estuarine ecosystems are closely linked to the local climate conditions created by coastal storms. Stronger and more frequent coastal storms are posing immediate threats and challenges to impounded wetland management schemes used on the refuge in the last three decades.

Hurricanes are usually more powerful than coastal storms along the Atlantic Coast, but coastal storms are more frequent in Delaware, last longer, and impact larger areas. While hurricane season runs from June 1 to November 30, coastal storms called nor'easters are a year-round threat to coastal Delaware. Prolonged flooding and extensive property damage are serious hazards more associated with nor'easters than hurricanes along the Delaware coast.

In Delaware, tidal flooding, or storm surge, associated with a nor'easter can actually exceed the levels associated with hurricanes. Storm surge is the result of water being dragged onto the shoreline by the storm's strong winds coupled with very low atmospheric pressure at the storm's center. Storm surge heights of 3 to 10 feet above normal are especially damaging when they bracket several high tide full and new moon cycles. The torrential rainfall from nor'easters can also cause extensive flooding in both coastal and inland areas and increase coastal erosion of sandy beach ecosystems (Carey and Dalrymple 2003).

It has been documented in the past that normal daily tide cycles and coastal storm processes actively change the configuration of the coastline. Normal low-energy processes move small volumes of sand and are both erosional and depositional in nature. High-energy coastal storm processes involve large volumes of sediment movement (Kraft et al. 1976).

Delaware's most damaging coastal storm on record occurred over a three-day period and five extreme full moon, high tide cycles March 6 to 8, 1962. Winds reached speeds of 70 miles per hour. Offshore waves were recorded at higher than 40 feet, while waves in the surf zone were 20 to 30 feet high. The storm surge associated with the storm was 9.5 feet, the highest tide ever recorded in Breakwater Harbor (Lewes Tide Gauge) at the mouth of the Delaware Bay (Carey and Dalrymple 2003).

Coastal storms with sustained winds can lead to prolonged flooding of refuge impoundments and roads and increase the erosion of refuge dunes. The surge of storm water landward results in heavy saltwater intrusion of freshwater wetlands and adjacent upland habitats. Long-term geologic changes from these coastal storms include beach erosion, dune erosion, and possible inlet formation from stronger flood and ebb tide surges.

Wind and saltwater intrusion, nearshore channeling, and sedimentation associated with coastal storms also cause landscape changes. In the past, this scenario and associated geological changes may have been experienced every other decade. Overwash at barrier coastlines is determined by the height and wave parameters. In 1978, Maurmeyer noted that "barriers along the southwestern shore of the bay generally require tide levels in excess of 3.0 meters (about 9 feet) above mean low water, which occur approximately once in 25 to 30 years before they overwash."

Since the 1990s, the refuge has been experiencing more frequent nor'easter activity with multiple big coastal storms making landfall during a single season, creating more rapid landscape and coastal changes. For example, the coastal storms of December 10 to 14, 1991 and January 4, 1992 had associated storm surges of up to 8.5 feet above mean high water. After these two storms, washovers and breaching of dunes occurred at scattered locations along the Delaware Bay. Geologic observations made by Delaware Geological Survey (June 1992) included the following notes relevant about the refuge (Ramsey et al. 1992):

> *"The dunes were flattened between the north end of Prime Hook Beach and the south end of Slaughter Beach. Washovers were observed to extend 20 to 30 feet into the marsh throughout this area. An artificial earthen berm that originally stood approximately 8 to 10 feet high at the end of Road 199 at Fowler Beach was almost completely removed. Based on the relative position of a concrete structure at the south end of Fowler Beach (WWII tower) to the beach profile after the October 31 1991 storm and the January 4, 1992 storm, beach retreat in this area may be as much as 20 feet inland."*

Six years later, another set of back-to-back coastal storms occurred again on January 27 to 29 and February 4 to 6 in 1998. Recorded storm surges from 1999 topped the 1992 storm surges, peaking at 9.0 feet above mean higher high water. Both storms produced near-record high tides, but the January 28 storm was slightly higher than the February 5 storm; ironically, the February 5 storm was more damaging. From a comparison of Lewes Tide Gauge data, the February 5 storm was more severe because the low tides were exceptionally high before the storm developed off the coast. Of all the storms of record, even the 1962 storm, this particular phenomenon is very unusual and this makes this storm unique among those recorded to date in Delaware (Ramsey et al. 1998). Damage and erosion of artificial dunes was extensive, as the entire duneline was flattened and large overwashes developed similar to those of the 1992 storms.

Not until the category one hurricane Ernesto in 2006 did a distinctive inlet form north of Fowler Beach Road in 2006. A relatively mild storm, Ernesto made landfall with little rain. However, Ernesto blew off shore for several days, generating higher than normal tide cycles that intensified flood and ebb tide water surges even before making landfall. Since Delaware Bay is a relatively shallow body of water, waves build up more quickly than in the open Atlantic (Kraft et al. 1976). The water level continued to rise and waves attacked the shoreline for several days with increasing intensity. Finally, when landfall did occur, a new inlet broke through the refuge's sandy barrier in Unit I.

A year and half later, a severe Mother's Day coastal storm on May 11, 2008, caused considerable coastal erosion and overwashed all refuge marshes in Units I and II. One year later, two more back-to-back nor'easters occurred on October 15 to 19 and then November 12 to 15, 2009. Both nor'easters generated tide surges of 9.0 feet above mean higher high water. Sand in the form of washover fans was transported across the flattened beach dunes back into the adjacent marsh and a new tidal water flow channel was created in Unit II just south of Fowler Beach Road. Several tide cycles after the second storm hit, high tide cycles continued to pile water across the barrier, intensifying flood and ebb tide water surges that etched out two additional mini-inlets further south of the first inlet, across the Unit II duneline.

The increased frequency and severity of coastal storms over the past decade has a direct impact on the management options and capability along the refuge shoreline and in the adjacent coastal wetlands.

Climate Change, Sea Level Rise and Refuge Shoreline Dynamics

In 2007, the Intergovernmental Panel on Climate Change (IPCC) projected that average global sea level will likely rise between 19 and 59 centimeters (7 and 23 inches) by the end of the century (2090 to 2099), relative to the base period (1980 to 1999), excluding any rapid changes in ice melt of Greenland and Antarctica ice floes. According to the IPCC, the average rate of global sea level rise is very likely to exceed the average rate recorded over the past four decades [IPPC Fourth Assessment Report-AR4] (USCCSP 2009).

The U. S. Climate Change Science Program (USCCSP) has generated a synthesis and assessment report in 2009 (product 4.1) determining coastal sensitivity to sea level rise and climate change scenarios with a focus on the mid-Atlantic region. Accelerated rates of sea level rise with stronger and more frequent storms pose increasing impacts to coastal communities, infrastructure, beaches, wetlands, and natural ecosystems.

Two major processes cause global mean sea level rise: ocean temperature increases causing water to expand and increase in volume, and land reservoirs of glaciers and ice sheets melt due to rising earth temperatures.

At the same time, the land in coastal areas is subsiding. When the rates of actual sea level increase is combined with the subsidence of land areas, scientists add these two factors and refer to the total as “relative sea level rise”, i.e. that the actual impact is the net of the two processes

Global sea level rise rates rose to an average of about 1.7 mm/year over the twentieth century. However, in the mid-Atlantic region from New York to North Carolina, tide-gauge observations indicate that relative sea level rise rates ranged from 2.4 to 4.4 mm/year, or about 0.3 meters (1 foot) during the same time frame (USCCSP 2009), which is higher than the global mean. Although the body of research supporting concerns regarding global climate change and sea level rise is substantial, the Service recognizes that there is not necessarily worldwide scientific consensus regarding global or even regional sea level rise rates and predictions (CITATIONS). Locally in Delaware, the rate of relative sea level rise has been estimated to be 3.2 ±0.28 mm/yr, (2.92 – 3.48 mm/yr, 95% confidence interval), which is approximately 1.5 mm/yr higher than the average global rate of seal level rise alone (NOAA Lewes, DE, Tide Gauge: *http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8557380;* accessed August 2012).

It is this current, local rate of sea level rise which will direct many of the refuge’s management decisions regarding achieving sustainable future conditions along the refuge shoreline and coastal wetlands. However, scientific projections for the 21st century are even higher, with predicted global sea level increase rates ranging from 2 to 7 mm/year (Rahmstorf 2007). Increasing sea level rise would greatly stress coastal wetlands, leading to either accelerated migration landward or wetland disintegration. Quantitative predictions of these future coastal changes remain difficult due to the complexity of coastal systems (Ashton et al. 2007). Predicting sea level rise impacts on shoreline changes or associated wetland losses with quantitative precision and certainty is not yet possible. If existing wetland habitats cannot keep pace with sea level rise through vertical accretion, the result will likely be extensive loss of coastal wetland habitats on the refuge and across the mid-Atlantic. Also the quality, quantity, and spatial distributions of other coastal habitats will change as a result of erosion, shoreline and salinity changes, and wetland loss (USCCSP 2009).

Regardless of the future rate of sea level rise locally, it is not simply a rise in sea levels, per se, that poses the most significant threat to refuge management. Higher sea levels will also provide an elevated base for storm surges to magnify flooding effects and diminish the rate and capability at which low-lying coastal areas can drain water. This will further intensify the magnitude of flooding and erosion effects from coastal storms. Rapid sea level rise will exacerbate existing problems experienced by coastal areas from waves, storm surges, shoreline erosion, wetland loss, and saltwater intrusion.

Natural coastal ecosystems evolved under conditions of sea level rise. Barrier islands and salt marshes can sustain their features, but not necessarily their location or configuration, in the face of more frequent coastal storm events, provided they are healthy and processes such as vertical accretion are not hindered.

Increased coastal storm-generated wind, waves, and higher astronomical tides will continually modify and change the refuge's physical shoreline and sandy beach templatesthrough breaching (inlet formation) and overwash processes with greater frequency. The refuge's undeveloped barrier island habitats may become completely reconfigured geomorphologically after each coastal storm. This reconfiguration will directly affect habitat availability and functionality and contribute to the redistribution of sediment along sandy beaches, shorelines, and refuge back barrier wetlands. This is how coastal ecosystems adjust to climate change, sea level rise, and more frequent storm surges (USGS 2010). Narrow, low-elevation barrier island communities, as found on the refuge, will become more susceptible to storm overwash development, barrier segmentation, the formation of new tidal inlets, and closing of previous inlets. These physical and geomorphic responses expedite landward migration or roll-over of shorelines as they readjust their equilibrium position in relation to rising sea levels and local storm conditions (USGS 2010).

In the past, the refuge coastal area was generally managed under the premise that sea level was relatively stable, shorelines remained static, and storms were regular and of predictable magnitude. Significant changes along the shoreline happened infrequently, and were considered to be unusual events. Within that scenario, little to no thought was given to shoreline and coastal monitoring or management. However, today it is recognized that refuge shoreline dynamics will be increasingly dominated by overwash and inlet processes as the coastline responds to the increased storm frequency and severety and relative sea level rise associated with climate change.

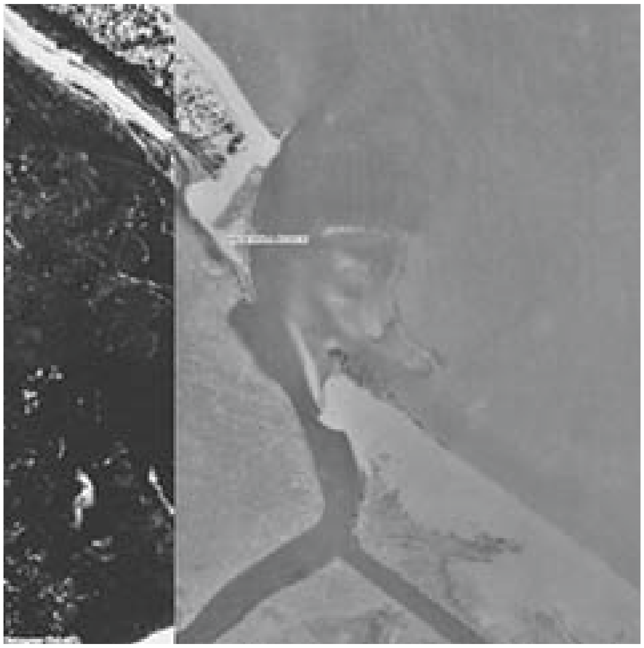
Refuge Shoreline Dynamics

Overwash and inlet processes are both integral parts of shoreline dynamics. Overwash processes deposit large sand fans across the beach and adjacent wetlands and serve to build barrier island elevation, widen beach width, and accrete sand in back barrier marshes. Storm overwash events assist in expanding barrier island width and also contribute to island roll-over or migration landward. Overwash deposition in many studied barrier island marsh systems have increased sedimentation rates that have promoted relatively stable marsh communities by enhancing vertical accretion mechanisms in the face of increased local rates of sea level rise (Ashton et al. 2007). Throughout Delaware, evidence of these coastal processes is prominent in the historic aerial imagery (appendix J). For example, portions of the Broadkill Beach community are constructed on sediments deposited naturally by the closure of an inlet that was present as recently as the 1940s (Figure 3-3). The formation, recovery, and reformation of overwashes in the Fowler Beach area is illustrated in figure 1-1 in chapter 1.

Inlet formation is also vital to the short-term maintenance of barrier island ecosystems and their estuaries, and long-term barrier island evolution necessary to maintain and conserve coastal wetlands (Mallinson et al. 2008). Once an inlet is created, usually during a storm event, active flood and ebb tide deltas form in association with an inlet. As the inlet closes, the ebb-tide delta collapses, causing temporary and localized shoreline accretion while adjacent shoreline areas may erode (map 3-7).

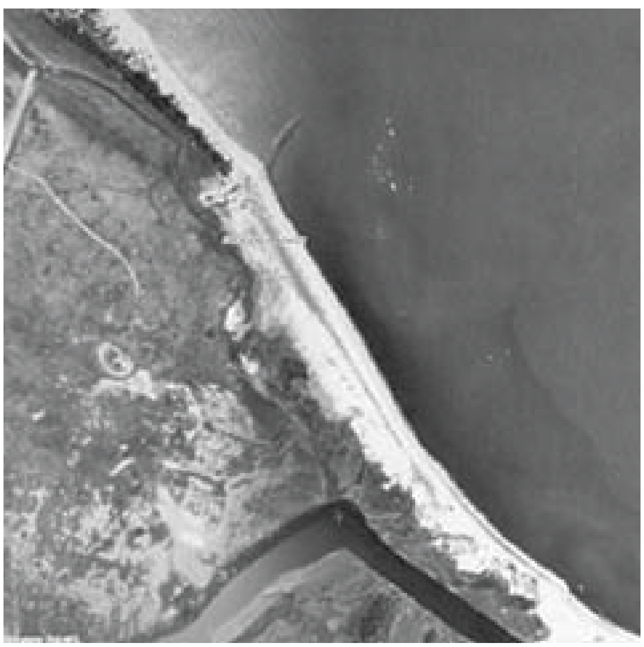
The floodtide delta, which provides a platform for the colonization of salt marsh, is abandoned and the marsh redevelops behind the newly positioned shoreline. This increases the barrier island's width and continues the evolutionary succession of the barrier island, while facilitating the vertical accretion of back barrier wetlands (Mallinson et al. 2008).

