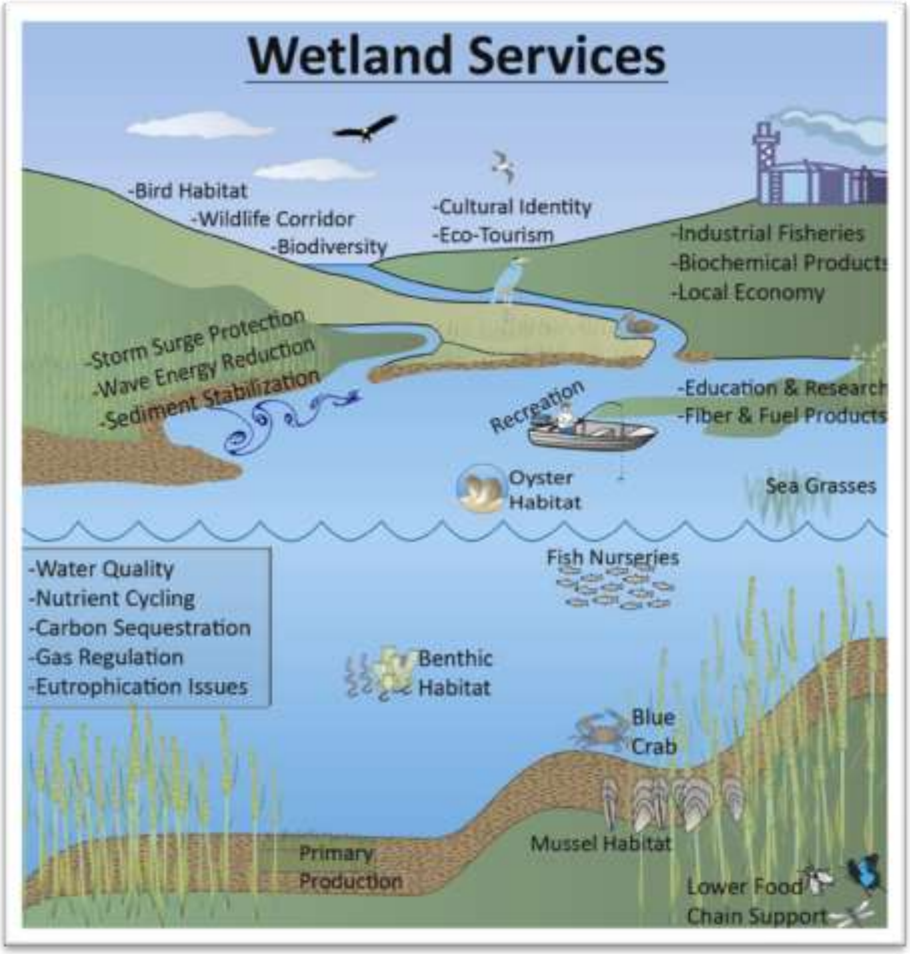
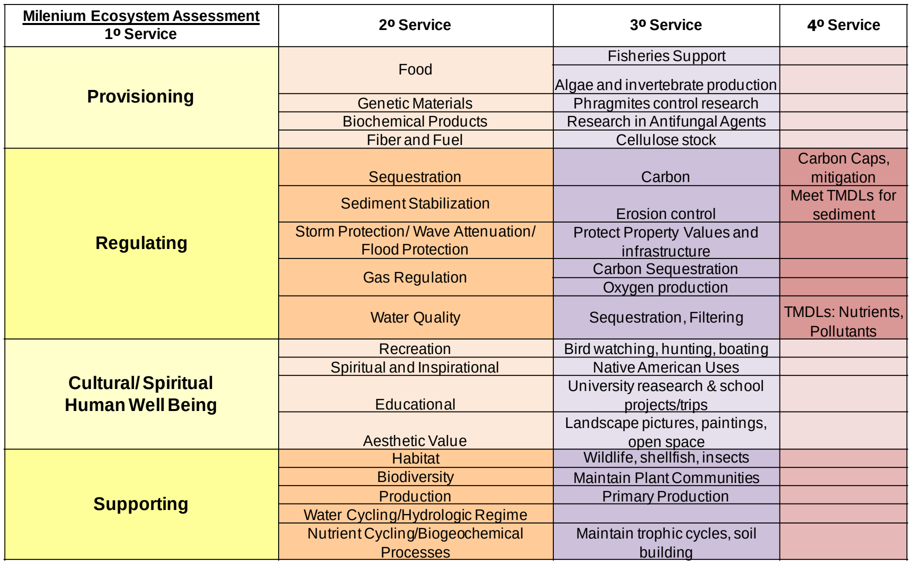


