Appendix F
Delaware Estuary Climate Ready Estuary Pilot:
Vulnerability Assessment and Adaptation Planning
Tidal Wetlands Case Study

March 2010

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INTRODUCTION

Tidal wetlands comprise a large portion of the Delaware Estuary coastline and provide important ecological services to the communities living around the Delaware Estuary. The ecosystem services provided by tidal wetlands include nutrient cycling, carbon storage, storm surge protection, natural flood control, and essential habitat for commercially important fish and shellfish. Climate change may impact the extent and function of tidal wetlands in significant and perhaps unpredictable ways. Increasing atmospheric concentrations of carbon dioxide, methane, chloroflorocarbons, and other gases result in a global temperature increase, which, in turn, increases the rate at which the ocean level rises and could impact weather patterns such as precipitation. An analysis of the projected temperature and precipitation patterns in the Delaware Estuary under two different greenhouse gas emission scenarios suggested that by the end of the 21st century there could be an increase in temperature of 2 – 4° C and precipitation by 7 – 9% (Najjar 2009). The confidence of predictions of how each of these factors will affect specific regions varies significantly. Predictions of increases in relative sea level rise are relatively strong. Over the last century, the Delaware Estuary has experienced a relative sea level rise rate of approximately 2.75 mm per year in Philadelphia, PA to 3.16 mm per year in Lewes, DE (Zervas 2001), which is predicted to increase in the future.

Sea level rise

Tidal wetlands are particularly susceptible to the effects of sea level rise (US EPA 2008). Sea level rise may directly affect tidal wetlands through the erosive forces of tidal action. Increased tidal action may lead to seaward edge erosion, altering the ratio of shoreline edge to marsh area and increasing channel and tidal creek scour also leading to a potential loss in marsh area. Salt marshes at the seaward edge of the estuary must maintain their elevation relative to sea level to prevent conversion to open water. Both plant production and sedimentation are processes that influence vertical marsh accretion rates. Salt marsh plants are adapted to tidal flooding to a certain physiological limit beyond which, they cannot survive. Therefore, an increase in tidal range associated with sea level rise may alter the productivity of wetland vegetation. The organic matter from emergent wetland vegetation and the water it holds comprise up to 95% of the soil volume (Bricker-Urso et al. 1989, Turner et al. 2002). High plant production and slow decomposition rates belowground are important for the maintenance of organic matter in marsh soils. Inorganic material makes up less than 5% of the soil volume but is extremely important for maintaining marshes at an elevation where plant growth can continue (Bricker-Urso et al.

1989, Turner et al. 2002). If soils do not accumulate enough organic and inorganic materials to overcome the rates of sea level rise and geologic subsidence, marsh surface elevations will fall below plant physiological limits of tidal inundation. Sea level rise relative to the elevation of the marsh platform may also increase the susceptibility of tidal wetlands to increasing heights of storm surges that accompany storm events.

In areas where marsh migration is not precluded by coastal development, hard structure, and/or a steep upland slope, shoreline transgression under relative sea level rise forces coastal marshes to migrate landward and upward (Kraft et al. 1992, Warren and Niering 1993, Donnelly and Bertness 2001). Landward migration describes the displacement of the entire tidal marsh platform towards the land and at any given geographic location along this gradient there may be a shift in species composition. Within salt marshes, low marsh species will replace mid- and high marsh species and likewise, salt marshes will replace brackish and fresh water marshes. However, in areas where marsh migration is precluded by development and/or a steep upland slope, community shifts would also favor a replacement of higher intertidal species by lower species but ultimately tidal flooding would limit plant survival. In other words, relative sea level rise could cause an inland migration of marshes and species shifts in some areas and species shifts and marsh loss in other locations depending on the degree of development and the slope of the land inland of the wetlands. Thus, the vulnerability of tidal wetlands to relative sea level rise will be largely contingent on three main factors, sufficient inorganic and organic sediment supply, the degree of development and the topography of the land inland from the wetlands.

Salinity

Of the tidal wetlands in the Delaware Estuary, there are brackish ($0.5 \leq 18$ psu, Odum 1988) and fresh water (< 0.5 psu, Odum 1988) wetlands. Salt water intrusion may occur over short time periods such as with a storm surge or over a longer time period as with an increase in relative sea level. Salt water intrusion to brackish and fresh water marshes may have a severe impact on the plant and microbial communities, particularly when there is a lack of flushing by fresh water through precipitation and/or streamflow (Weston, 2006; Craft et al., 2008, Weston et al., 2009). When porewater salt concentrations remain high, plant species adapted to lower salinity will become stressed and less productive, and may die, potentially leading to conversion to open water or more salt tolerant plant species. The pathways for anaerobic decomposition will also be altered by an influx of sea water to fresh water wetlands. Anaerobic decomposition in fresh water wetlands in dominated by the reduction of carbon dioxide (CO_2) to methane (CH_4) pathway. An introduction of sea water containing sulfate would potentially increase the rate at which organic matter is decomposed, due to a more efficient pathway of sulfate (SO_4^{-3}) reduction.

In situations where salt water intrusion occurs slowly, an influx of salt water to less saline areas may shift the competitive balance toward species that are more salt tolerant, thereby resulting in a change in species composition. Tidal fresh water wetlands support a variety of organisms and a increase in salinity will result in a loss of non-mobile organisms and cause mobile biota to move into more fresh water habitats where available.

Stress related to salt water intrusion of a previously fresh water habitat may also increase the vulnerability to invasions by species. Invasive species, such as *Phragmites australis*, have been observed colonizing former freshwater forested wetlands following meadow dike breaches (K. Philipp, pers. com.).

Salinity concentrations may also change in salt marsh soils depending on the temperature and precipitation patterns. Under warmer temperature conditions, evapotranspiration rates increase resulting in higher porewater salinities.