Figure 3-3. Former inlet at south end of Broadkill Beach, dated 1937, 1954, 1968, and 2007 showing pattern of natural inlet filling, overwash, revegetation, and subsequent island community development



1937

1954



1968

2007

The most important impacts on the physical environment resulting from overwash and inlet formations are the natural transport and deposition of sand to back barrier wetlands. Overwash fans and inlets that develop across wetlands and adjacent beaches are in equilibrium with the coastal dynamics of rising sea levels, more frequent storm surges, and local geomorphic conditions. If a barrier island is not allowed to roll back or migrate landward and provide back barrier marsh environments with the only potential to accrete sand, the barrier island shoreline will eventually collapse and back barrier marshes will not be able to keep up with sea level rise.

Map 3-7. Development of Overwash and Breaches near Fowler Beach

Where shoreline regression landward is not allowed, sea level rise can expedite coastal fringe marshes reverting to open water habitats sooner and quicker. Where wetlands are degraded, the reversion to open water can be even more rapid. As described in more detail in the next section, this disruption of natural coastal processes and resulting consequences in adjacent wetlands has become evident in the impoundment complex on the refuge.

Climate Change Adaptation and Vulnerability Assessment of Refuge Wetland Impoundments

Climate change and associated impacts such as sea level rise and increased storm frequency and severity are proving to be the defining wetland management issue for the refuge, increasing our challenges to managing the refuge's impounded wetland complex. Future climate change adaptation strategies used by the refuge must anticipate an increasingly different physical environment than the one in which we managed our impounded marshes from 1988 to the present. Numerous factors associated with climate change and coastal processes are interacting to affect the refuge's ability to conduct wetland management as it has been for recent decades, particularly in Unit II.

During the last phase of establishing the refuge impoundment in Unit II in 1988, DNREC required that the Service build up the duneline from the last house in Slaughter Beach (Unit I) to the first house on Prime Hook Beach in Unit II, which incorporated about 3 miles of shoreline. Although the Service felt it was not necessary, the State of Delaware reconfigured the natural barrier island berm in 1988 in anticipation of the potentially erosive effects of natural barrier beach movement. Artificial dunes were again rebuilt in 1992, 1998, 2006, and 2008 by the State, in coordination with the refuge. In 2006, a breach (mini-inlet) developed across the Unit I duneline, and in 2009 several breaches (1 large and 2 smaller inlets) of the duneline across Unit II occurred (map 3-7). Efforts to restore the dune line one more time while management and restoration plans could be developed were made by DNREC, in coordination with the refuge, in September 2011. However, Hurricane Irene (August 2011) had further depleted the affected shoreline of sand and the dune restoration failed shortly after completion, during a period of high tides and strong winds. As of the completion of this final CCP/EIS, the Unit II shoreline contains several persistent breaches, permitting salt water to continue entering Unit II. Much of Unit II has converted to open water as a result.

Numerous factors are influencing our management capability and the response of the managed wetland ecosystem. We have been striving to better understand the various components of this comprehensive system, which includes natural elements and processes as well as human-controlled infrastructure. Information about the state of the ecosystem, the physical processes at work, and the management investments that would be necessary to maintain the Unit II impounded marsh are outlined below. Although these management challenges most imminently affect Unit II, it is clear that the future of management in Unit III will be affected by these same factors.

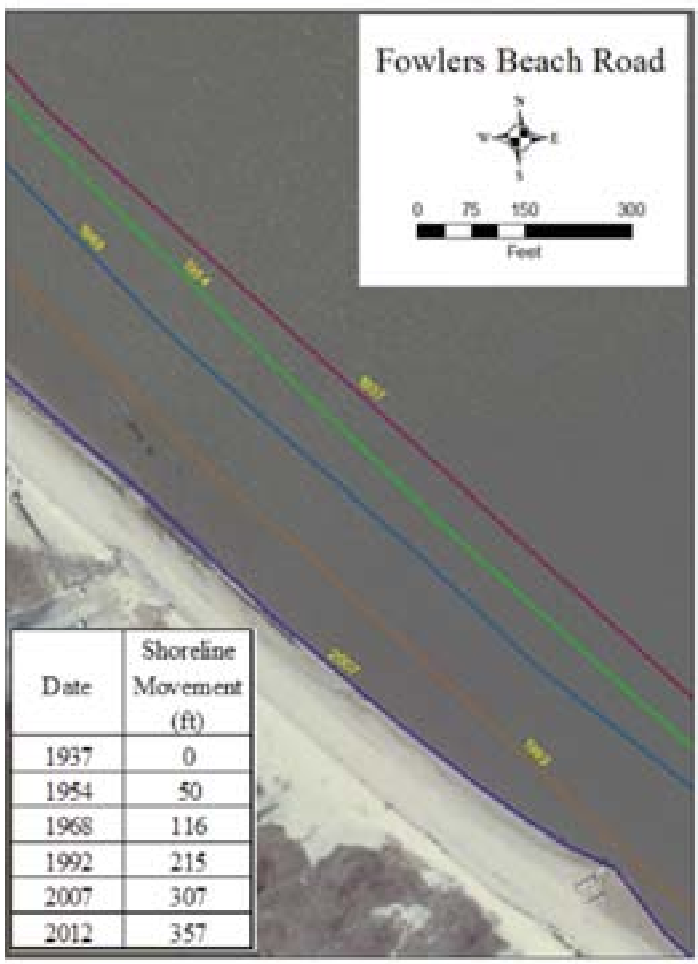
Washover and Beach Migration:
Starting in 2006 with tropical storm Ernesto, the natural beach barrier has been breached or overwashed numerous times. The physical forces that shape, move, and maintain barrier beach systems have been recognized by many government agencies and studied by coastal geographers for decades. Lewis et al. (2005), described the nature of fetch limited barrier islands, or those barrier islands typical of estuaries, in contrast to the ocean front. Of particular note is the relatively thin veneer of sand laid over a salt marsh base and the lack of significant wave energy outside of storm events necessary to maintain a relatively consistent beach profile. Large, continuous dunes, such as found along the Atlantic Ocean coast, are rare in estuarine environments.

Fetch limited barrier islands are backed by salt marshes and maintained in part by the overwash of beach and marine sediments. The direction of beach movement as periodic storms occur is landward. These events are natural and outside the control of refuge management. However, they impact refuge coastlines through creation of overwashes and landward migration of the shoreline. It is well established that these processes are natural and beneficial to salt marsh communities (Ashton et al. 2007), and are common along the Delaware Bay shoreline (Appendix J).

The rate of erosion and landward migration of the refuge shoreline along Unit II, in the vicinity of Fowler Beach, from 1937 to 2012 has been quantified using a series of historic aerial images (DNREC Coastal Programs unpub. data), and more recently ground measurements and observations (Psuty et al. 2010). It has been clearly demonstrated that the rate of shoreline erosion and retreat has been increasing during that time frame. Whereas the shoreline at Fowler Beach eroded 50 feet in the 17 years between 1937 and 1954, it later eroded 50 feet in only 5 years between 2007 and 2012 (Figure 3-4). The rate of erosion between 1937 and 1954 was under 3 feet/year, and increased steadily to a rate of 10 feet/year between 1997 and 2012 (Figure 3-5). This non-linear increase in the erosion rate will be problematic for refuge management for many years into the future (Figure 3-6).

In 2011, the refuge began tracking shoreline position seasonally following a detailed protocol developed and used widely by the National Park Service (Psuty et al. 2010). That protocol will allow more detailed observation of seasonal and annual changes in shoreline position, as well as shoreline responses to management and restoration actions in the future.

Figure 3-4. Shoreline erosion in the vicinity of Fowler Beach Road in Unit II. Shoreline position from 1937 was determined using aerial imagery. Shoreline position in 2012 was determined through ground measurements and observations (Courtesy of DNREC Delaware Coastal Programs)



Date	Shoreline Movement (ft)
1937	0
1954	50
1968	116
1992	215
2007	307
2012	357

Figure 3-5. Annual shoreline erosion rates in the vicinity of Fowler Beach Road in Unit II. Shoreline position from 1937 was determined using aerial imagery. Shoreline position in 2012 was determined through ground measurements and observations (Courtesy of DNREC Coastal Programs)

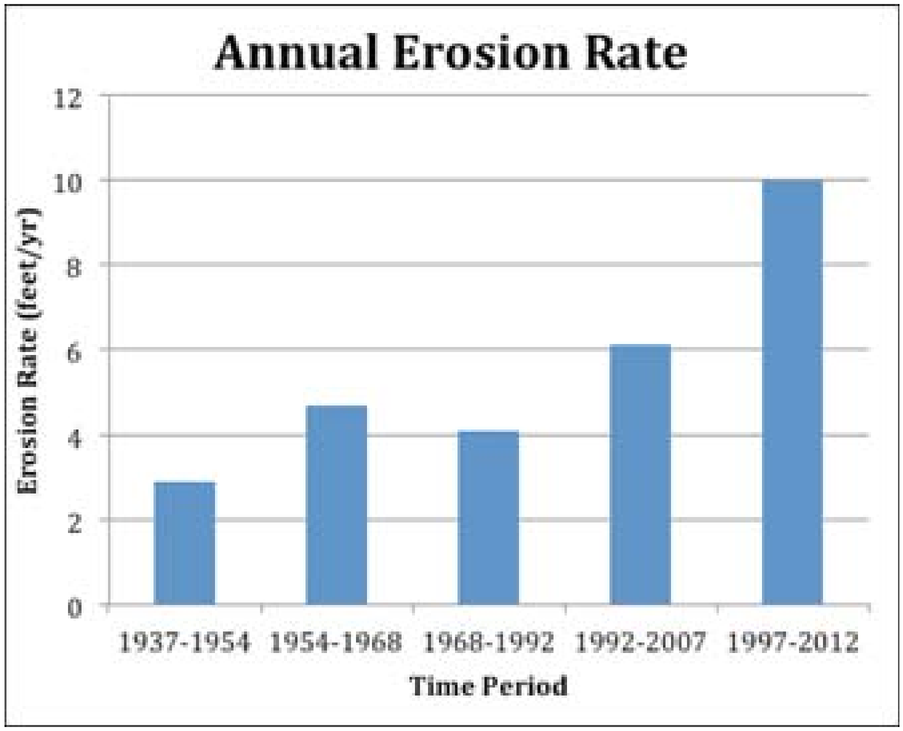
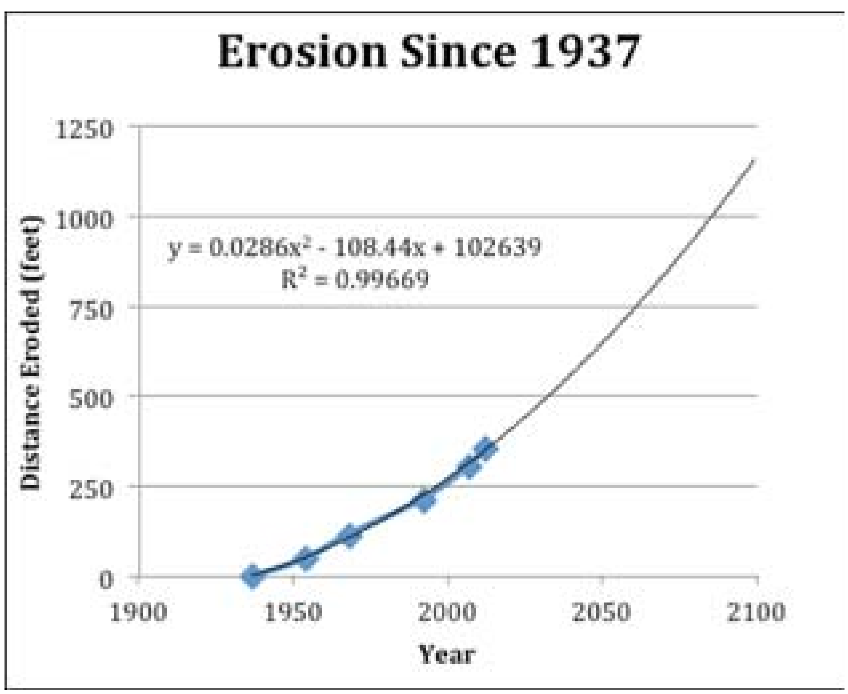
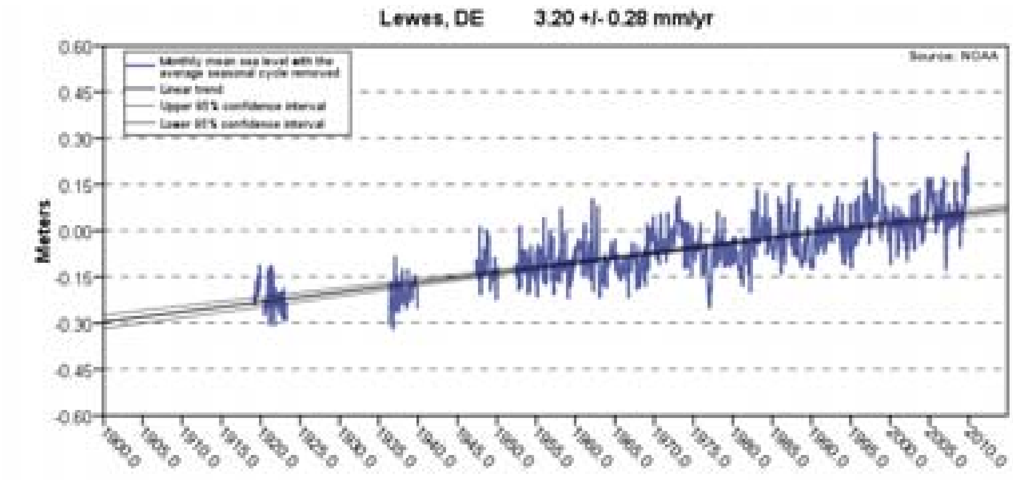


Figure 3-6. Trend of increasing annual shoreline erosion rates in the vicinity of Fowler Beach Road in Unit II. Shoreline position from 1937 was determined using aerial imagery. Shoreline position in 2012 was determined through ground measurements and observations (Courtesy of DNREC Delaware Coastal Programs, unpublished data)



Sea Level Rise:
Sea levels have been rising due to melting of major ice sheets after the last major glaciation 20,000 years ago and thermal expansion of ocean water as it warms (CCSP, 2009). The Atlantic coast was located about 180 miles to the east of its present location during the immediate post-glacial period and the ocean has risen over 100 meters (330 ft) since that period. Currently, the average annual local sea level rise (Figure 3-7), as measured at the NOAA tide gauge in Lewes, is 3.20 mm/yr since 1919, or 1.05 ft. in 100 years *(http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8557380;* accessed January 2012).