Figure 3-11. Portrayal of the diverse ecosystem services furnished by tidal wetlands in the Delaware Estuary (see also Table 3-8.)

Table 3-8. Summary of ecosystem goods and services provided by tidal wetlands in the Delaware Estuary, grouped as in the Millennium Ecosystem Assessment.



Milenium Ecosystem Assessment 1º Service	2º Service	3º Service	4º Service
Provisioning	Food	Fisheries Support	
		Algae and invertebrate production	
	Genetic Materials	Phragmites control research	
	Biochemical Products	Research in Antifungal Agents	
	Fiber and Fuel	Cellulose stock	
Regulating	Sequestration	Carbon	Carbon Caps, mitigation
	Sediment Stabilization	Erosion control	Meet TMDLs for sediment
	Storm Protection/ Wave Attenuation/ Flood Protection	Protect Property Values and infrastructure	
	Gas Regulation	Carbon Sequestration	
		Oxygen production	
	Water Quality	Sequestration, Filtering	TMDLs: Nutrients, Pollutants
Cultural/ Spiritual Human Well Being	Recreation	Bird watching, hunting, boating	
	Spiritual and Inspirational	Native American Uses	
	Educational	University reasearch & school projects/trips	
	Aesthetic Value	Landscape pictures, paintings, open space	
Supporting	Habitat	Wildlife, shellfish, insects	
	Biodiversity	Maintain Plant Communities	
	Production	Primary Production	
	Water Cycling/Hydrologic Regime		
	Nutrient Cycling/Biogeochemical Processes	Maintain trophic cycles, soil building	

3.8 Tidal Wetlands - Synthesis

Climate change is likely to affect different types of tidal wetlands in different ways in the Delaware Estuary. For freshwater tidal wetlands, a unique feature of the Estuary, the greatest threat was found to be the expected rise in salinity of the upper Estuary. Plants and animals that comprise these wetlands are intolerant of even brief exposure to seawater. As sea level rises and more saltwater begins to mix in, freshwater tidal marshes will shrink as they are replaced by brackish communities. Landward migration of freshwater tidal marshes is virtually impossible because more than 85% of buffer lands in the upper estuary are developed and expected to be maintained as such. For these reasons, the most vulnerable elements of tidal freshwater wetlands are loss of habitat acreage, shifts in community composition, and the concomitant loss of habitat support for any fish and wildlife that depend on these rare habitats.

In addition to their vulnerability to salinity, freshwater tidal wetlands are threatened by the physical effects of rising sea level, such as erosion of seaward edges, an amplified tidal range, and exposure to more frequent storm surge. Increases in storm intensity and frequency will hasten the conversion of some freshwater tidal marshes to brackish marshes, possibly dominated by invasive species that thrive under more frequent disturbance regimes. Sediment supply is expected to be ample for these marshes since they are closer to sources of sediment brought to the estuary by large rivers, and greater precipitation during cooler months could lead to more sediment-laden runoff. For this reason, freshwater tidal marshes are expected to keep pace (vertically) with rising seas in areas that are not exposed to saltwater despite the expected increase in tidal range.