Temperature

A significant increase in greenhouse gas (GHG) emissions is resulting in an increase in the earth's temperature (IPCC, 2007). From the late 1800's to the early 2000's, the global total temperature increase has been 0.76° C (IPCC, 2007). Depending on current and future GHG emission, the earth's surface temperature is predicted to continue to increase by 1.1 – 6.4° C during this century (IPCC, 2007). While an increase in temperature would generally cause the rate of production and decomposition to increase in a marsh, regional temperature change is difficult to predict and is dependent on many other factors such as thermohaline ocean circulation. Increased temperatures would affect wetland plants through interactions with soil moisture and salinity. Temperature, dessication, and/or salinity stress in wetlands would have consequences to the productivity and habitat support functions, allowing increased susceptibility to aggressive, non-native species invasions.

Increased temperatures in the mid-Atlantic may influence the northern migration of southern species, thereby changing species composition. For example, the mid-Atlantic is currently the northern most range of the brackish - salt marsh plant, *Juncus roemerianus* (Tiner 1987). While this species forms large monospecific stands in the south Atlantic and Gulf coasts of the U.S., it is found in small, scattered patches in the mid-Atlantic. An increase in temperature could increase the percentage of the species in mid-Atlantic brackish/salt water wetlands.

Precipitation and Storm Events

Changes in precipitation patterns will affect tidal wetlands that depend on fluxes of fresh water. In salt marshes, low rainfall periods may cause extremely high soil salt concentrations to develop, which may be stressful for all but the extremely halophytic species. In both salt and fresh water wetlands, a change in precipitation patterns may result in an increase in desiccation and/or an increase in flooding altering sediment supply and erosion. Because plant productivity is closely related to the physical environment of tidal wetlands, which depends largely on precipitation, productivity may be vulnerable to changes in rainfall. Changes in the frequency and severity of the extremes of drought, heat waves, "unseasonably" wet or cold periods all may affect long term tidal marsh life by exceeding the tolerances of individual species over the short term. In general, an increase in precipitation, which is predicted for the Delaware Estuary region (Najjar 2009), may 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).

An increase in the frequency and intensity of storm events will directly impact tidal wetlands through wind, wave, and surge effects. The long term integrity of the tidal wetlands effected by storm events will be dependant on their resiliency and the length of time of the impact.

Atmospheric CO_2

The average atmospheric CO_2 concentration has increased by a rate of 1.9 ppm yr^{-1} from 1995 to 2005 and is predicted to continue to increase (IPCC 2007). An increase in atmospheric CO_2 concentration may affect the composition of wetland plant communities, through an interaction between productivity and photosynthetic pathway. Salt marshes are dominated by species that utilize the C_4 photosynthetic pathway, such as the *Spartina* species of grasses, but also have mixed assemblages of C_3-species, such as sedges, rushes, which may be more common in brackish and fresh water wetlands, and shrubs. C_4 photosynthesis evolved during a time period in the Earth's history when atmospheric CO_2 levels were relatively low. C_4-species are more efficient in fixing C during photosynthesis than C_3-species due to several mechanisms that serve to increase the concentration of CO_2 at the site where Rubisco fixes carbon. The advantages of the C_4 photosynthetic pathway include less water loss and a lower nitrogen requirement (Chapin et al. 2002). Increased CO_2 concentration does not have a significant effect on the growth and production of C_4-species, whereas the rates of photosynthesis and above- and belowground growth of C_3-species are stimulated (Curtis et al. 1990, Rozema et al. 1991). Under elevated CO_2 conditions, the competitive balance between C_3 and C_4 species is likely to shift in favor of an expansion of C_3 species (Curtis et al. 1990, Ehleringer et al. 1991). Increasing atmospheric CO_2 concentration will also affect transpiration rates through greater leaf CO_2 exchange over shorter periods of time that stomates need to be open.

A recent study indicated that increased atmospheric CO_2 concentrations, as well as accompanying increased salinity and flooding, stimulated marsh elevation gain in a brackish tidal marsh through increased belowground productivity (Langley et al. 2009). This may be one of the complex interactions of climate change factors that will influence changes in tidal marshes. In this case, increased atmospheric CO_2 may compensate for increased rates of relative sea level rise.

Need for a regional assessment of the vulnerabilities to climate change factors and adaptation options for a strategic response to climate change

Tidal wetlands are important ecosystems that may be particularly vulnerable to certain effects associated with climate change, such as sea level rise. However, a comprehensive assessment of the impact of climate change on tidal wetland integrity and services as well as feasible and effective adaptation options specific to the Delaware Estuary has not been conducted. Wetlands of the Delaware Estuary may be influenced by different human related impacts than wetland systems in other geographic regions. By assessing which climate change factors are the most likely to have severe impacts on tidal wetlands, regional planners, managers, and the wetland science community can develop strategic adaptation plans (ASWM 2009).

In order to assess the vulnerability of Delaware Estuary tidal wetlands and their services to five climate change factors as well and potential adaptation options, a comprehensive survey was developed and distributed to regional tidal wetland experts, representing federal and state agencies, universities and research centers, industry, and private consultants. The impacts associated with climate change may affect tidal fresh and tidal brackish/salt marshes differently in that their primary stressors may be different. Therefore, this survey was designed to assess the vulnerability of both tidal fresh and tidal brackish/salt marshes to climate change. Results from the survey will be used to provide guidance towards further assessment of the impact of climate change and the development of adaptation plans.

METHODS

Vulnerability and adaptation option identification

A workgroup was established to identify specific and likely vulnerabilities to tidal fresh and tidal brackish/salt water wetlands in response to physical climate drivers, adaptation options and science gaps and needs. The following climate drivers were identified as potential causes of vulnerabilities: temperature change, sea level rise, salinity increase, an increase in the frequency and intensity of precipitation and storm events, and an increase in atmospheric CO_2 concentration. Specific vulnerabilities to tidal fresh water and tidal brackish/salt water wetlands associated with the five physical drivers as well as adaptation options were also identified (Table 1).

Survey development

Once the vulnerabilities and adaptation options were identified by the workgroup, a survey was conducted through Survey Monkey ™ to gather input from regional tidal wetland experts. The aim of the survey was to establish the relative vulnerabilities of specific impacts of climate change on wetland integrity and services to determine where future efforts should be focused for research, monitoring, and regional planning. In addition, the results of the survey would identify the most effective and feasible adaptation options to address these issues.

The wetland survey was designed to determine the difference between tidal fresh and tidal brackish/salt water wetlands in each category, the impact level for the vulnerability on wetland condition/acreage, the confidence level that the impact will occur, the change in ecosystem services due to the vulnerability, and the effectiveness and feasibility of proposed adaptation options.