Figure 3-7. Mean Sea Level Trend for NOAA Tide Station 8557380–Lewes, Delaware Increasing Frequency of Above Average High Tides



No official tide data is currently being collected on or in the immediate vicinity of the refuge. Tide data for the nearby gauge at Lewes (DISTANCE) have been collected by NOAA since 1919. Although tides at the Lewes station are likely to read somewhat lower than at the refuge for high tide, the data will be adequate for analysis of long-term trends. We acquired the daily high and low tide data for Lewes for the period 1984 to 2009. We selected this period because all data were available in a format relative to a single baseline elevation, referred to as an epoch, and coincides with the history of impoundment management on the refuge. NOAA's Web-based interface *(http://tidesandcurrents.noaa.gov/;* access January 2012) outputs all high and low tides in relation to the mean higher high tide, or the average of the higher of two high tides that occur per day. We extracted all individual tidal events falling at or above mean higher high water. Figure 3-8 plots the total number of individual events by year for the period 1984 to 2009, and shows an increase over time in the frequency of higher than average tidal events. The total number of individual events above mean higher high water ranged from a low of 152 in 1988 to 323 in 2009.

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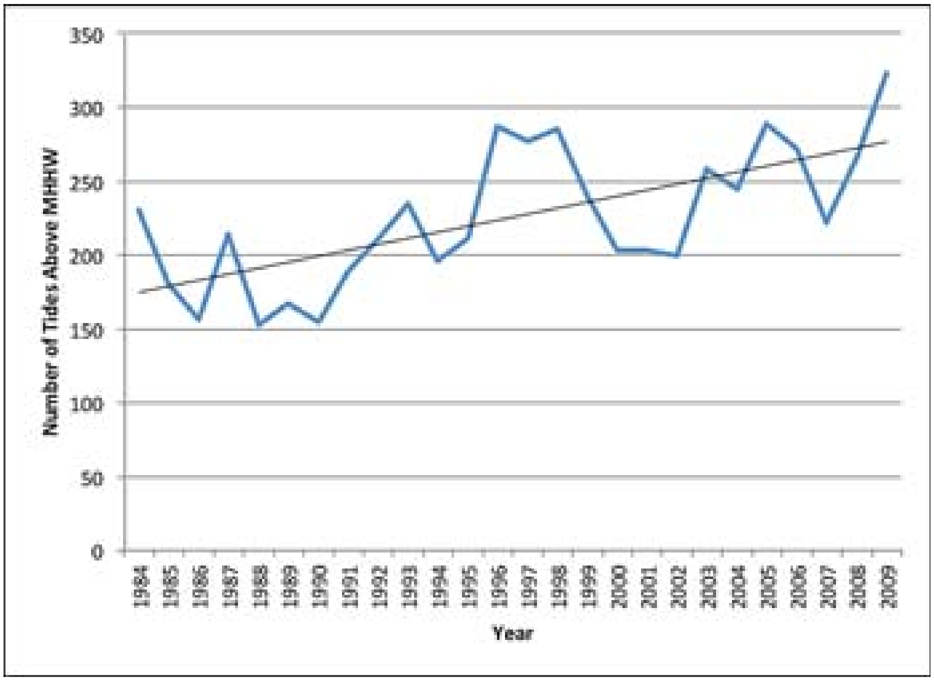
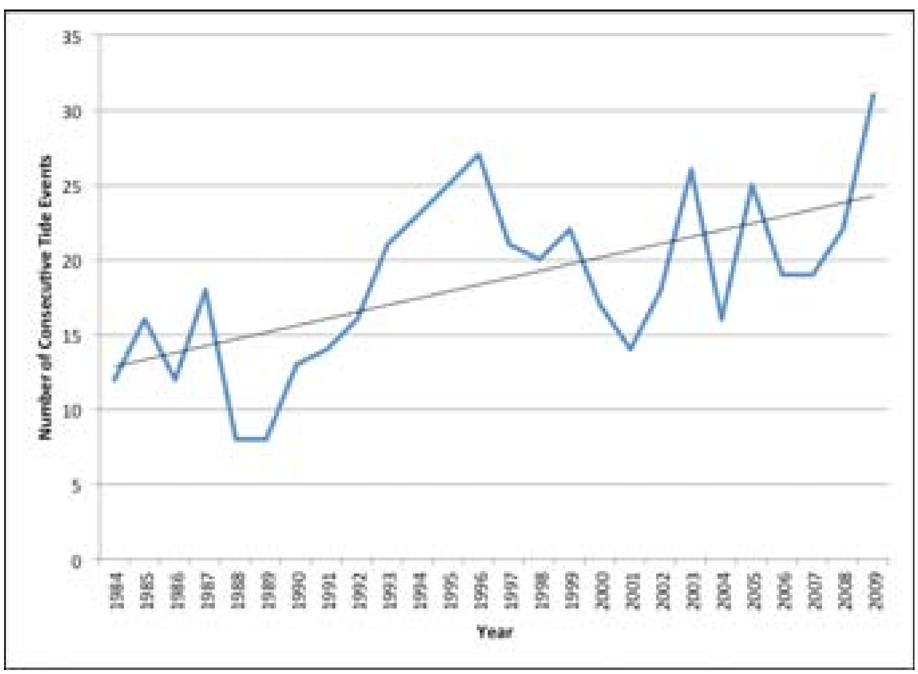
Short-billed dowitchers

Figure 3-8. Number of Individual High Tides Per Year Above MHHW Recorded at the Lewes, DE Tide Gauge



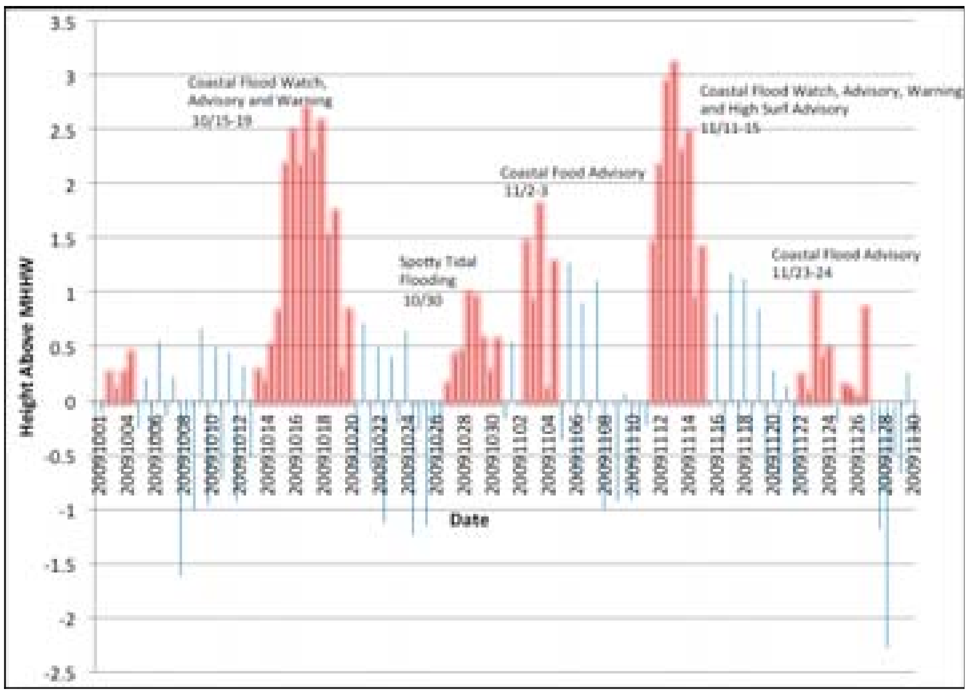
We also compiled consecutive above-normal high tide events, which are two or more consecutive high tides that were recorded at or above mean higher high water. Figure 3-9 shows an increase over time of the frequency of these events. The consecutive events ranged from 2 to 24, or the equivalent of 1 day to 12 days of consecutive high tides above mean higher high water. The total number of such events ranged from 8 in 1988 and 1989 to 31 in 2009.

Figure 3-9. Number of Consecutive High Tide Events Above MHHW Per Year Recorded at the Lewes, DE Tide Gauge



These figures show a general trend toward a higher frequency of individual above-average high tides, but perhaps more importantly, a higher frequency of consecutive above-average tides. This has important implications for the dynamics of tidal flooding, overwash, and beach migration along the Delaware Bay shore. More frequent periods of sustained high water in combination with high wave energy associated with storms contribute to erosion and overwash of natural beaches. To illustrate one period of particularly active high tide events, we have graphed all high tides occurring during October to November 2009 (Figure 3-10). The zero line on the Y axis represents mean higher high water. All highlighted red lines above mean higher high water represent periods of consecutive above average tides. The periods range from 4 to 14 consecutive tides, or the equivalent of 2 to 7 days. As noted, five of the seven highlighted periods were accompanied by NOAA coastal flood watches, advisories, warnings, and in one case during the period November 11 to 15, a high surf advisory. Much of the undeveloped region along the Delaware Bay shore sustained significant breaching and overwash during these events. As a result of a breach, much of refuge Unit II was opened to daily tidal flow.

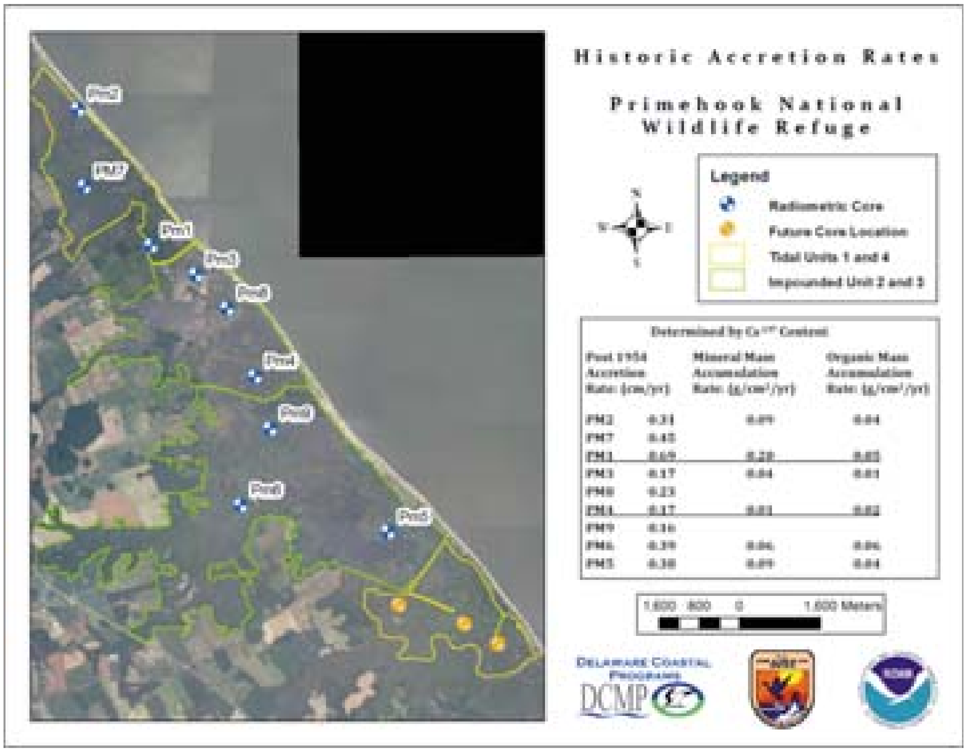
Figure 3-10. Consecutive High Tide Events Above MHHW During Oct–Nov 2009



Wetland Elevation:

Under natural conditions, salt marshes build elevation by trapping sediment during flood events, building up below ground biomass (e.g. roots and rhizomes), and accumulating organic matter (Cahoon et al. 2009). The accretion of marsh elevation must be maintained in relation to sea level or the marsh will drown, deteriorating and leaving open water in its place. Analysis of sediment cores for the presence of radioisotope fallout (^{137}Cs and ^{210}Pb) deposited at a known time in the past can provide a measure of marsh accretion over recent decades. Preliminary data from radiometric coring conducted by DNREC's Coastal Program, in partnership with the University of Delaware (UD), indicate that the salt marshes in refuge Units I have been accreting over approximately the last 50 years at a rate nearly equal to or greater than the current local sea level rise of approximately 3.2 mm/yr (Figure 3-11). However, the average rate of accretion for the same period in the Unit II is 1.7 mm/year, nearly half of the sea level rise rate.. While the average accretion rate for the southern half of Unit III was determined to be 3.85 mm/year, a core in the northern half of Unit III suggests accretion in that portion is only 1.6 mm/year – the lowest recorded anywhere in the state of Delaware during the DNREC/UD study (Figure 3-11). It should be noted that these estimated accretion rates are an average for about the past 50 years, and the current management regime has only been in place for a portion of that time.

Figure 3-11. Historic accretion rates within refuge wetlands and impoundments as determined by analysis of radiometeric core (137Cs content). (Courtesy of DNREC Delaware Coastal Programs and University of Delaware, unpublished data).



In addition to radioisotopic cores, the Delaware Coastal Program conducted elevation surveys of the various wetland units utilizing real-time kinematic GPS survey techniques. The surveys documented the difference in elevation between the wetland vegetation and open water areas. In some areas, less than an inch of elevation stands between the existing vegetation and open water/mud flat (appendix K). Marshes with such a small amount of elevation capital are the most vulnerable to increases in sea level (Cahoon and Guntenspergen 2010). As of the preparation of the final CCP/EIS, elevation/bathymetric data throughout the wetland complex was being updated again using new sonar technology ideal for collecting such data in shallow water environments. Because the elevation of the impoundments is barely above sea level, they are susceptible to salt water inundation in the short term during coastal storm events, unless and until additional sediment is present to increase the elevation. New and proposed marsh elevation monitoring (surface elevation tables and marker horizons) on the refuge will add additional critical data to our understanding of short-term accretion within the impoundments under current management regimes, as we evaluate refuge wetland management options, and as we monitor the impacts of future management actions.