Brackish and salt marshes were examined together, although there are notable differences in species assemblages that occur along the very broad salinity gradient in the Delaware Estuary. In contrast to freshwater tidal wetlands, these saltwater adapted wetlands are most vulnerable to sea level rise which will interact with various other stressors to push many marshes past their sustainable threshold. The lower portion of the Delaware Estuary is microtidal, meaning that the tidal range is small and there is little vertical relief across the expansive marshes that form a near contiguous fringe around Delaware Bay. In most areas, the rate of sea level rise is expected to increase to up to 10 mm per year or more, probably exceeding the ability of tidal marshes to keep pace since recent accretion in most areas is less than this. Marshes grow vertically by accumulating dead plant matter as well as by trapping suspended sediments brought in with the tides. But sediment deficits, nutrient loadings, and projected increases in storm energy disrupt normal accretion rates, and all of these factors are certain to change with changing climate contributing to stress on native plant species *like Spartina alterniflora*, which is the dominant species of extensive low marsh communities.

Not all projected effects are negative. Increased carbon dioxide levels, combined with nutrients, might boost overall productivity and help these marshes keep pace through organic matter accumulation in some areas. On the other hand, the species that are most likely to benefit from higher CO_2 levels are different from the current biomass dominants. Paradoxically, nutrient loadings can decrease organic matter accumulation by favoring aboveground production over belowground production. Aboveground production is more apt to wash out of the marsh following senescence, and tall plants with little rooting are more vulnerable to physical dislodgement during storms. These reasons explain why some marshes can look very lush and healthy just before they collapse.

The top five climate change vulnerabilities for tidal wetlands in the Delaware Estuary are summarized in Table3-6, considering all available information examined in this study.

Table 3-6. Top five vulnerabilities of Tidal Wetlands to climate change in the Delaware watershed, ranked by the Wetland Work Group.

Ranking	Vulnerability
1	Sea Level Rise Effects on Brackish/Saltwater Wetlands
2	Salinity Effects on Freshwater Tidal Wetlands
3	Sea Level Rise Effects on Freshwater Tidal Wetlands
4	Precipitation and Storm Effects on Freshwater Tidal Wetlands
5	Precipitation and Storm Effects on Brackish/Saltwater Wetlands

The latest version of SLAMM (Sea Level Affecting Marshes Model) helped to predict how tidal marshes and adjacent natural areas on the landward and seaward sides will respond to rising sea levels (Section 3.7.2). Using our climate predictions (Chapter 2) and best available acreage data for the uplands, non-tidal wetlands, tidal wetlands, mud flats and open water, SLAMM outputs indicated that more than 45,000 acres of natural areas that are currently landward of tidal wetlands will be converted to tidal wetlands by 2100. This gain in tidal wetlands is expected to be more than offset however by an increase of more than 105,000 acres in unvegetated tidal flats and open water, mainly in brackish/saltwater wetlands. The net effect is predicted to be a loss of more than 40,000 acres of tidal wetlands, roughly a tenth of current acreage. Projected losses of tidal wetlands are similar in Delaware and New Jersey.

All natural habitats provide ecosystem services; however, the combined services furnished by tidal marshes exceed those of the other habitats examined in this analysis, leading to a substantial net loss. For example, primary production is expected to decrease by more than 60,000 metric tons. Loss of associated carbon sequestration services by tidal marshes will be felt doubly because of lost future services combined with the release of formerly sequestered carbon by erosion of peat from marshes converted to open water. Similarly, the loss of 10% of the system's tidal wetlands could hamper efforts to establish nutrient criteria since these extensive tidal marshes are thought to be important for maintaining water quality in the Delaware Estuary.

In order to adapt to climate change, greater attention will need to be paid to the current plight and functional significance of our wetland resources. Management of these habitats is governed by an outdated paradigm that seeks to sustain them in the same places as they exist today. There is also limited system-level appreciation for the effects on tidal wetlands of watershed flow, sediment supply and nutrient loadings, as examples. Tidal wetlands are so extensive in the Delaware Estuary that a 10% loss (or more) is certain to affect fisheries, water quality, flood protection and more.