Survey distribution

The Partnership for the Delaware Estuary maintains a technical workgroup for tidal wetlands consisting of regional tidal wetland experts from federal and state governments, universities and research institutions, industry and private consulting firms. This group of regional experts is instrumental in collaborative efforts for wetland monitoring and restoration, and for the State of the Estuary wetland condition reporting.

Survey analysis

Survey respondents had a range of responses from which to choose (Table 2) when assessing vulnerabilities to tidal wetlands and adaptation options in response to climate change drivers. Each answer was assigned a weighting (Table 2) except for the ecosystem services questions. The number of responses to each question ranged from 11 to 21 with the majority of questions at the beginning of the survey answered by all participants. To determine the relative ranking of the vulnerabilities, the impact scores were multiplied by the confidence scores under the assumption that the vulnerability should not receive a high ranking unless it had both a high impact and high confidence score. Ecosystem services were displayed only for those vulnerabilities which ranked high for both impact and confidence. This is assuming that ecosystem service changes will not be that great if the impact is low. If confidence levels are low for the impact, then it follows that confidence levels in ecosystem services will also likely be low. Therefore the workgroup chose to only focus on those ecosystem services changes where impact and confidence levels were high. Survey respondents were also asked to rate the effectiveness and feasibility of the adaptation options proposed by the wetland workgroup. Much like the vulnerability assessment, the scores for the weighted effectiveness were multiplied by the weighted scores for feasibility to capture which adaptation options were most viable to address the climate impacts.

Vulnerability grade and adaptation option grade

Once scores were calculated for the vulnerabilities (impact multiplied by the confidence) and adaptation options (effectiveness multiplied by the feasibility), a grading system was assigned according to the distribution of scores. These grades help to demonstrate where the greatest vulnerabilities occur due to the climate drivers' impacts. This means that the greatest vulnerabilities of tidal wetlands to climate change appear in the dark red and orange colors. The most viable adaptation options are also identified by these colors.

RESULTS

Vulnerability of tidal fresh water wetlands to climate change

Of the potential physical climate change factors, a salinity increase was assessed to be the greatest threat to tidal fresh water wetlands. Specifically, an increase in the salinity range would most likely increase the vulnerability to salt water intrusion; shifts in species composition (e.g., plant, animal and microbial), and alter the function of habitat support for fauna. Although there was a high risk of tidal fresh wetlands being vulnerable to salt exposure and stress events, it was not given the highest ranking.

Relative sea level rise was considered the second greatest threat to tidal fresh water wetlands, which would be most vulnerable to changes in wetland area, the ability for landward migration, species shifts, storm surges, and edge erosion.

The vulnerability of tidal fresh water wetlands to a change in the frequency and intensity of precipitation and storm events would have a medium to high likelihood of resulting in shifts in species composition, influencing salt exposure and stress events, desiccation, flooding, or erosion, altering sediment supply, and causing physical impacts due to wind, wave and storm surge.

Tidal fresh water wetlands had a medium to high vulnerability to shifts in species composition in response to temperature changes. An increase in atmospheric CO_2 concentration had a low vulnerability in altering species shifts and productivity.

Predicted effects on ecosystem services

Tidal fresh water wetlands were considered to be the most vulnerable to a salinity increase and relative sea level rise. An increase in salinity was predicted to have an overall negative effect on ecosystem services associated with shifts in species composition (Figure 2). Salt water intrusion to fresh marsh habitats was also considered to have a negative effect on ecosystem services provided by fresh marshes (Figure 2).

An increase in relative sea level was predicted to have a negative effect on marsh area directly reducing ecosystem services through a loss of habitat (Figure 2). In addition, in response to relative sea level rise, tidal fresh marsh services may be vulnerable to hindrances to landward migration and therefore, fresh marshes may be squeezed between a barrier to migration (high topography and/or development) and salt water inundation (Figure 2).

Vulnerability of tidal brackish/salt water wetlands to climate change

Relative sea level rise was assessed to have the greatest impact on tidal brackish/salt water wetlands. The greatest vulnerabilities are predicted to be the ability to keep pace with relative sea level rise through vertical accretion, the ability to migrate landward, shifts in species composition, a change in marsh area, seaward edge erosion, and susceptibility to storm surge. Also of high concern is an increased tidal range and a change in the ratio of marsh edge to interior area, associated with a relative rise in sea level.

An increase in the salinity range would cause a medium to high vulnerability in species shifts and salt water intrusion. Likewise an increase in temperature would cause a medium to high vulnerability to shifts in species and productivity in tidal brackish/salt water wetlands. A change in precipitation and storm events may have a medium to high likelihood of causing physical impacts associated with wind, waves, and surge.

Predicted effects on ecosystem services

Tidal brackish/salt marshes were considered to be the most vulnerable to the effects of relative sea level rise causing many specific issues such as the loss of marsh area, increased susceptibility to storm surge, edge erosion, etc. The loss of marsh area, edge erosion, and storm surge susceptibility were considered to have the greatest negative impact on the ecosystem services provided by tidal brackish/salt marshes (Figure 3). The greatest amount of uncertainty was associated with the ability of marshes to vertically accrete at a rate similar to relative sea level rise as well as migrate landward in response to relative sea level rise and the effects on ecosystem services however, the predicted effects were mostly negative (US EPA 2008) (Figure 3).

Effective and feasible adaptation options for reducing the vulnerability of tidal fresh water wetlands to climate change

Tidal fresh water wetlands were considered to be the most vulnerable to increases in salinity. To prevent or respond to an increase in salinity, adaptation options included watershed flow management, creation of a salt barrier, designation of buffer lands, and strategic retreat (Table 4). The highest ranked adaptation option in terms of effectiveness and feasibility was watershed flow management, and secondarily, strategic retreat.

Tidal fresh water wetlands were also considered vulnerable to the impacts of relative sea level rise. The most effective and feasible adaptation options to reduce the vulnerability of tidal fresh water wetlands to the effects of relative sea level rise were determined to be strategic retreat and the creation of buffer lands (Table 4). Structure setbacks and the creation of living shorelines were also considered highly effective and feasible options to protect tidal fresh water wetlands from the effects of relative sea level rise.