The potential effects of sea level rise on refuge land cover have been modeled through the sea level affecting marshes model (SLAMM) effort described in chapter 2. The model was applied utilizing inputs representing a range of possible future scenarios. It is anticipated that the reality could fall anywhere within these predicted outcomes. As an example, if sea level rises as predicted by the A1B greenhouse gas emission scenario in the Special Report on Emissions Scenarios (IPCC 2000), the total sea level increase on the refuge would be 0.50 meters in 100 years. If the model assumes that salt marsh accretion keeps pace with current sea level rise rates and that there is full tidal influence along the coast, then the refuge is predicted to lose more than half of its marsh and the amount of open water and tidal mudflat (combined) will more than quadruple (Figure 3-12). If the model assumes that salt marsh accretion will increase to 5.0 mm/yr, keeping pace with sea level rise as salt marshes often can, then the loss of marsh is small and conversion to open water and tidal mud flat are not as pronounced (Figure 3-12). In both cases, more than half of the upland is predicted to be lost. The primary difference is whether or not the remaining areas are maintained in some form of wetland cover or are converted to open water, which may depend on marsh accretion processes. Under each sea level rise and marsh accretion scenario, if the model assumes that coastal dunes will instead be maintained, these predictions do not change appreciably. Results for additional scenarios, such as an increased rate of sea level rise, can be found in Scarborough (2009).

An updated version of SLAMM (6.0.1) is now available, but was not available at the time the analysis was completed for the refuge. Although modeling data should be considered with caution, as high levels of uncertainty and unforeseeable factors can significantly alter model output projections and habitat predictions for the future, the results of this modeling effort can give us a general sense of how climate change and sea level rise will likely affect refuge habitats in the future. The potential land cover changes predicted by the SLAMM modeling are considered in the development of management objectives and strategies (chapter 4). However, these modeling results are certainly not the primary factor driving evaluatoins of shoreline and wetland management regimes on the refuge, as the refuge increasingly has current locally collected data to rely upon.

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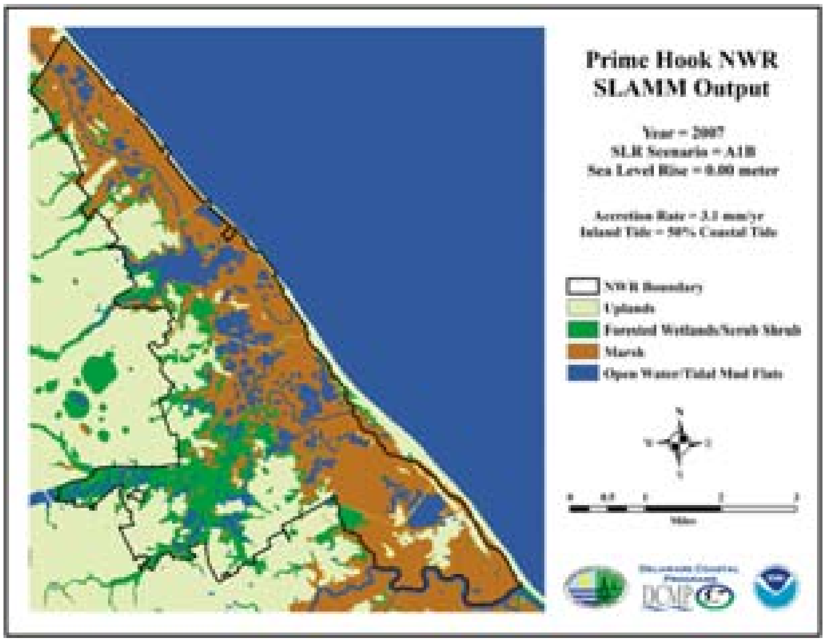
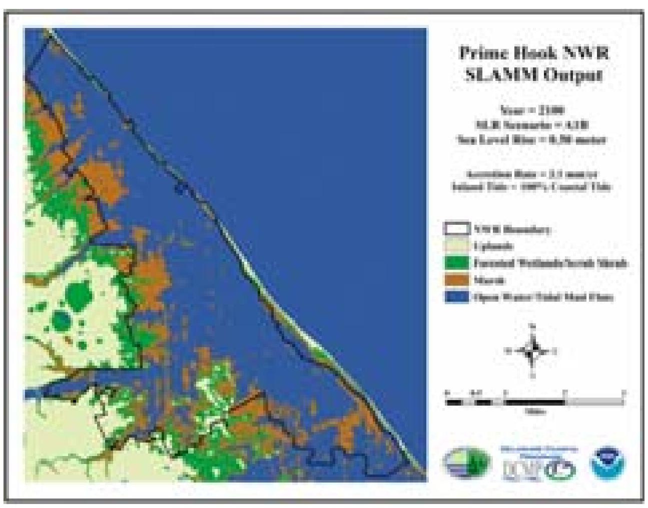
Diamondback terrapin

Figure 3-12. Selected SLAMM Output Maps from Scarborough 2009. (A) = Current (2007) land cover; (B) = 2100 Predicted land cover assuming 0.5 meters of sea level rise, marsh accretion keeping pace with current sea level rise (3.1 mm/yr), and full tidal influence

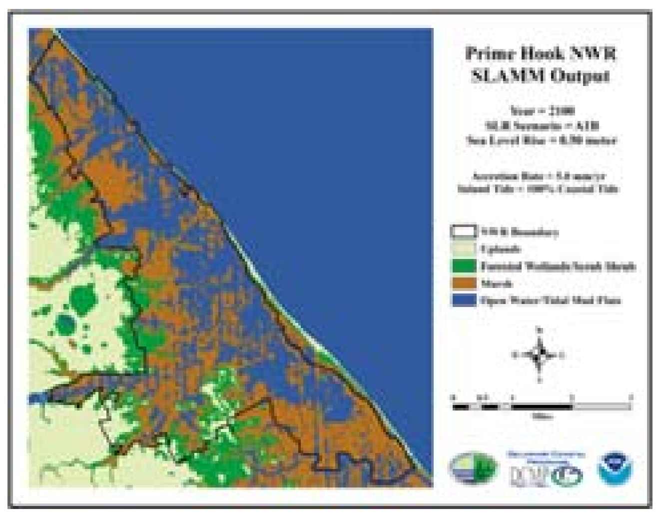
(A)



(B)



(C)



The Cost of Infrastructure Rehab/Replacement:
To maintain Unit II as a freshwater system, it is anticipated that significant infrastructure rehabilitation or replacement would be necessary. A cost analysis included three factors: dune construction, water control structure redesign and replacement, and elevating two State roads, Fowler Beach Road and Prime Hook Road.

Dune Construction
No formal beach management plan has been developed for Prime Hook NWR beaches. However, we can use the data provided in the management plan for Delaware beaches completed in March 2010 to make some rough estimates. Table

3-12 provides estimates for design, permitting, construction, and monitoring of existing sand dunes within the neighboring communities of Slaughter Beach and Prime Hook Beach. Design scenarios and their associated costs are estimated based on the projected average return interval of storm events that result in a particular degree of severity and resulting storm damage. The State's analysis considered the dune design that would be required to withstand a 5 or a 10-year storm. For example, a five-year storm is a severe storm that is expected to hit our area one year in five. Another way of stating it is that there is a 20 percent chance that we will experience a five-year storm in any given year. Similarly, one can expect a 10-year storm on average once every 10 years, or a 10 percent chance of having the storm in any one year. The actual number of years between storms of any given severity varies because of the naturally changing climate. It is possible to have more than one five-year storm in a year. Therefore, beaches that endure damage from successive five-year storms would require reconstruction on a more frequent basis. In addition to the 5 and 10-year scenario, the State has projected costs for strategic fill, i.e., fill placed along the specific locations of greatest need.

American oystercatcher

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Table 3-12. Cost Estimates from DNREC Beach Management Plan Associated with Dunes within Slaughter Beach and Prime Hook Beach communities

	Prime Hook Beach					Slaughter Beach				
Strategic Fill Placement	**Budget Estimate**									
Project Element	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**
*Geotechnical Investigation	$45,193.00				$45,193.00	$139,802.00				$139,802.00
*Design/Permitting	$22,596.00				$22,596.00	$69,901.00				$69,901.00
Construction				$416,835.00	$416,835.00				$499,975.00	$499,975.00
Env. Permit Monitoring				$17,500.00	$17,500.00				$17,500.00	$17,500.00
Beach Survey	$8,000.00	$8,000.00	$8,000.00	$8,000.00	$36,000.00	$16,000.00	$16,000.00	$16,000.00	$16,000.00	$64,000.00
Total	$75,789.00	$8,000.00	$8,000.00	$442,335.00	$534,124.00	$225,703.00	$16,000.00	$16,000.00	$533,475.00	$791,178.00
5 Year Scenario										
Project Element	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**
*Geotechnical Investigation	$45,193.00				$45,193.00	$139,802.00				$139,802.00
*Design/Permitting	$22,596.00				$22,596.00	$69,901.00				$69,901.00
Construction				$787,800.00	$787,800.00				$2,112,800.00	$2,112,800.00
Env. Permit Monitoring				$35,000.00	$35,000.00				$70,000.00	$70,000.00
Beach Survey	$8,000.00	$8,000.00	$8,000.00	$8,000.00	$36,000.00	$16,000.00	$16,000.00	$16,000.00	$16,000.00	$64,000.00
Total	$75,789.00	$8,000.00	$8,000.00	$830,800.00	$922,589.00	$225,703.00	$16,000.00	$16,000.00	$2,198,800.00	$2,456,503.00
10 Year Scenario										
Project Element	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**	**FY10/11**	**FY11/12**	**FY12/13**	**FY13/14**	**Total**
*Geotechnical Investigation	$45,193.00				$45,193.00	$139,802.00				$139,802.00
*Design/Permitting	$22,596.00				$22,596.00	$69,901.00				$69,901.00
Construction				$1,522,800.00	$1,522,800.00				$3,680,800.00	$3,680,800.00
Env. Permit Monitoring				$35,000.00	$35,000.00				$70,000.00	$70,000.00
Beach Survey	$8,000.00	$8,000.00	$8,000.00	$8,000.00	$36,000.00	$16,000.00	$16,000.00	$16,000.00	$16,000.00	$64,000.00
Total	$75,789.00	$8,000.00	$8,000.00	$1,565,800.00	$1,657,589.00	$225,703.00	$16,000.00	$16,000.00	$3,766,800.00	$4,024,503.00

*Notes: The costs for these items are proportional to total volume placed for all of the seven communities included in this management plan

Renourishment costs based on restoring 60 percent of initial volume to restore historic losses; costs are based on work being performed on a regional basis; costs shown are in July 2009 prices.

The costs range from $534,124 to $1,657,589 for the three scenarios at Prime Hook beach, and from $791,178 to $4,024,503 at Slaughter Beach. We have no cost estimates at this time for dune construction along the overwashed portion of Unit II barrier beach. The combined linear footage of privately and refuge owned beach along Unit II, of which only 60 percent is refuge owned, is approximately 1.5 miles. The 5 and 10-year scenarios at Prime Hook Beach are to be conducted along nearly 1.5 miles of beach, as well. It would therefore be reasonable to expect that the costs of constructing a dune along Unit II would be comparable with the costs of dune construction at Prime Hook Beach.

There are, however, some very important differences between the Prime Hook and Unit II beaches. First, active beach management has been occurring at Prime Hook beach to some degree throughout the years. Prime Hook beach has an intact dune system that is currently elevated several feet above mean high water. Conversely, the Unit II barrier has largely succumbed to natural overwash events, leaving small isolated dunes. The berm typically overwashes over much of its length during storm events. Additionally, there are 2 active inlets, currently on private land, that receive at least some tidal flow during most high tide events. We, therefore, conclude that the cost of strategic placement of sand as listed for Prime Hook beach is not a useful figure for comparison because strategic placement assumes supplementing an intact dune system. Since the existing berm along Unit II is barely above mean high water, a considerably larger quantity of sand, and a much higher cost, would be required to achieve the 5 or 10-year specifications considered adequate for Prime Hook beach. The costs of dune construction on Unit II may approach the cost of construction for 2.7 miles of Slaughter Beach, or as high as $4,000,000.

Table 3-13 summarizes the length of beach, quantity of sand required for initial fill, quantity of sand required in subsequent years, the return maintenance interval and cost of construction alone, without permitting, design, and monitoring costs. The maintenance intervals are 4, 5, and 10 years, respectively for strategic, 5-year and 10-year scenarios. Maintenance would be required more often if storm severity or frequency becomes more intense in the years after initial treatment.

Table 3-13. Summary of Material Requirements and Costs for Construction of Dunes According to DNREC Beach Management Plan

					Maintenance	Initial Constr.
	Berm Length	Berm Width	Berm Elev. (NAVD 88)	Initial Fill	Placement (Interval)	Cost Only
Prime Hook Beach						
Strategic	2,800′	20′	7.2′	24,000 cy	14,400 cy (4 years)	$416,835.00
5 Year	7,500′	20′	7.2′	71,000 cy	36,600 cy (5 years)	$787,800.00
10 Year	7,500′	55′	7.2′	176,000 cy	105,600 cy (10 years)	$1,522,800.00
Slaughter Beach						
Strategic	2,500′	15′	7.5′	36,500 cy	21,900 cy (4 years)	$499,975.00
5 Year	14,500′	15′	7.5′	252,500 cy	151,500 cy (5 years)	$2,112,800.00
10 Year	14,500′	55′	7.5′	476,500 cy	285,900 (10 years)	$3,680,800.00

Importantly, if the purpose of dune reconstruction is to provide an intact barrier to artificially maintain fresh water marshes, then constructing a berm with the assumption that it will be intact only in the face of a 5 or 10-year storm will not sustain a fresh water marsh system. Since fresh water marshes are very vulnerable to rapid increases in salinity, a barrier system should be designed to withstand, at least, a 30-year storm, otherwise the marsh vegetation and obligate fresh water biota can be expected to die frequently. A berm of this magnitude, with accompanying periodic replenishment, will increase costs, not by a factor of three above the 10-year costs, but more geometrically, because the commensurate increase in sediment requires substantially more sand to be placed over a far broader footprint, as well as formed into a higher berm.

Water Control Structures
In addition to the dunes, the three water control structures are maintained to manage water levels within the impoundment. The replacement costs of the three water control structures and associated levees are listed in table 3-14.