In the Delaware Estuary, watershed flow management should be considered the most effective and feasible adaptation option for offsetting the most vulnerable climate change driver to tidal fresh water wetlands, a salinity increase. A salinity increase in freshwater tidal marshes will probably occur quickly during a storm event or drought, and river flow managers should consider tidal freshwater wetland protection along with other factors in setting flow targets to potentially offset salinities above 0.5 ppt. A longer term watershed flow plan should account for the incremental build-up of salinity.

Freshwater tidal wetlands would also benefit from a dedicated effort to set aside and preserve natural areas, or to remediate dilapidated developed areas, to facilitate their landward migration. This is especially challenging in the urban corridor of the upper estuary where there is little opportunity. However, conversion of poorly used city properties to natural areas provides additional ecosystem services for society, such as added recreational opportunities, flood protection and temperature modulation.

In the extensive brackish and salt marshes of the lower estuary and especially around Delaware Bay, the most beneficial adaptation options are also ones that facilitate landward migration. In this region, there is greater opportunity because much of the 1 km buffer landward of tidal marshes in undeveloped. Agricultural lands abound here, and farmers or other landowners could be provided with incentives to donate or sell easements to protect marsh buffers. There are many types of easements along rivers and estuaries. A “rolling conservation easement” is designed to permit landward marsh migration. Made between a willing property owner and an easement holder/purchaser (such as the state, or a conservation organization), a rolling conservation easement allows the property owner to continue development and use of the property, but prohibits armoring of the shoreline to prevent inundation (Titus 1998.) So as sea level rises, the marsh can advance unimpeded, and the rising tide eventually causes more and more of the property to fall under public ownership (from mean high tide seaward).

Strategic retreat, defined here as the removal of infrastructure that would otherwise be protected, is also an option in some areas although it is costly. Along the Delaware Estuary, a 1 m rise in sea level would inundate at least 1000 hectares and perhaps up to 10000 hectares of agricultural land, 280–1040 hectares of barren land, 210–1760 hectares of developed land, 590–4280 hectares of forested land, and 80 – 130 hectares of open water (e.g., impoundments,) and 900–2420 hectares of non-tidal wetlands (Gill et al. 2009). Many of these areas could be managed to facilitate tidal marsh development depending on such factors as slope, sediment condition, and hydrodynamics.

Smart landward retreat requires adoption of a new paradigm that accepts coastal landscapes as dynamic. Structures and policies that seek to fix habitats in place are counter to natural processes and will thwart the ability of tidal wetlands to sustain themselves, especially as the rate of sea level rise increases. Therefore, proactive climate adaptation should prohibit and remove construction in areas vulnerable to the effects of sea level rise and allow for coastal habitats to undergo their natural successional march across the coastal zone.

In the short term, however, shore protection will be needed in some areas to allow enough time to build needed capital or engineering prowess to perform strategic retreat. Careful planning will also be needed to use LIDAR and other emerging technologies to forecast where future shorelines will be most sustainable. New development must be set back far enough from estuarine shorelines or at a sufficient elevation so that structures and policies are designed conservatively to accommodate a significant acceleration in the rate of sea-level rise (Titus et al. 2009a). In undeveloped areas where shore protection may be unnecessary and certainly ineffective at maintaining tidal wetland extent and services over the long term, strategic retreat is the best option (displayed in blue; Figure 4). Living shorelines are promising and cost effective tactics that slow erosion along seaward margins of tidal wetlands, buying time for them to establish themselves inland, while also boosting habitat service values.

Discerning between undeveloped lands and ecologically and economically important lands will be critical for targeting conservation and restoration efforts in response to sea-level rise and its effects. Preserving undeveloped, vulnerable lands also offers a significant opportunity to avoid placing people and property at risk to sea level rise and associated hazards including storm surge, coastal flooding, and erosion.