Three adaptation options for preventing or offsetting the negative effects of changes in precipitation and storm event patterns to tidal fresh water marshes were identified as being moderate to highly effective and feasible (the highest rank for this category), structure setbacks, strategic retreat, and the creation of buffer lands (Table 4).

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.

Effective and feasible adaptation options for reducing the vulnerability of tidal brackish/salt water wetlands to climate change

Strategic retreat was considered the most effective and feasible adaptation option for reducing the vulnerability of tidal brackish/salt water wetlands to the effects of relative sea level rise (Table 4). This option was given the highest ranking. The creation of buffer zones and living shorelines were also considered highly effective and feasible options.

Watershed flow management and strategic retreat were considered moderate to highly effective and feasible options for reducing the vulnerability of tidal brackish/salt water wetlands to an increase in salinity.

Many adaptation options were identified as moderate to highly effective and feasible options for reducing the vulnerability of tidal brackish/salt water wetlands to changes in precipitation and storm event patterns (Table 4). These included building dikes, bulkheads, and/or tide gates, structure setbacks, rebuilding infrastructure, strategic retreat, and creation of buffer lands and living shorelines.

Description of the most effective and feasible adaptation options identified

Watershed flow management- Watershed flow is largely regulated upstream of the Delaware Estuary to provide drinking water for communities,…. Flow regulators may manage water discharge to offset negative impacts of drought, storm surge, relative sea level rise impacts to Delaware Estuary wetlands.

Strategic retreat- Strategic retreat is the planned response of relocating structures and development inland from the coast to allow for the inland migration of natural coastal environments (buffers) and to avoid the devastating effects of natural disasters that occur in the coastal zone. An optimal retreat would require long term planning and investment. Strategic retreat regarding climate change adaptations for tidal wetlands, generally refers to the retreat of man made structures and facilities that would be barriers to the landward migration of tidal wetlands, mainly roads, dikes, culverts, and bridges. This would also include not furthering the increasing extent of existing shoreline hardened against relative sea level rise. The most ambitious relocation of a structure in the Mid-Atlantic during the last decade was the landward relocation of the Cape Hatteras Lighthouse (Titus et al. 2009a).

Structure setbacks- Structure setbacks would prohibit development on land that is expected to erode or be inundated within a given period of time. Stucture setbacks can prevent erosion or flood damages as well as allow for 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).

Creation of buffer lands- The creation of buffer lands would require the protection, maintenance, and/or establishment of natural habitat types that lie between developed lands and tidal wetlands. This allows for tidal wetlands incur limited human impacts while providing the opportunity for landward migration.

Living shorelines- Living shorelines involve using non-structural shoreline stabilization measures to provide erosion control benefits while also enhancing the natural shoreline habitat. Living shorelines can allow natural coastal processes to occur through the strategic placement of plants, stone, sand fill, and other structural and organic materials.

Building dikes, bulkheads, and tide gates- Dikes are high, impermeable earthen walls designed to protect areas from flooding or permanent inundation. Dikes are usually associated with a drainage system to channel the flood water away from vulnerable lands and infrastructure. Land below mean low water requires a pumping system to remove rainwater and any water that seeps through the ground below the dike. Lland whose elevation is between low and high tide can be drained at low tide, except during storms (Titus et al. 2009a).

Bulkheads are vertical walls designed to resist waves and currents to prevent the land from eroding into the water. Bulkheads hold soils in place, but they do not normally extend high enough to keep out foreseeable floods. They are usually found along estuarine shores where waves have less energy (Titus et al. 2009a).

Tide gates are barriers across small creeks or drainage ditches that enable a low-lying area above mean low water to drain to low tide elevations without the use of pumps. They are designed to open during low tides and close during high tides (Titus et al. 2009a). Self regulating tide gates may be used to allow normal tidal flow, but protect against storm tides. Muted or restricted tide regimes may also be managed by self regulating tide gates.

RECOMMENDATIONS

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 fresh marshes may occur quickly during a storm event and river flow managers may want to be prepared to offset high salinities that are sustained when precipitation and regulated flows do not reduce salinities below 0.5 psu. A longer term watershed flow plan should account for the slower and long term effects of a salinity increase associated with increased salt water inundation through relative sea level rise on fresh marshes, particularly in areas where landward migration is inhibited.

Strategic retreat may be the most effective and feasible adaptation option for maintaining the extent and services of tidal brackish/salt water wetlands and tidal fresh marshes in response to relative sea level rise. Along the Delaware Estuary, a 1 m rise in sea level would cause low - high estimates of inundation to affect 950 – 9590 hectares (ha) of agricultural land, 280 – 1040 ha of barren land, 210 – 1760 ha of developed land, 590 – 4280 ha of forested land, 80 – 130 ha of open water, and 900 – 2420 ha of wetlands (Gill et al. 2009). Landward retreat would include prohibiting and removing construction in areas vulnerable to the effects of relative sea level rise and allowing room for landward migration of tidal wetlands. Retreat may be most feasible in relatively undeveloped coastal areas, but may be difficult in urban centers such as Philadelphia. Along urban shores and industrialized corridors, shore protection may be necessary options (Figure 4).

Shore protection, however, may be a short term solution, which also prevents the inland migration of tidal wetlands. Most shore protection structures are designed for the current sea level, and retreat policies that rely on setting development back from the coast are designed for the current rate of relative sea-level rise. Those structures and policies would not necessarily accommodate a significant acceleration in the rate of relative sea-level rise (Titus et al. 2009a). In other relatively undeveloped areas, where shore protection may be unnecessary and certainly ineffective at maintaining tidal wetland extent and services over the long term, strategic retreat may be the best option (displayed in blue; Figure 4).

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

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. Trial programs need to be implemented, developing mechanisms that allow and promote strategic retreat, such as rolling easements (Titus 1998). Funding programs and policies must be increased to be comparable with land values for development in order to be effective. The development and implementation of a package of appropriate regulations, financial incentives, and educational, outreach, and enforcement approaches is needed to retain and expand wetlands in areas suitable for long-term survival. State programs, addressing adaptation planning for the impact of climate change on coastal lands, are being developed (DNREC 2009, Frizzera et al. 2009).