Table 3-14. Replacement Costs of Refuge Water Control Structures

Water Control Structure/Levees	Estimated Cost
Prime Hook Creek WCS	$436,000.00
Petersfield WCS	$852,040.00
Petersfield West Dike	$463,610.00
Petersfield East Dike	$208,311.00
Fowler Beach WCS	$1,033,725.00

Although the Prime Hook and Petersfield structures play a role in the Unit II water management, only the Fowler Beach water control structure is used for this analysis. The replacement of the structure would cost approximately $1,033,725, but could cost more. Even if the structure is replaced, the refuge can only manage water levels to 2.8 feet mean sea level (msl), according to deed restrictions. But, mean sea level in 1981 is different from mean sea level today. The deed is recorded in Deed Book 1097, page 249. Currently, larger storm events have overtopped the existing structure, allowing water in excess of 2.8 feet msl to enter the impoundment. Rising sea levels, subsidence, and other factors make it unlikely that the refuge will be able to manage water levels in the future. Saltwater intrusion is inevitable at the water control structures as we lose control to the rising seas.

Further complicating our water management challenges is the fact that the water control structures are sitting at an elevation different from the original planned construction elevation. Although we do not know the exact post-construction elevations of the water control structures, we assume they were very close to the planned elevations. In 2010, the Delaware Coastal Program resurveyed our water control structures to determine their current elevation. Subsidence of both upland and the marshes in the Delaware region is extensive, but varies based on local conditions. The results (table 3-15) show that the water control structures are lower than their planned construction elevations by approximately 5.8 to 11.25 inches. This data further supports our assumption that we will lose water management capabilities in the near future. See appendix K for further details.

Table 3-15. Estimated Subsidence of Refuge Water Control Structures

Water Control Structure	Suspected subsidence (inches)
Prime Hook Creek WCS	11.25″
Petersfield WCS	10.07″
Fowler Beach WCS	5.83″

Integrity of Road Infrastructure:
There are three roads crossing the marsh to the barrier island, forming the dikes on the northern and southern borders of Units II and III. These roadways, built in the 1950s and 1960s at relatively low elevation, have sustained numerous tidal overwashes in recent years. In 2009, the State conducted elevation surveys of the roads for analysis. Figure 3-13, Figure 3-14, and Figure 3-15 illustrate the results of those surveys for Fowler Beach, Prime Hook, and Broadkill Road, respectively. Road elevation has been plotted in relation to the local mean higher high water elevation (red line). For each road, significant portions of the road (blue line) lie below mean higher high water, suggesting that the roads may have subsided. These roads routinely flood during forecast NOAA coastal flood events. As sea levels and high tide events continue to increase, the ability of these roads to serve as dikes will be reduced.

Figure 3-13. Elevations along Fowler Beach Road in relation to MHHW along the segment depicted in red on the map

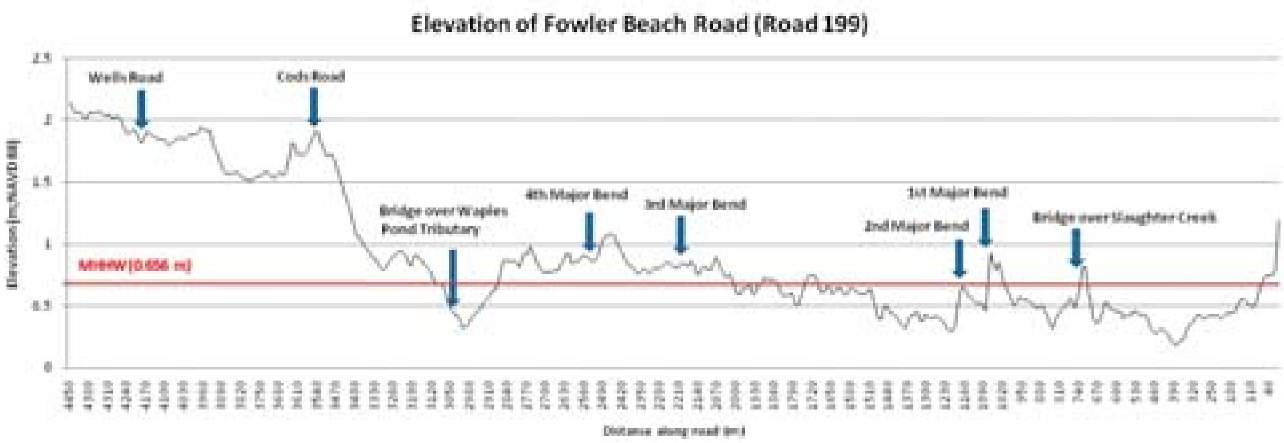


Figure 3-14. Elevations along Prime Hook Road in relation to MHHW along the segment depicted in red on the map

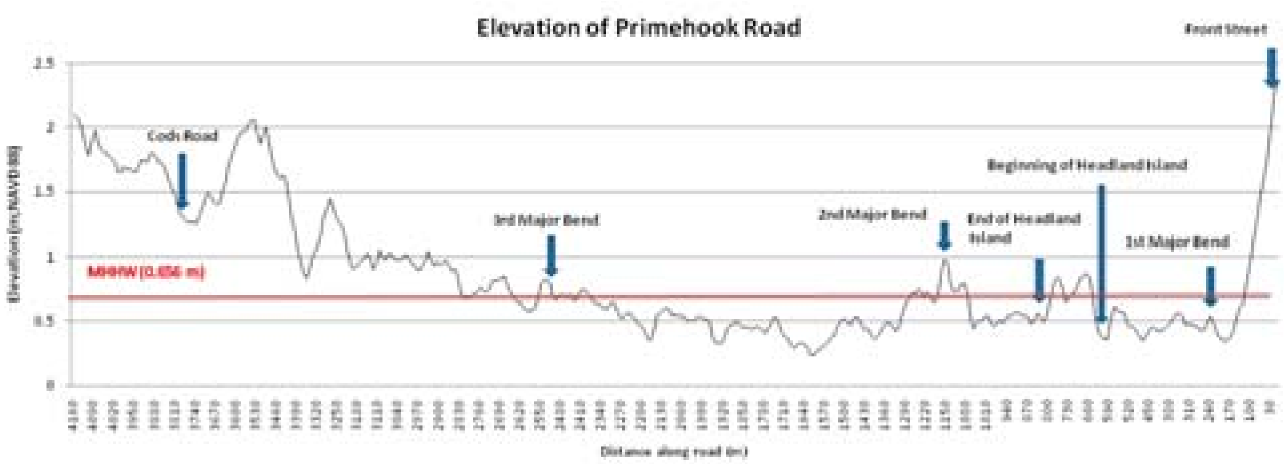
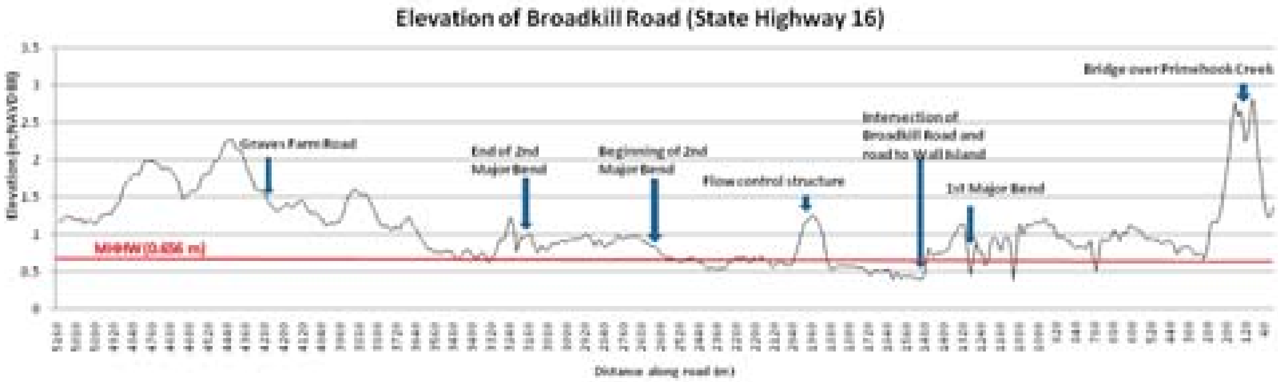


Figure 3-15. Elevations along Broadkill Beach Road in relation to MHHW along the segment depicted in red on the map



Delaware Department of Transportation (DelDOT) currently owns a 50-foot right-of-way easement on Prime Hook and Fowler Beach Roads. Additionally, it owns a 60-foot right-of-way along U.S. 16, also known as Broadkill Road. DelDOT is the responsible agency for the construction and maintenance of these roads.

There are a number of different options to consider for each roadway area that could be affected by restored tidal flows. These include raising the roadway elevation in its current location, tolerating a certain degree or frequency of flooding, and/or abandoning a specific road or portion of road, subject to DelDOT approval and procedures. Hydraulic analysis would be necessary before raising any road crossing the marsh. Some of these roadways are well-traveled and provide access for residents. Prime Hook and Fowler Beach Roads are not adjacent to higher ground, but may need widening. In order to raise these roadways and avoid costly retaining wall construction, the toe of each roadway embankment would need to extend horizontally into adjacent wetland resource areas.

Some low-lying roadways along the coast have historically been subjected to varying degrees of flooding during coastal storms. When such flooding is infrequent, such as during storm events, the effect on the public may be minimal and can be accommodated. Issues to consider include public health and safety relative to access. This would require further assessment as more detailed hydrologic analyses are conducted. At Fowler Beach Road, abandonment may be an option. Any decision on such roadway abandonment would be subject to public hearings in nearby towns.

Planning for reconstruction of these roads must also include an assessment of impacts to fire department and emergency medical vehicle access routes and alternative access options. The refuge has long-standing mutual aid agreements with Milton Fire Department, Inc. and the Memorial Volunteer Fire Department of Slaughter Beach. These agreements need to be updated to better describe the authority and responsibility and to include other emergency situations on refuge lands or adjacent to the refuge.

To maintain a freshwater system, these roads need to be elevated 2 to 4 feet with the sides sloped at a ratio of 3:1. Costs will easily exceed $1 million per road. Some estimates put the costs closer to $2 million per road (Service's cost-estimating guide). It should be noted that if Fowler Beach Road is abandoned, costs may be considerably less. Instead of a road, a levee or other type of barricade could serve the same purpose at a fraction of the cost. In either scenario, costs for road elevation and/or levee construction would range from over $1 million to $4 million.

Management Implications:
Significant environmental, physical, structural, monetary, and regulatory hurdles need to be addressed to maintain freshwater impoundments on Prime Hook NWR. The SLAMM model and the State's inundation maps (DNREC, unpublished) predict accelerated rates in sea level rise in the next 50 to 100 years. Portions of the refuge's marshes or impoundments may have already reached a tipping point. It is important to note that the time frame of impoundment management has been relatively short on the refuge, in relation to the time frame of natural coastline processes. Relatively speaking, freshwater impoundment management is not a long-standing management regime on the refuge but was conceived to meet valid wildlife management objectives. It was established, in part, using existing roads, which had not been formally engineered for long-term water level management as dike infrastructure.

Preliminary data indicate portions of our managed impoundments may be losing ground to sea level rise. Unit II, for example, is accreting new sediment at a pace that is half the documented rate of local sea level rise. It is not reasonable to expect that such a large deficit in elevation-capital can be recovered within Unit II under current freshwater impoundment management strategies. Freshwater marshes dominated by annual vegetation differ from salt marshes in that predominantly annual wetland plants contribute to high above-ground biomass, whereas the persistent below-ground organic matter of perennial vegetation, such as that found in tidal salt marshes, makes greater contributions to vertical accretion (Cahoon et al. 2009). This means that the vegetation in salt marshes build up the elevation of the marsh and that freshwater marsh plants do not, so that salt marsh can be sustained in light of rising sea levels but freshwater plants not only die if flooded by salt waters, they also leave the marsh substrate at a depressed elevation compared to salt marsh species.

Biological Resources of Delaware Bay Estuary

The Delaware Bay Estuary is an important ecosystem recognized nationally, internationally, and globally as a resting and feeding area for millions of migrating birds each spring and fall. It supports rare and endangered species, supports commercial fisheries, and acts as a major horseshoe crab spawning ground on the East Coast. It is an ecosystem where many biogeographic provinces come together, resulting in overlapping habitat types and high biodiversity. The increase in economic pressures on these habitats of the Delaware Estuary dictates that remaining natural uplands and wetlands conserved for wildlife will require extra protection and conservation efforts in the future (Webster 1996).

There are three major ecological zones of the Delaware Estuary, which are distinguished by differences in salinity, turbidity, and biological productivity. The upper zone is tidal freshwater and extends from Trenton to Marcus Hook. The transition zone, which extends from Marcus Hook to Artificial Island, has a wide salinity range (0 to 15 ppt) and is characterized by high turbidity and low biological productivity. The lower zone, where Prime Hook NWR is located, is open bay and extends to the ocean. It has higher salinity distributions fluctuating from polyhaline to euhaline waters (18 to 30 ppt), broad areas of fairly shallow water (less than 9 meters), and over 90 percent of the primary biological productivity of the three zones (Partnership for the Delaware Estuary 1996).

Land use is a term that refers to the way land is developed or conserved. Demographic predictions provide compelling evidence for planning growth and protecting natural resources. Nine of the ten most densely populated U.S. counties are in the Northeast. Because of our love of the water, almost half of the U.S. population now lives in coastal areas, including along the shores of estuaries.

This population trend is accelerating and coastal counties are growing three times faster than anywhere else in the nation.

Escalating population growth and the demand for new housing, shopping centers and places of employment are projected to rapidly continue throughout the Delaware River basin region between now and 2020 with an overall increase of 14 percent. The States of Delaware and New Jersey are expected to see population increases of 24.3 percent and 21.5 percent respectively, by that date. By 2020, projected development increases of 14 percent will affect over 50 percent of the total land area within the region, leaving less than 50 percent of the land cover in agricultural, wooded, open space, or water (Seymour 1994). Major problems and future threats for living resources of the Delaware Estuary are identified in the 1996 comprehensive conservation management plan.

The Delaware Estuary is one of the most heavily used estuary systems in the nation. The estuary supports one of the world's greatest concentrations of heavy industry, and the second largest oil refining and petrochemical centers in the U.S. About 70 percent of transported oil (over one billion barrels of crude and refined oil products) reaches the east coast of the U.S. through the Delaware Estuary by way of the ports of Philadelphia, Camden, Gloucester City, Salem, and Wilmington. The estuary also receives wastewater discharges from 162 industries and municipalities and approximately 300 combined sewer overflows. The Delaware River basin supplies 10 percent of the U.S. population (20 million people) with water for drinking and industrial uses. Much of this water is transferred out of the basin through runoff into the Delaware Estuary (Partnership for the Delaware Estuary 1996).