The costs of wetland conservation and expansion are associated primarily with capital costs of land purchases and/or easements in areas identified as critical to buffering against the impacts of sea-level rise. Funding for tidal marsh preservation and expansion must be increased, perhaps fueled by our increasing understanding of the value of the ecosystem services provided by these habitats.

The Wetland Work Group identified many other adaptation options that ranked lower in terms of either their projected benefits or their feasibility. As new information and technologies develop, some of these may become more promising. As examples, development of carbon trading markets could help focus attention on the carbon sequestration services provided by tidal marshes, especially salt marshes which appear to sequester more carbon than any other habitat in the Mid-Atlantic. The beneficial use of dredge material and marsh nourishment with sediments also represents a potential tactic to help them keep pace with sea level areas where those measures are feasible. Sediment supply for tidal marshes appears to be an important determinant of their carbon sequestration capacity (Mudd et al. 2009). It will also be important to ensure marshes receive the necessary sediment subsidy through regional sediment management practices.

The top five climate adaptation options for sustaining or enhancing tidal wetlands in the Delaware Estuary watershed are summarized in Table 3-7, considering all available information examined in this study. This list does not include monitoring and research activities.

Table 3-7. Top five adaptation options to assist tidal wetlands in adapting to climate change in the Delaware watershed, ranked by the Wetland Work Group.

Ranking	Adaptation Tactic
1	Strategic Retreat for Landward Migration
2	Natural Buffers for Landward Migration
3	Living Shorelines to Stem Erosion
4	Manage Water Flow to Maintain Salinity Balance
5	Structure Setbacks for Landward Migration

In addition to these adaptation tactics, participants also stressed the importance of research and monitoring in climate change adaptation planning. In order to determine the effectiveness of adaptation plans and tactics, research and monitoring will be necessary to develop geospatial planning tools relevant for local decision-makers, to track changes in environmental conditions, and to set appropriate benchmarks for gauging success of adaptation measures. Because of uncertainties regarding the rate and severity of climate-related effects and the rapidly changing science and tools that will underlie any climate plan, climate change adaptation will require frequent reassessment and perhaps realignment of plans and actions; i.e., an “adaptive adaptation plan” will need to be refreshed frequently to sustain the tidal wetlands of the Delaware Estuary.

3.9 Tidal Wetlands - Recommendations

The following recommendations were provided by the Wetland Work Group to help sustain tidal marsh habitats in the Delaware Estuary.

1. Identify and protect areas adjacent to tidal wetlands that are suitable for wetland migration. Allowing wetlands to migrate inland is the highest priority adaptation action. Adjacent undeveloped areas with suitable elevation, slope, and no physical impediments to migration should be treasured and protected where recognized. However, since many of these lands may not be easily recognized, a geospatial framework incorporating LIDAR, land use, and monitoring information is needed to identify them, based on location in the buffer zone, suitable elevations, slopes, and other traits. A variety of measures can be used to protect these areas for marsh migration, including: strategic retreat, set backs for building/development, incentives or buyouts for farmers, and conservation easements to ensure that marsh migration can progress unimpeded.

2. Identify and restore areas where living shorelines (or other restoration techniques) can slow erosion and stem marsh losses. The same geospatial framework referenced in 1. above is needed to identify vulnerable areas of tidal wetlands that could benefit from restoration/adaptation projects to increase the amount of acreage that is sustainable. Identifying areas with suitable edge conditions, energy conditions, and ownership conditions for living shorelines should be a priority based on assessment results. This process could also identify areas for other types of adaptation, for example, where dikes could be removed from impounded former tidal marshes and a thin layer of sediment could be applied to raise their elevation.