Although excluded from the survey analyses, wetland experts (survey respondents) stressed the importance of research and monitoring in climate change adaptation planning. In order to determine the effectiveness of certain management and adaptation plans, research and monitoring will be necessary. The ability of tidal marshes of the Delaware Estuary to vertically accrete at the anticipated accelerated rates of relative sea level rise and migrate landward, both on regional spatial basis, are among the highest priorities of research needs. 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.

Table 1. The potential vulnerabilities to tidal wetlands due to physical climate change drivers and potential adaptation options.

Physical Climate Drivers	Potential Wetland Vulnerabilities	Adaptation Options
Temperature Change	• Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species	• Monitor/Research Vulnerability Impacts
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 Impacts • Beach/marsh nourishment • Elevating homes/structures • Dikes and Bulkheads - short term management or removal • Structure Setbacks • Rebuilding infrastructure • Strategic Retreat • Creation of Buffer Lands • Living Shorelines
Salinity Range Increase	• Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species	• Monitor/Research Vulnerability Impacts • Watershed flow management • Salt barrier • Strategic Retreat • Creation of Buffer Lands
Precipitation & Storms	• 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 Impacts • Beach/marsh nourishment • Elevating homes/structures (To facilitate landward migration of wetlands) • Dikes and Bulkheads - short term management or removal to create incentives for wetland landward migration • Structure Setbacks (move structure relative to increase flooding) • Rebuilding infrastructure • Strategic Retreat • Prioritize lands to preserve (allow marshes to retreat) • Living Shorelines
Atmospheric Carbon dioxide increase	• Shifts in Community Species Composition • Productivity	• Monitor/Research Vulnerability Impacts • Carbon Trading (acquisition incentives for landward migration)

Table 2. The range of responses from which survey respondents had to choose from when assessing tidal wetland vulnerabilities and adaptation options to climate change drivers.

	Survey Choices	Weighting
Impact Score (Likely severity of climate drivers on each vulnerability	Severe	5
	High	4
	Moderate	3
	Low	2
	No Significant Impact	1
Confidence Score (Confidence in the impact score)	High	4
	Moderate	3
	Low	2
	Not Confident	1
Ecosystem Service (Net Change due to the anticipated impact)	Positive Change	N/A
	Negative Change	
	No Net Change	
	Not Sure	
Adaptation Options	Highly Effective	3
	Moderately Effective	2
	Low Effective	1
	High Feasibility	3
	Moderate Feasibility	2
	Low Feasibility	1

Table 3. The relative ranking of the vulnerabilities of tidal fresh and tidal brackish/salt water wetlands to climate change. Rankings include both vulnerability and confidence levels.

Vulnerability Assessment - Tidal Wetlands	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

Low
MED-LOW
MED-HIGH
HIGH
HIGHEST

Table 4. The relative effectiveness and feasibility of different adaptation options that would minimize specific vulnerabilities to climate change.

Adaptation Options	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

Legend
Low
MED-LOW
MED-HIGH
HIGH
HIGHEST

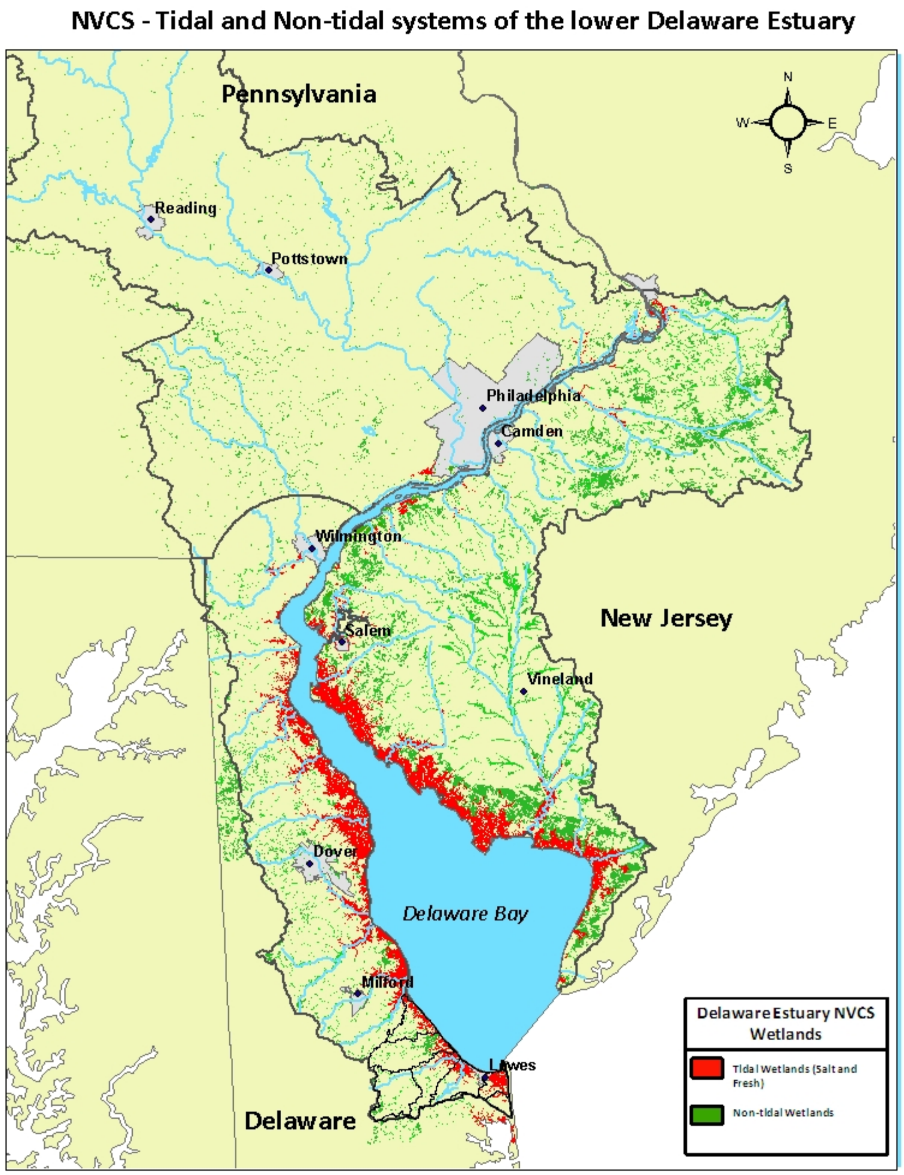

Figure 1. Tidal wetlands (red) surround the Delaware Estuary.