Phytoplankton are the dominant source of organic matter for most of the Delaware Estuary's biological communities forming the base of the food web. The phytoplankton in the estuary are relatively healthy despite high-nutrient concentrations and turbidity. The primary consumers of phytoplankton in the estuary are zooplankton. Copepods dominate the zooplankton and directly consume a high percentage of the phytoplankton (primary production) in the lower bay or zone three.

Marine mysids or small shrimp-like crustaceans also play a critical role in the Delaware Estuary food web. While mysids are often associated with bottom communities, they can also be found in the water column and in this way regularly make up a large part of the zooplankton. At times they are very abundant and serve as a significant food resource for juvenile fish.

Benthic organisms are important consumers and a major link in the food chain between primary producers and higher trophic levels such as fish, shellfish, birds, and other wildlife. The annual production of a healthy blue crab fishery is important to the Delaware economy. Water quality does not appear to be affecting these populations. Benthic organisms are also excellent indicators of the overall ecological health of the estuary due to their sensitivity to pollution exposures. Because benthic organisms stay in one place, they are affected by the pollution at a site over the long term.

The Delaware Bay horseshoe crab *(Limulus polyphemus)* population is the largest in the world and a key species in the estuary, which is the epicenter of spawning activity along the Atlantic coast. In addition to providing food for migratory shorebirds, the horseshoe crab is economically important, as bait and in the manufacture of products used for medical testing of drugs and presence of bacteria and for surgical sutures and implants. Limulus amoebocyte lysate (LAL), a clotting agent in horseshoe crab blood, has made it possible to detect human pathogens like spinal meningitis in patients, drugs, and intravenous equipment.

To obtain LAL, manufacturing companies catch large horseshoe crabs (mostly females) and collect a portion of their blood. The LAL test is currently the worldwide standard for screening medical equipment for bacterial contamination, and any drug produced by a pharmaceutical company must pass an LAL screening. No other known procedure has the same speed and accuracy as the LAL test, and if LAL were to become unavailable, there is no universally accepted, ready substitute yet available (ASMFC-PID 1995).

The socioeconomic impacts of horseshoe crabs are extensive. Horseshoe crabs are the primary bait for the American eel and conch fisheries in most Mid-Atlantic States. In 1996, the commercial harvest of these crabs was estimated to be $5 million. As part of the medical research and pharmaceutical products industry, the worldwide market for LAL is about $50 million per year. The biomedical industry pays about $375,000 annually for an estimated harvest of 250,000 horseshoe crabs. Eco-tourism is also critical to New Jersey and Delaware in relation to horseshoe crabs' dependence on a healthy bay estuary, and the horseshoe crab-shorebird connection. The 1996 regional economic impact of expenditures made by wildlife watchers in New Jersey and Delaware created 15,127 jobs and generated a total household income of $399 million (ERDG 2006).

The overharvesting of horseshoe crabs in the late 1800s to early 1900s for the fertilizer industry and again in the 1990s for bait used in the conch and eel fisheries has caused their populations in the estuary to decline. Since 1998, red knots *(Calidris canutus)*, which are highly dependent on horseshoe crabs spawning in dense numbers, have fallen from possibly as high as 150,000 to as low as 15,000. By 2000, the Atlantic States Marine Fisheries Commission implemented a state-by-state cap of horseshoe crab bait landings by 25 percent. In 2004, harvest in New Jersey and Delaware was further reduced to 150,000 per state and included a seasonal ban from May 1 through June 7. In 2006, additional reductions were imposed, eliminating all harvest of female horseshoe crabs and reducing the harvest of males to 100,000, in addition to expanding the seasonal ban from January 1 to June 7. As a result of these restrictions, Atlantic coastal states collectively reduced horseshoe crab landings by 75 percent in 2005 (ASMFC 2006).

On March 7, 2001, the Carl N. Shuster, Jr. Horseshoe Crab Reserve, which encompasses 1,500 square miles of Federal waters off the mouth of the Delaware Bay, was established by the National Marine Fisheries Service (NMFS) to prohibit the harvest of horseshoe crabs in these Federal waters. This action was taken to further the goal of the fishery management plan for *(Limulus polyphemus)* of "managing horseshoe crab populations for continued use by current and future generations of the fishing and non-fishing public (including the biomedical industry, scientific and educational research; migratory shorebirds; and other dependent fish and wildlife (including federally listed sea turtles)" (ASMFC 1998).

In 2006, New Jersey and Delaware took action to ban all harvest of horseshoe crabs in their states to address concerns of the declining population of red knots. Delaware's ban was overturned in court, but New Jersey was able to maintain its ban and in 2008 succeeded in getting legislation passed that implemented a ban that would remain in place until red knots have sufficiently recovered. In 2009, work was completed on an adaptive management framework for the management of horseshoe crabs in support of red knots (ASMFC 2009).

Dragonflies. More than 100 species of Odonata occur in the Delaware Estuary. Damselflies and dragonflies (Odonata) have received increased attention as indicators of the health of wetland habitats. Activities that adversely affect water quality or alter specific habitats can eliminate odonate species or alter the composition of an area. The alteration of aquatic environments through channelization, siltation, draining, or chemical spraying has resulted in notable recent declines in many odonates throughout their ranges (Carle 1991). Because odonates are widespread and inhabit all wetlands, their absence could be an early indication of environmental degradation from a variety of sources. Odonates are beneficial to man by consuming large numbers of mosquitoes (Barber 1995).

Fish. More than 200 fish species, both residents and migrants, use the Delaware Estuary. The residents include fresh and saltwater species like the white perch which has a broad range of salinity tolerances. Resident species conduct all aspects of their life history within the estuary. Migrant species are highly dependent on the estuary for spawning habitats and nursery and feeding grounds. Ocean migrants include both warm and cool water species. A large number of migrants, such as the herrings and shad, are anadromous, living in ocean water but migrating to fresh water to breed. One species, the American eel, is catadromous, living in fresh or brackish waters and migrating downstream toward the ocean to reproduce. In the Delaware Estuary, the American eel is a very important resource from both a biodiversity and human use perspective. In all its life stages, eel serves as a prey species for many species of fish, aquatic mammals, and fisheating birds. Eel continue to support valuable commercial, recreational, and subsistence fisheries in the bay.

Major fish species in the Delaware Estuary include various sharks, skates and rays, shortnose and Atlantic sturgeon, American eel, blueback herring, alewife, American shad, Atlantic menhaden, common carp, various catfish, white perch, striped bass, bluefish, weakfish, spot, Atlantic croaker, black drum, and various flounder species. In the Delaware Estuary, changes in abundance of anadromous species have been historically linked to a decline of available spawning habitat due to obstructions in watercourses (dams, pollution blocks) that prevent access to spawning beds, overall water quality, and overfishing. Destruction and alteration of wetland habitats have decreased available nursery areas for juvenile fish development, and recreational fishing pressure has consistently increased. There are at least 31 species that are commercially harvested from the estuary valued at about $1.4 million in 1996 (De. Estuary-CCMP).

Birds. Four major estuaries in North America are critical shorebird stopover areas, and each supports more than one million shorebirds during migration. These are the Bay of Fundy and the Delaware Bay on the East Coast, and Alaska's Copper River Delta and Washington's Grays Harbor on the West Coast. At these stopover areas, shorebirds feed on amphipods, chironomids, and horseshoe crab eggs and nearly double their weight before moving on. These areas are unique in their mix of natural resources and consistently support high percentages of the entire world's populations of certain bird species.

Historical survey data has recorded that up to 200,000 red knots (80 percent of the Western Hemisphere population), 10,000 short-billed dowitchers, and half the ruddy turnstones in North America visit the Delaware Bay to feed on horseshoe crab eggs. Red knots fly 19,000 miles round-trip between wintering and breeding grounds and rely on one or two staging areas. After leaving its wintering grounds in southern Argentina, the red knot makes only one stop on the coast of Brazil (Lagoa do Peixe), and then flies nonstop to Delaware Bay, which is a distance of 5,000 miles (Chipley 2003).

Total birds counted in aerial surveys in Delaware Bay over the six-week migration period from May to mid-June range from 250,000 to more than 1,000,000 birds. Birds observed in tidal marsh habitats are estimated at 700,000. Red knots, sanderlings, ruddy turnstones, and semipalmated sandpipers make up 97 percent of the individuals of 30 species of shorebirds utilizing Delaware Estuary habitats. Many migratory raptors, waders, and waterfowl also use the estuary, including brant and up to 400,000 snow geese (State-De/NJ aerial survey data).

<u>Delaware Estuary Program Priority Species List</u>. In spring 1993 a habitat task force brought experts from across the region to develop a list of priority species for management purposes. Of the thousands of plant and animal species in the estuary, participants extracted the indicator and keystone species and assemblages of species that are critical to maintain and monitor the biological integrity, diversity, and environmental health and functioning of the Delaware Estuary. Scientists have deemed that this ecosystem would lack wholeness and integrity without them.

A final list of approximately 100 species and assemblages were identified that are critical in maintaining the Delaware Bay's biological integrity, diversity and environmental health. A supplemental publication to the Delaware Estuary comprehensive conservation management plan describes the habitat requirements and species profile histories of these keystone and indicator species of ecosystem health. The document is entitled "*Living Resources of the Delaware Estuary*" (Dove and Nyman 1995). This information was stepped down to the refuge level when we developed and fine tuned our refuge-specific focal species list and identified the refuge's top priority resources of concern. This process is described in more detail in chapter 2 of this CCP, which describes the planning process.

The Delaware Estuary is impacted by toxic substances, mainly human-created chemicals that have been introduced into the waters. Elevated levels of many toxic substances have been detected in the sediments, the water column, and in the tissues of organisms dependent on the estuary. Primary toxic substances include heavy metals, mercury, and organic contaminants such as polychlorinated biphenyls (PCBs) and Dieldrin. High concentrations of these contaminants of concern have prompted DNREC to post fish consumption advisories from the C & D Canal down to the mouth of the Delaware Bay for following finfish species: striped bass, channel and white catfish, American eel, white perch, and bluefish (DNREC 2010).

Refuge Biological Resources

As in our discussion of rarity patterns of plant species, we also refer to Delaware Natural Heritage Program (DNHP) rankings in describing refuge biological resources such as birds, invertebrates, reptiles, and amphibian species.

The only resident federally endangered species on the refuge is Federal and State-listed Endangered or Threatened Species the Delmarva fox squirrel *(Sciurus niger cinereus).* The current population is very small but represents the core population for expanding Delmarva fox squirrel habitats on the refuge in coming years. In recent years, due to State-managed areas protecting and increasing piping plover productivity each summer, coupled with expanding overwash habitats and new beach acquisitions on Prime Hook NWR, greater numbers of piping plovers are using refuge sandy beach areas as foraging habitats during spring and fall migration periods. Piping plover breeding has not been observed occurring on the Refuge to date.

State endangered resident species on the refuge include two pair of bald eagles. State endangered species that breed on the refuge include pied-billed grebe, northern harrier, Cooper's hawk, black rail, and Forster's tern. In most recent years State endangered species that have attempted breeding on the refuge include American oystercatcher, least tern, and common tern. Uncommon occurrences of other State endangered species using the refuge in the spring, fall, or winter include brown creeper, black-crowned night heron, yellow-crowned night heron, least tern, hooded warbler, red-headed woodpecker, and sedge wren.

Birds

The bird assemblage in the project area is as diverse as its natural vegetation communities. The project area's geographic location on the southwestern shore of the lower mouth of the Delaware Bay situates the refuge at the heart of key staging areas for migrating, breeding, and wintering habitats for waterfowl, shorebirds, waterbirds, and land birds along the Atlantic Flyway and in the Western Hemisphere. The refuge is located in the Northeast Bird Conservation Region 30 and Partners in Flight Physiographic Region 44 of the Mid-Atlantic.

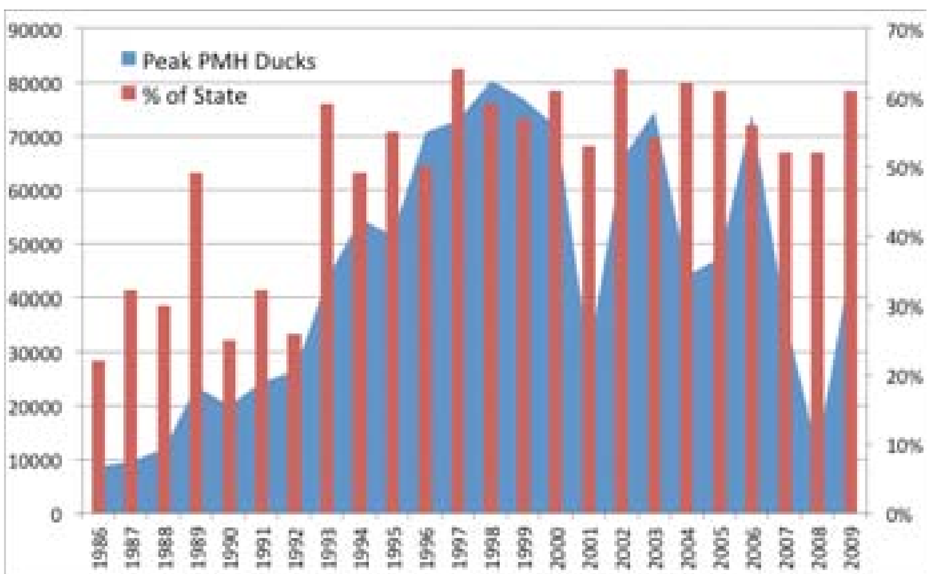
The project area has also been designated a significant site for shorebirds within the Western Hemispheric Shorebird Reserve Network (WHSRN 1986), a Ramsar Wetland Site of International Importance (1992) and an Important Bird Area of the Delaware Bay (IBA) in 2000.

Waterfowl

Waterfowl have been a target species group for refuge management since the refuge was first established. In the past, the refuge farming program was focused on providing food for certain duck species (mallard, American black duck, northern pintail, and wood duck) and Canada geese during the fall, winter, and spring. A secondary objective of the farming program was duck production, for which croplands in grass or clover stages of rotations were designed to provide nesting habitats for ducks. In addition, waterfowl have utilized the refuge's wetland habitats, throughout several different phases of wetland management.