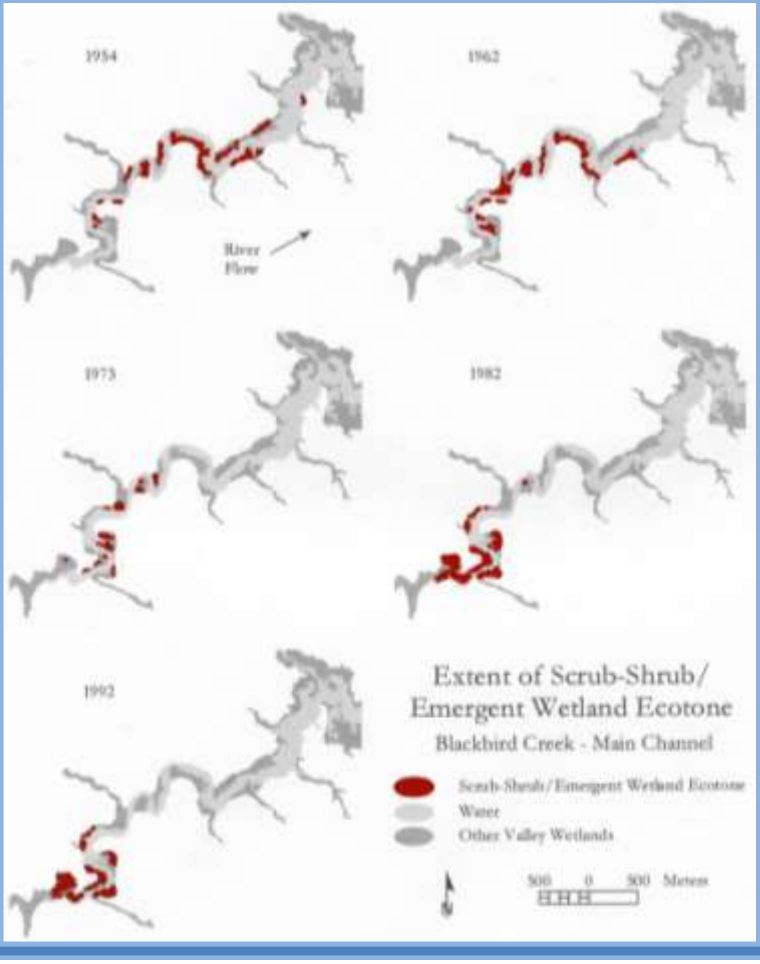
3. Develop indicators to track both impairments (and possibly benefits) to tidal wetlands from climate change (e.g., see feature 3-2) and monitoring to support them. Scientific analysis should be directly relevant for managers, helping to bolster our understanding of the benefits of these habitats to watershed health as well as the consequences of watershed management on these habitats. This information is critical to carrying out the other recommendations presented here.

4. Identify special protection or management areas based on those areas with the greatest natural capital value based on key ecosystem services furnished by tidal wetlands. Repeat the analysis of production services in this study for carbon sequestration, which is increasingly being valued as a mitigation tactic for climate change. Results of the NJ Natural Capital study could be transferred to the entire Delaware Estuary region using the association of natural capital values to land use / land cover types.

1. Educate the broader resource management community regarding the importance of tidal wetlands for watershed health and also the effects of water quality and quantity on wetland habitats. Much of the future for tidal wetlands hinges on having suitable flows, sediments and water quality. In turn, tidal wetlands can hePlp managers attain water quality targets, preserve fisheries, and provide flood protection.

Tidal wetlands are a hallmark feature of the Delaware Estuary and they supply more ecosystem goods and services than any other natural habitat. A coordinated, watershed-based approach to tidal wetland preservation and landward migration is needed to help these habitats adapt to climate change.

Feature 3-2. Scrub-Shrub as an Indicator of Change



A scrub-shrub wetland typifies a community in transition. Many emergent wetlands, left undisturbed, will gradually be replaced through succession by woody vegetation. Estuarine scrub / shrub wetland includes all tidal wetlands dominated by woody vegetation less than 5 meters in height. Such wetlands occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent. Therefore, the time series maps shown the left indicate that the salinity line may be migrating upstream in the Blackbird Creek. Scrub-shrub wetlands help stabilize stream banks and provide cover for birds and other wildlife.

-Vinton Valentine, Kurt Philipp & Laura Whalen