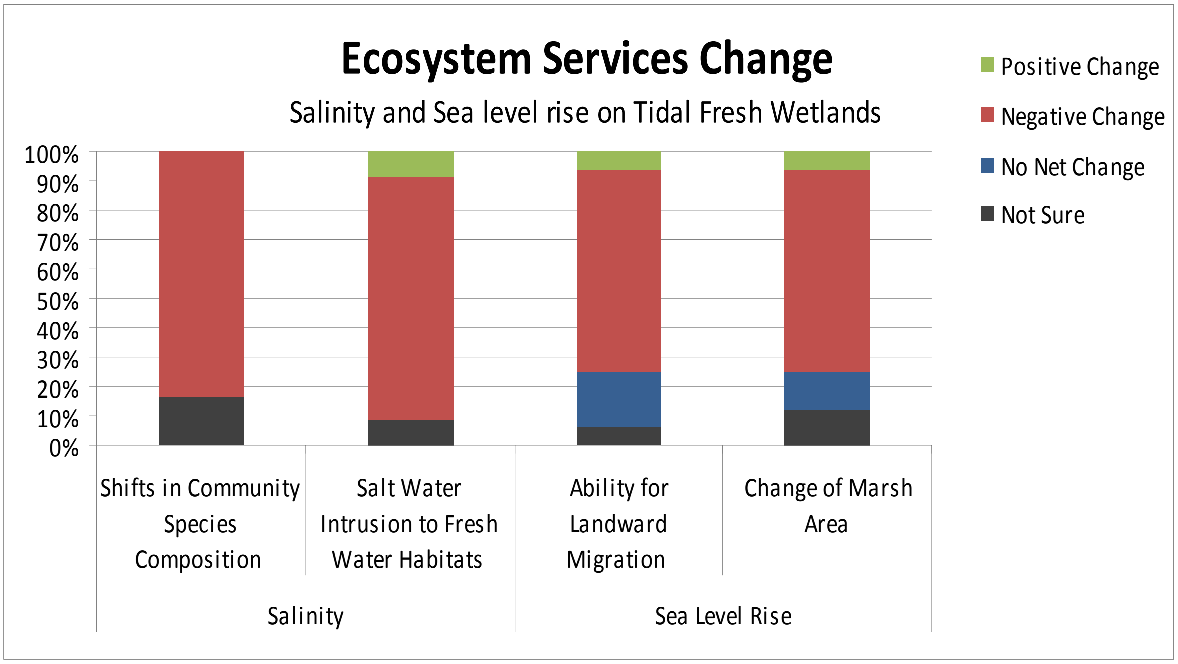

Figure 2. The percentage of wetland experts that predict a relative direction of change for the most vulnerable effects of an increase in salinity (n = 13) and sea level rise (n = 17) on tidal fresh water wetlands.

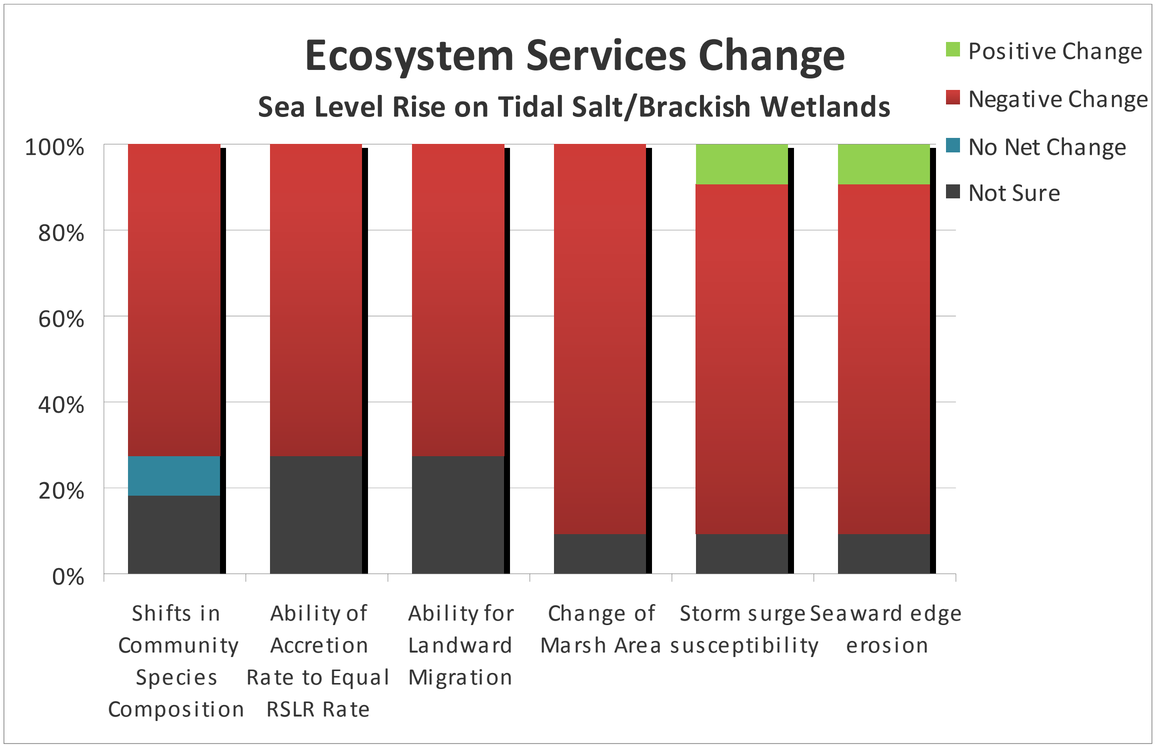

Figure 3. The percentage of wetland experts that predict a relative direction of change for the most vulnerable effects of sea level rise on tidal brackish/salt water wetlands (n = 14).