Waterfowl management on the refuge greatly improved habitat conditions for migrating and wintering birds when water level management capability was established in the mid-1980s. Excellent freshwater wetland habitat conditions providing abundant food resources are reflected by subsequent increased bird use of the refuge after 1986. For example, in October 2005, the refuge hosted 52 percent of waterfowl surveyed in Delaware, 71 percent of the State's snow geese, 82 percent of Northern pintails (22,800 birds), 54 percent of American green-wing teal (20,360), and 40 percent (1,889) of the State's American black ducks wintering in Delaware (DNREC, personal communication). Peak duck numbers of 47,116 ducks wintering on the refuge's marsh-complex represented 61 percent of the State's peak number of ducks (Figure 3-16).

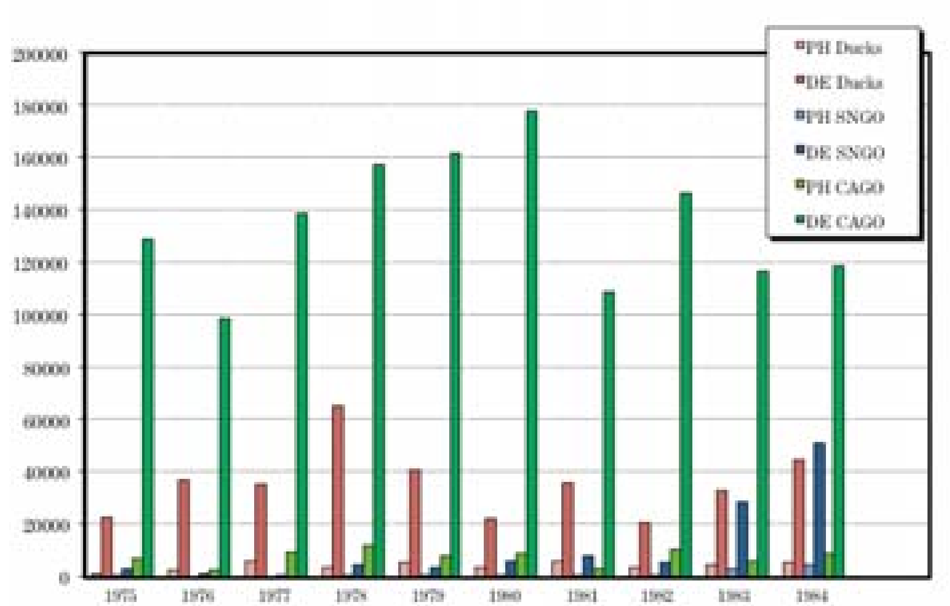
Figure 3-16. Peak Duck Populations Counted on Prime Hook NWR Marshes as a Percent of Delaware's Statewide Peak Duck Numbers



Historically, the Delaware Division of Fish and Wildlife has conducted aerial waterfowl surveys each year to measure long-term trends in duck and goose populations in the State. These surveys were flown in a small plane by the same waterfowl biologist for 30 years, using the same routes and techniques each time. The survey biologist staff changed after 2005, but DNREC waterfowl biologists have continued to provide waterfowl survey data directly to the refuge. These surveys cover the primary waterfowl habitats found in Delaware. The surveys give fairly accurate information about geese and most duck species with the exception of wood ducks and sea ducks, which are almost impossible to count from a fixed-wing aircraft. The important feature of these counts is that they provide long-term trends that are useful to measure changes in waterfowl management strategies and the environment. In most cases, no single count is especially important in itself but the collection of counts over the years has shown significant changes. These surveys detected the decline in the migrant Canada geese in the Atlantic Flyway, the loss of duck use in Christiana marshes after the construction of I-95, and recent increases in ducks using Prime Hook NWR. An analysis of this 30-year data set shows how marsh restoration and rehabilitation projects, after an early period of no management, improved habitat conditions for waterfowl.

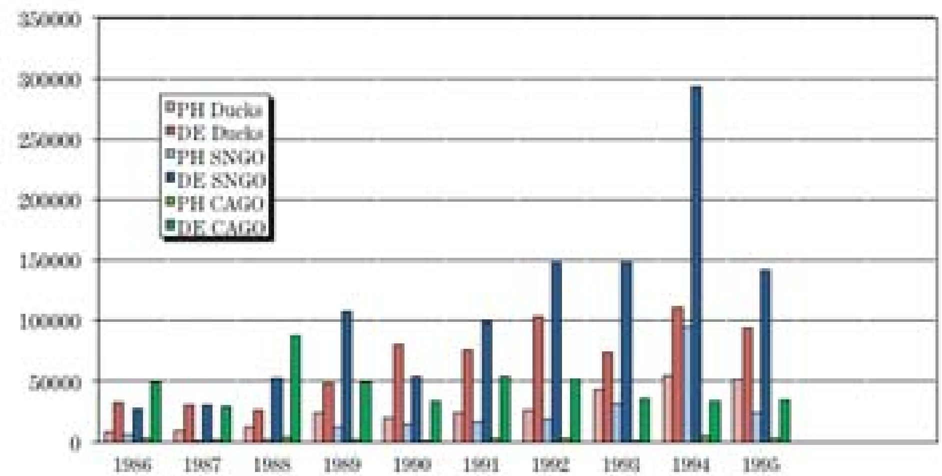
During a decade of the no wetland management era, proliferation and invasion of *Phragmites* throughout the refuge's wetland areas reduced the quality of habitat conditions for ducks. During this time, average duck use of refuge marshes was 3,905 birds (peak 5,795 to low of 2,254), which accounted for less than 10 percent of the State's total duck numbers. Average snow goose numbers were 748 birds, ranging from 0 to 4,310 birds. State average totals for snow geese were 11,000 and ranged from 678 to 50,726 birds. State migratory Canada goose numbers were at an all time high of 177,811 birds in 1980 and refuge peak numbers of Canada geese during this decade were 11,942 birds in 1978 (DNREC personal communication). For waterfowl population distributions and use of refuge marshes compared to Statewide numbers (Figure 3-17).

Figure 3-17. Average Waterfowl Use during the No Wetland Management Era



During the next decade of marsh rehabilitation of Prime Hook NWR's wetlands consisted of the large-scale control of *Phragmites* and establishment of impoundment infrastructure, waterfowl use increased. These habitat improvements and increased waterfowl use on the refuge are reflected in the State of Delaware's waterfowl aerial survey data. Statewide, ducks numbers doubled from the 1986 to 1995 period compared to the 1975 to 1984 period, while duck use and numbers on the refuge increased sevenfold, ranging from a low of 8,582 ducks in 1986 to a peak of 54,606 in 1994. Pintails (28,920) and green-winged teal (39,611) were the duck species contributing the highest total numbers to duck counts during this period. Snow geese also showed increases on the refuge and throughout the State. Peak snow goose numbers recorded in 1995 for the refuge were 95,300 birds and 293,651 birds for the State. In contrast, Canada geese numbers dropped sharply with average numbers during the 10-years of no management of 7,486 dropping to 2,573 birds during the marsh rehabilitation era. Likewise, Statewide numbers of Canada geese dropped from an average of 135,213 birds down to 45,678 birds in the second decade of trend monitoring data (Figure 3-18) (DNREC, personal communication).

Figure 3-18. Average Waterfowl Use during Marsh Rehabilitation Era



Continuing this 30-year trend analysis, during the intensive wetland management strategies of integrative moist-soil management, waterfowl use of Prime Hook NWR's marshes continued to increase. Teasing out the duck numbers from the waterfowl data, the State experienced a general 37 percent increase in duck numbers during this decade (1996 to 2005), while Prime Hook NWR recorded a 72 percent increase from prior decades in duck use. At Prime Hook NWR, duck use ranged from a low of 29,638 ducks in 2001 to a high of 80,261 ducks in 1998.

Increases in snow goose numbers were recorded both Statewide and refugewide. Peak snow geese numbers on the refuge were 143,432 birds occurring in 1999 and a low of 13,775 snow geese in 2005, compared to a Statewide high of 371,715 birds in 1997 and low of 91,654 also in 2005. Canada goose numbers using the refuge doubled from the prior decade but Statewide Canada goose numbers continued to spiral downward.

Thirty-two waterfowl species have been recorded using refuge habitats. The two duck species contributing the most in the 30-year trend data analysis were green-winged teal and northern pintail. Green-winged teal numbers were 41,047 in 1996; 46,795 in 1997; 53,260 in 1998; and 65,727 in 1999; and peak northern pintail numbers include 28,920 in 1993; 21,061 in 1998; 21,835 in 2000; and 35,497 in 2003. Other duck species contributing to duck totals included American black duck, mallard, gadwall, American wigeon, northern shoveler, wood duck, scaup, ring-necked duck, ruddy duck, and hooded merganser.

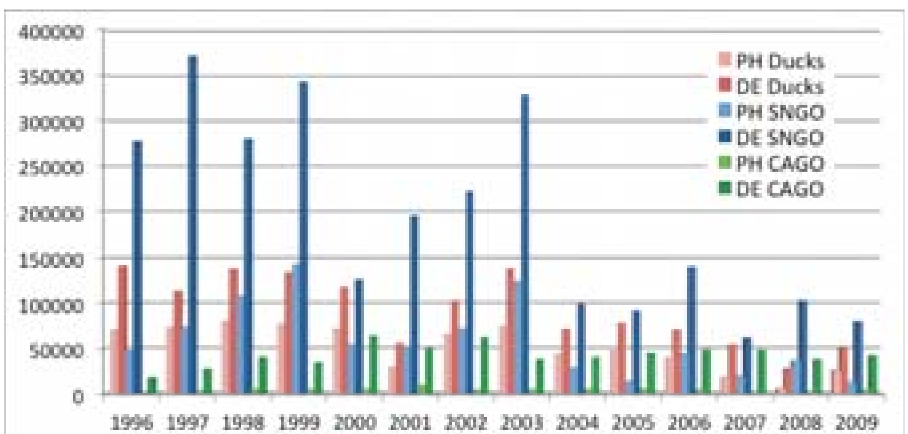
By means of marsh rehabilitation and integrative moist-soil management techniques through water level manipulation strategies, Prime Hook NWR has demonstrated considerable success in increasing both waterfowl and shorebird use of the refuge's wetland habitats simultaneously. Fredrickson and Laubhan (1994) described how intensive wetland management strategies are the keys to enhancing biodiversity in the face of continuing wetland degradation and loss throughout all landscape scales.

The basic premise of intensive wetland management is producing a diverse array of plant and animal food resources that can feed a greater abundance of target species of waterfowl and shorebirds on smaller patches of marshland. Intensive wetland management has demonstrated improvement in wetland productivity and biodiversity when the correct combination of water level manipulations and other habitat management techniques are applied at the appropriate times for an array of target wetland species (Fredrickson and Laubhan 1994).

The general strategy of intensive wetland management is predicated on knowing the life history requirements of target waterfowl and shorebird species, annually creating abundant native plant and animal food resources consistently, and making these annually produced food resources available to target species at the right time of the year.

Annually from 1995 to 2005, Prime Hook NWR attempted to match the chronology of particular biological events such as molting, migration, and reproduction requirements of target waterfowl and shorebird species with specific water level drawdown and reflood regimes conducted asynchronously between the refuge's three impoundment units. Concurrent waterfowl and shorebird habitat management can be accomplished each year by producing abundant invertebrate food resources and then linking drawdowns to local migration phenology. Management success is reflected in the bird use data (Figure 3-19).

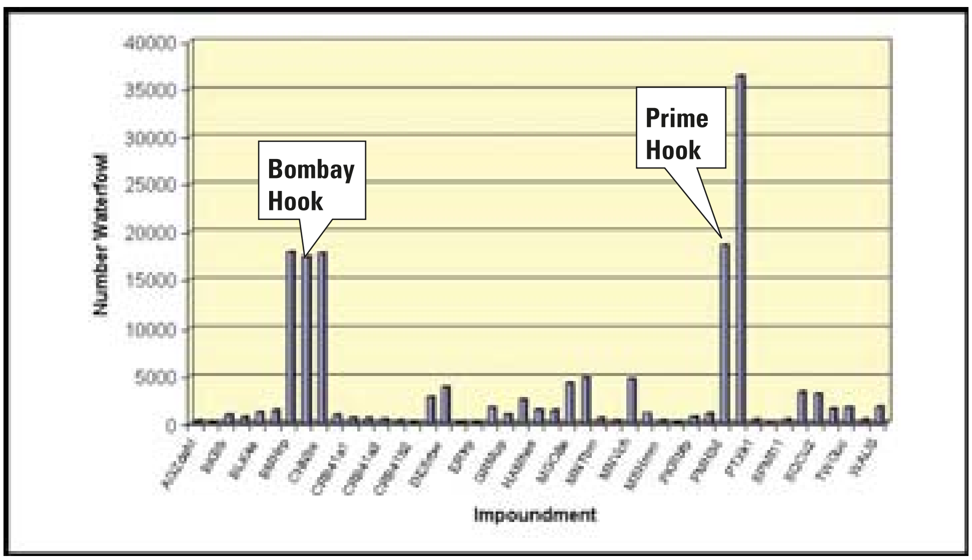
Figure 3-19. Average Waterfowl Use during the Integrative Wetland Management Era



Managed wetlands provide a broad spectrum of resources to migratory birds throughout the annual cycle. Successful conservation and management of waterfowl, shorebirds, and waterbirds depend on integrated approaches. Few managed wetlands have the capability to provide habitat during both spring and fall migration. Whether management actions are designed to benefit spring or fall migrant shorebirds, hydrologic regimes will also impact waterfowl and other waterbirds, primarily through changes to invertebrate and plant communities. With this in mind, the refuge participated in a 3-year, multi-regional wetland management study from 2005 to 2007 to understand the differential impacts of spring versus summer/fall drawdowns on the vegetation structure, invertebrate communities, and use of impoundments by waterfowl, shorebirds, and other waterbirds (USGS 2005). The refuge used study areas in Unit III (PMH3D) and Unit IV (PMH4A).

Preliminary analysis of study results (Green et al 2007) after two seasons of field data (2005 and 2006) indicated that early spring drawdowns conducted in PMH3D to prepare habitat conditions for spring migrating shorebirds, also yielded excellent waterfowl use in mid-November in the same wetland, with more than 20,000 ducks and geese recorded using the area. During the same timeframe Unit IV (PMH4A) experienced a late summer drawdown targeting fall migrant shorebirds which also generated excellent waterfowl use with a peak of 15,000 birds using the same wetland by the first week of November. Of the 22 national wildlife refuges from regions 3 and 5 participating in this study, most refuges recorded waterfowl use in the tens and hundreds range while Prime Hook and Bombay Hook recorded waterfowl numbers in the thousands of birds range, indicating the importance of the Coastal Delaware NWR Complex to waterfowl resources (Figure 3-20). A final analysis and study report will soon be released by the U.S. Geological Survey.