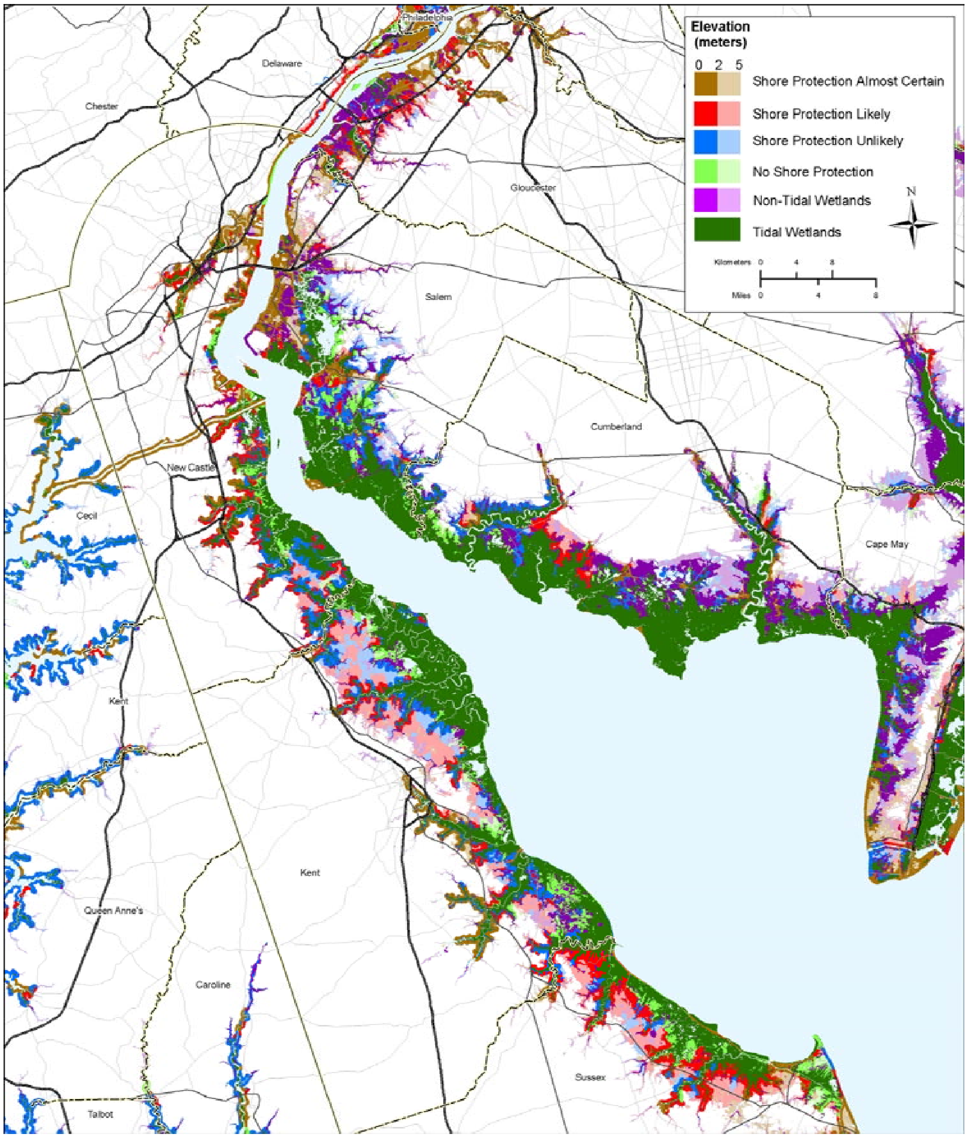

Figure 4. Landuse and likelihood of shoreline protection along the Delaware Estuary (Titus et al. 2009b). Areas in blue indicate areas where shore protection is unlikely and therefore areas where strategic retreat may be effective and feasible means of maintaining the extent and function of tidal wetlands displayed in green.

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APPENDIX

Survey Questions

Temperature Changes - Tidal Fresh	What impact will Temperature Changes at 2100 have on TIDAL FRESH WETLANDS in the Delaware Estuary? (Means, Extremes, Growing Season Length, etc) • Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species
	How confident are you (in your answers above) that Temperature changes at 2100 will impact TIDAL FRESH WETLANDS in the following categories? • Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species
	How will Ecosystem Services in TIDAL FRESH WETLANDS be affected if the vulnerabilities from Temperature Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species
	Please Indicate both the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. (Check Two; one effectiveness and one feasibility) • Monitor/Research Vulnerability Impacts
Temperature Changes – Tidal Salt	What impact will Temperature Changes at 2100 have on TIDAL SALT/BRACKISH WETLANDS in the Delaware Estuary? (Means, Extremes, Growing Season Length, etc) • Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species
	How confident are you (in your answers above) that Temperature changes at 2100 will impact TIDAL SALT/BRACKISH WETLANDS in the following categories? • Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity • Invasive Species
	How will Ecosystem Services in TIDAL SALT/BRACKISH WETLANDS be affected if the

<table>
<tr><td></td><td>vulnerabilities from Temperature Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.)
• Shifts in Community Species Composition
• Desiccation of Marsh Sediments
• Change in Habitat Support
• Productivity
• Invasive Species</td></tr>
<tr><td></td><td>Please Indicate both the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. (Check Two; one for effectiveness and one for feasibility)
• Monitor/Research Vulnerability Impacts</td></tr>
<tr><td rowspan="4">Sea Level Rise – Tidal Fresh</td><td>What impact will Relative Sea Level Rise at 2100 have on TIDAL FRESH WETLANDS in the Delaware Estuary? (Increased Rate)
• 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</td></tr>
<tr><td>How confident are you (in your answers above) that Relative Sea Level Rise at 2100 will impact TIDAL FRESH WETLANDS in the following categories?
• 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</td></tr>
<tr><td>How will Ecosystem Services in TIDAL FRESH WETLANDS be affected if the vulnerabilities from Relative Sea Level Rise occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.)
• 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</td></tr>
<tr><td>Please Indicate both the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. (Check Two; check one for effectiveness and one feasibility)</td></tr>
</table>

	• Monitor/Research Vulnerability Impacts • Beach/marsh nourishment • Elevating homes/structures (facilitate landward migration of wetlands) • Dikes and Bulkheads - short term management or removal • Structure Setbacks (move structure relative to increase flooding) • Rebuilding infrastructure • Strategic Retreat • Creation of Buffer Lands • Living Shorelines
Sea Level Rise – Tidal Fresh	What impact will Relative Sea Level Rise at 2100 have on TIDAL SALT/BRACKISH WETLANDS in the Delaware Estuary? (Increased Rate) • 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
	How confident are you (in your answers above) that Relative Sea Level Rise at 2100 will impact TIDAL FRESH WETLANDS in the following categories? • 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
	How will Ecosystem Services in TIDAL SALT/BRACKISH WETLANDS be affected if the vulnerabilities from Relative Sea Level Rise occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • 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
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Options. (Check Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Beach/marsh nourishment

	• Elevating homes/structures (facilitate landward migration of wetlands) • Dikes and Bulkheads - short term management or removal • Structure Setbacks (move structure relative to increase flooding) • Rebuilding infrastructure • Strategic Retreat • Creation of Buffer Lands • Living Shorelines
Salinity Rise – Tidal Fresh	What impact will Salinity Range Changes at 2100 have on TIDAL FRESH WETLANDS in the Delaware Estuary? (Increased Rate) • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	How confident are you (in your answers above) that Salinity Range Changes at 2100 will impact TIDAL FRESH WETLANDS in the following categories? • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	How will Ecosystem Services in TIDAL FRESH WETLANDS be affected if the vulnerabilities from Salinity Range Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Options. (Check Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Watershed flow management • Salt barrier • Strategic Retreat • Creation of Buffer Lands
Salinity – Tidal Salt	What impact will Salinity Range Changes at 2100 have on TIDAL SALT/BRACKISH WETLANDS in the Delaware Estuary? (Upper Estuary migration of salinity range, season changes, and extremes) • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats

	• Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	How confident are you (in your answers above) that Salinity Range Changes at 2100 will impact TIDAL SALT/BRACKISH WETLANDS in the following categories? • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	How will Ecosystem Services in TIDAL SALT/BRACKISH WETLANDS be affected if the vulnerabilities from Salinity Range Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats • Salt exposure/stress event • Change in Habitat Support • Productivity • Invasive Species
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Options. (Select Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Watershed flow management • Salt barrier • Strategic Retreat • Creation of Buffer Lands
Precipitation/Storms – Tidal Fresh	What impact will Precipitation/Storm Changes at 2100 have on TIDAL FRESH WETLANDS in the Delaware Estuary? (Change in seasonal pattern, amount, extremes, storm frequency/intensity, insolation/cloud cover) • 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
	How confident are you (in your answers above) that Precipitation/Storm Changes at 2100 will impact TIDAL FRESH WETLANDS in the following categories? • 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
	How will Ecosystem Services in TIDAL FRESH WETLANDS be affected if the vulnerabilities from Precipitation/Storm Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • 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
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Option. (Select Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Beach/marsh nourishment • Elevating homes/structures (To facilitate landward migration of wetlands) • Dikes and Bulkheads - short term management or removal to create incentives for wetland landward migration • Structure Setbacks (move structure relative to increase flooding) • Rebuilding infrastructure • Strategic Retreat • Prioritize lands to preserve (allow marshes to retreat) • Living Shorelines
Precip/Storms - Tidal Salt	What impact will Precipitation/Storm Changes at 2100 have on TIDAL SALT/BRACKISH WETLANDS in the Delaware Estuary? (Change in seasonal pattern, amount, extremes, storm frequency/intensity, insolation/cloud cover) • 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
	How confident are you (in your answers above) that Precipitation/Storm Changes at 2100 will impact TIDAL SALT/BRACKISH WETLANDS in the following categories? • 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

	How will Ecosystem Services in TIDAL SALT/BRACKISH WETLANDS be affected if the vulnerabilities from Precipitation/Storm Changes occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • 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
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Option. (Select Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Beach/marsh nourishment • Elevating homes/structures (To facilitate landward migration of wetlands) • Dikes and Bulkheads - short term management or removal to create incentives for wetland landward migration • Structure Setbacks (move structure relative to increase flooding) • Rebuilding infrastructure • Strategic Retreat • Prioritize lands to preserve (allow marshes to retreat) • Living Shorelines
Carbon Dioxide – Tidal Fresh	What impact will increased atmospheric carbon dioxide at 2100 have on TIDAL FRESH WETLANDS in the Delaware Estuary? • Shifts in Community Species Composition • Productivity
	How confident are you (in your answers above) that increased atmospheric carbon dioxide at 2100 will impact TIDAL FRESH WETLANDS in the following categories? • Shifts in Community Species Composition • Productivity
	How will Ecosystem Services in TIDAL FRESH WETLANDS be affected if the vulnerabilities from increased atmospheric carbon dioxide occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • Shifts in Community Species Composition • Productivity
	Please Indicate both the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. (Select Two; one effectiveness and one feasibility) • Monitor/Research Vulnerability Impacts • Carbon Trading (acquisition incentives for landward migration)
Carbon Dioxide	What impact will increased atmospheric carbon dioxide at 2100 have on TIDAL SALT/BRACKISH WETLANDS in the Delaware Estuary? • Shifts in Community Species Composition • Productivity
	How confident are you (in your answers above) that increased atmospheric carbon dioxide at 2100 will impact TIDAL SALT/BRACKISH WETLANDS in the following categories?

	• Shifts in Community Species Composition • Productivity
	How will Ecosystem Services in TIDAL SALT/BRACKISH WETLANDS be affected if the vulnerabilities from increased atmospheric carbon dioxide occur: (e.g. sediment stabilization, providing habitat, storm buffering, water filtrating, etc.) • Shifts in Community Species Composition • Productivity
	Please Indicate the EFFECTIVENESS and FEASIBILITY of the proposed Adaptation Option(s) to address the Vulnerabilities. Indicate additional Adaptation Option. (Select Two; one for effectiveness and one for feasibility) • Monitor/Research Vulnerability Impacts • Carbon Trading (acquisition incentives for landward migration)