Figure 3-20. Relative Abundance of Waterfowl Using Refuge Impoundments Enrolled in Multi-Regional Impoundment Study. Note importance of Delaware refuge impoundments.



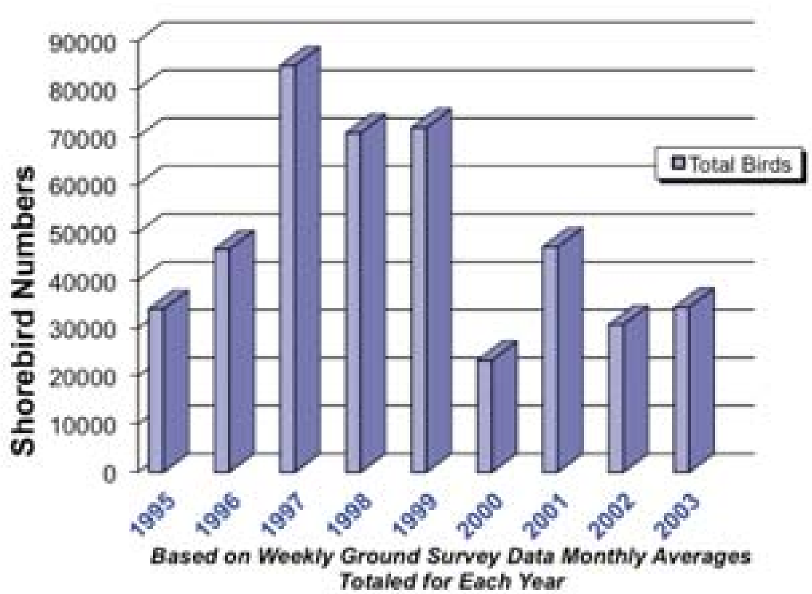
Shorebirds, Gulls, Terns, and Allied Species

The refuge provides diverse fresh and saltwater marsh and impoundment habitats that support 54 species of shorebirds, gulls, terns, and allied species. Most species are migrants, but 13 of these species breed on the refuge (black rail, clapper rail, king rail, Virginia rail, sora, common moorhen, American coot, killdeer, black-necked stilt, willet, spotted sandpiper, American woodcock, and Forster's tern), while 12 species winter in marsh habitats (sanderling, killdeer, American woodcock, willet, greater and lesser yellowlegs, western sandpiper, dunlin, common snipe, ring-billed, herring, and lesser black-backed gulls). Common terns, least terns, and black skimmers seasonally utilize refuge habitats; these three bird species are on the State's endangered species list.

Refuge saltwater marsh, sandy beach, and impoundment habitats support a shorebird migration that has worldwide ecological significance. Abundance of invertebrate foods is recognized as an important determinant of habitat quality for migrant shorebirds. High densities of chironomid larvae are common in the diets of breeding, migrating, and wintering shorebirds (Batzer et al. 1993). As previously mentioned, intensive management of Prime Hook NWR's seasonally flooded impoundments for migrant shorebirds has been a part of the refuge's habitat management strategies by incorporating methods to increase annual invertebrate biomass production. It is possible to successfully manage for such macroinvertebrates as chironomids and other short-cycle invertebrates, purposefully for shorebird consumption, using water level manipulations to produce invertebrate densities of at least 100 individuals per square meter (Baldassarre and Fisher 1984, Helmers 1992). The essence of successful shorebird management within impounded wetland habitats is based on the seasonal production of high densities of macroinvertebrates and their availability at critical times of the year for spring and fall shorebird migrants (Rundle and Fredrickson 1981, Elridge 1992).

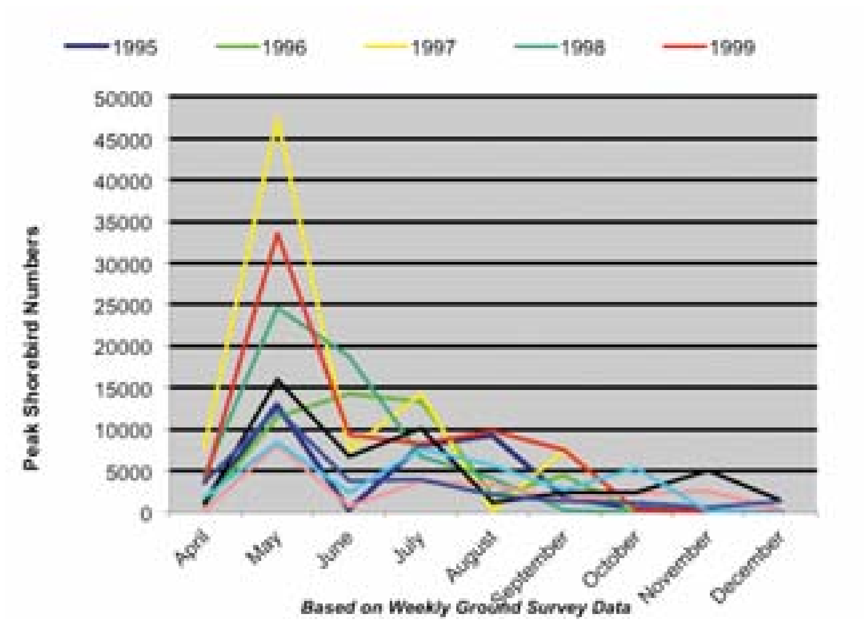
Manipulating water levels at the appropriate times to create areas with a mosaic of open mudflats with shallow water levels (between 1.0 and 10.0 cm deep) and invertebrate densities of at least 100 individuals/M2 have yielded excellent results on the refuge. A decade of shorebird ground surveys were conducted weekly from April to December on Prime Hook NWR's impounded marsh units (Figure 3-21).

Figure 3-21. Refugewide Shorebird Use of Prime Hook NWR's Impoundments



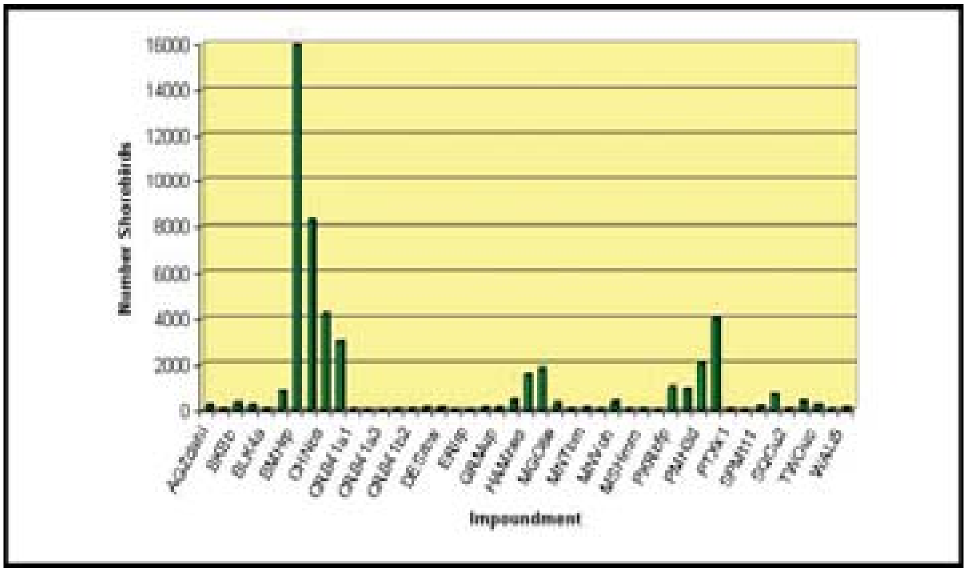
Dominant shorebird species contributing to shorebird numbers on Prime Hook NWR from weekly ground surveys included the following spring migrants: semipalmated sandpipers, short-billed dowitchers, dunlin, sanderlings, and red knots; and fall migrants: short-billed dowitchers, semipalmated plovers and sandpipers, dunlin, least sandpipers, and yellow-legs. Chronology of use information for the years of 1997, 1998, 2000, 2001, 2002, and 2003 shows that spring migrants start arriving by mid-April and peak during the last two weeks of May, while fall migrants start arriving by the last week of June and peak during the first two weeks of July. Local spring migrants arrived 2½ weeks later in 1996 and peak fall migrant numbers were three weeks later in 1995 and 1999 (Figure 3-22).

Figure 3-22. Chronology of Shorebird Use at Prime Hook NWR



As previously mentioned in the waterfowl section, the refuge participated in a multi-region refuge cooperative research impoundment study, whose primary objective was to monitor management actions that created shallow water and mudflat habitat for shorebirds either for the northward or southward migration. While management actions targeted shorebird habitat creation within the impoundments, we also simultaneously monitored the responses of waterfowl and wading birds in addition to shorebirds. The preliminary shorebird monitoring results (Green et al. 2007) suggest that both early spring drawdowns and late summer drawdowns generated greater numbers of fall migrants (peak about 4,000 birds) using Units III and IV impounded study sites, compared to spring migrants (peak about 1,500 birds). Chronology of use plots suggest that the first week of September was when the greatest shorebird use occurred (about 3,000 birds) in Unit III during 2005 and 2006; fall migrant shorebird use in Unit IV occurred in mid-August, and again September 1st and mid-September (about 4,000 birds for all 3 plot peaks) during the same timeframe as Unit III. Preliminary results suggest that refuge impoundments are more important for the southward migration. Overall, impoundments at Prime Hook NWR, as well as Bombay Hook NWR also in Delaware, are clearly important to migratory shorebirds, relative to other impoundments evaluated in the study (Figure 3-23). A final study report is pending that will analyze and compare study results of 22 national wildlife refuges representing regions 3 and 5.

Figure 3-23. Relative Abundance of Shorebirds Using Refuge Impoundments Enrolled in Multi-Regional Impoundment Study. Note importance of Delaware refuge impoundments.



Marsh and Water Birds

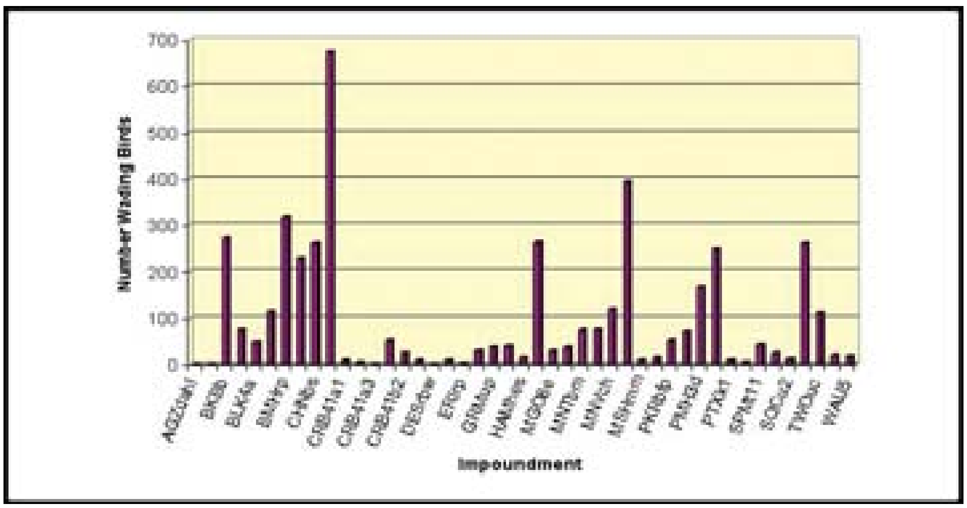
Freshwater impoundments, brackish marsh, and salt marsh wetland areas provide excellent feeding and resting areas for 30 species of marsh and water birds. Pied-billed grebe, least bittern, and green herons all nest on the refuge. Pied-billed grebes are on the State endangered species list and American bitterns and little blue herons use refuge habitats for portions of the year. These three species are ranked as (S1) species of special conservation concern in the Delaware Wildlife Action Management Plan (2005).

The most important heron and egret rookery in Delaware is located in the middle of Delaware Bay Estuary on a 310-acre island named Pea Patch Island. Located about 54 miles north of the refuge, it is the largest heronry on the East Coast north of Florida. It is a resource of both regional and national significance. Ten species of herons, egrets, and ibises nest on this isolated island, which supports 3,000 nesting pairs of wading birds. Many of these birds spend the months of August and September feeding on diverse and plentiful fish resources found in refuge habitats. Of particular note are the black-crowned and yellow-crowned night herons found on the refuge during this timeframe which are listed as State endangered bird species of Delaware.

The Mid-Atlantic/New England/Maritime Waterbird Conservation Plan (2006) has identified the highest priority species in need of immediate conservation action. Highest priority species that breed or migrate through the refuge include pied-billed grebe, American bittern, least bittern, snowy egret, little blue heron, tricolored heron, black-crowned night heron, glossy ibis, black rail, least tern, gull-billed tern, common tern, black skimmer, yellow rail, sora, black tern, and Forster's tern.

An integrated wetland management approach to create optimal shorebird habitats at appropriate times for spring and fall shorebird migrants can also provide a broad spectrum of resources for marsh and water birds. This group of birds was also targeted for monitoring during the Refuge Cooperative Research Program Region 3/5 Impoundment Study previously mentioned in the waterfowl and shorebird sections of this chapter. The objective of conducting management actions to create shallow water and mudflat habitats for shorebirds and monitor the subsequent responses of invertebrate populations and plant communities also included monitoring water bird use of the various seasonal habitat conditions that were generated during the study in two designated study areas (PMH3D and PMH4A). Preliminary data analysis (Green et al. 2007) indicated that marsh and water birds utilized impounded wetland study sites throughout the year, with peak use occurring during mid-August and September during the 2005 and 2006 field seasons. Peak water bird use in Unit PMH4A occurred in late August (approximately 350 birds) and peak use in PMH3D (approximately 250 birds) occurred during the first week in September (Figure 3-24).

Figure 3-24. Relative Abundance of Wading Birds Using Refuge Impoundments Enrolled in Multi-Regional Impoundment Study.



Landbirds

The conservation of birds is a primary purpose of the National Wildlife Refuge System, and refuges provide important breeding and migrating habitats for a variety of landbirds, many of which are of state, regional and national management concern (USFWS 2008a, DWAP 2005, BCR 30 and PIF 44 plans). The term landbirds generally refers to the smaller birds (exclusive of raptors and upland game birds) not usually associated with aquatic habitats. This group refers to songbirds (Family Passeriformes) also known as passerines. These include resident songbirds that breed on refuge lands, such as corvids,