The Best Strategy to Support the Back Bay National Wildlife Refuge Marsh Ecosystem in the Transition from Freshwater to Saltwater While Upholding the Mission Under the Threat of Sea Level Rise and Storm Surges.

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Contents:

List of Tables and Figures:

Executive Summary

The mission of the U.S. Fish and Wildlife Service is to "work with others to conserve, protect and enhance fish, wildlife and plants and their habitats for the continuing benefit of the American people" (USFWS, 2020). Unfortunately, many of U.S. Fish and Wildlife Services refuges are threatened by storm surges and sea level rise; Back Bay National Wildlife Refuge is a key refuge along the Atlantic Flyway and is one of these refuges being threatened. Its mission is "to serve as a breeding ground and as an inviolate sanctuary for migratory birds, to conserve and protect other wildlife including endangered and threatened species and wetlands" (Brandwein et al., 2010). How will Back Bay National Wildlife Refuge uphold its mission while supporting the transition from a freshwater ecosystem to a saltwater ecosystem? Based on global sea level rise scenarios it is expected that Back Bay National Wildlife Refuge will be completely inundated between the years 2050 and 2100 (NOAA, 2020), because the background rate of sea level rise for the Back Bay region is double that of common scenarios in other coastal regions (Karlov et al., 2017).

Water flows into Back Bay National Wildlife Refuge from the Albemarle and Currituck sound by the process of wind tides; strong southern winds in the summer months bring in water while northern winds in the winter months push water south, although the closest ocean inlet that connects the Albemarle and Currituck sound to the Atlantic Ocean is 96.5 km south of the refuge (Brandwein et al., 2010). This means that global sea level rise may take a long time to affect the refuge over strong storm surges. During the spring and summer months impoundments on the refuge are drained down to exposed mudflats for migrating shore birds, respectively during fall and winter months these impoundments are filled to feed the wintering waterfowl, it has been observed that waterfowl on the refuge has been in decline since the year 1954 (Settle and Schwab, 1991). Wintering waterfowl rely on the freshwater march ecosystem of Back Bay for a breeding ground and sanctuary. While migrating shore birds use both the freshwater marsh ecosystem of Back Bay and the barrier dune system on the beach side of the refuge for a breeding ground and sanctuary.

There are two main components that cause inundation on the refuge, severe storms causing a dune barrier breach and sea level rise from the Albemarle and Currituck Sound. These two components lead to land loss on the refuge and an increase in salinity levels within the bay and impoundment system, an increase in salinity levels would then cause a decrease of submerged aquatic vegetation and mud flats; these together create a loss of habitat for migrating waterfowl that inhabit Back Bay National Wildlife Refuge. Therefore, leading to a loss of the refuges mission. According to sea level rise projections by NOAA, Back Bay National Wildlife Refuge should expect to see a 0.1-0.3 m rise in sea level by the year 2030, a 0.2-0.4 m sea level rise by the year 2050, a 0.3-1.3 m sea level rise by the year 2100, and in worst case modeling projection a 2.4 m sea level rise by 2100. Although this is not factoring in that Back Bay has seen double the rate of sea level rise than other regions. Based on NOAA's projections it would only take between 0.9 m and 1.2 m of sea level rise to completely inundate Back Bay National Wildlife Refuge (NOAA 2020). There are several strategies Back Bay National Wildlife Refuge could use to combatant strong storm surges and sea level rise; these include, building a sea wall,

elevating the dune system, and building pumps into the impoundment system. While these are not solutions to the problem of strong storm surges or sea level rise, they could slow down the effects seen on the refuge.

After taking into consideration that strong storm surges and sea level rise cannot be completely preventable it is recommended that refuge managers, stakeholders, and U.S. Fish and Wildlife Service seek to buy low-lying farmland located west of the refuge in Pungo and slowly convert it to a freshwater marsh ecosystem so the current freshwater marsh ecosystem of Back Bay can migrate before sea level rise turns the refuge into a saltwater marsh ecosystem. Secondly, refuge managers, stakeholders, and U.S. Fish and Wildlife Service should construct a buried sea wall underneath the dune barrier system of Back Bay as well as elevating the dune, therefore preventing dune barrier breaches from strong storm surges. While sea level rise in unpreventable this recommendation would give the freshwater marsh ecosystem of Back Bay enough time to migrate westward before the refuge is turned into unconsolidated shore and open water because of sea level rise, therefore still upholding the mission of Back Bay National Wildlife Refuge.

Introduction

Back Bay National Wildlife Refuge (BBNWR) is located on the U.S. East Coast in Southeast Virginia and was first established on June 6th, 1938, to protect and preserve part of Virginia Beach from urban development so that land could be used as a critical part of the Atlantic Flyway, which stretches from Maine to Florida and includes Puerto Rico (Brandwein et al., 2010). The Atlantic Flyway is home to a wide variety of ecosystems that include forests, beaches, and coastal wetlands, as well as encompassing more than a third of the human population in the United States (Audubon, 2015). As of 2010 BBNWR is a 9,120-acre refuge spanning over 1.3 square meters that includes ten on refuge impoundments and an additional two impoundments that are located in False Cape State Park but are overseen and managed by BBNWR. This refuge serves as a breeding ground and sanctuary for migratory birds found along the Atlantic Flyway including thousands of geese, ducks, and swans as well as other endangered and threated wetlands and wildlife such as the Loggerhead Sea Turtle, Piping Plover, Brown Pelican, and Bald Eagle (Brandwein et al., 2010). The ecosystems that make up BBNWR are freshwater forested wetlands, freshwater shrub wetlands, freshwater emergent wetland, brackish/transitional marsh, saltwater marsh, unconsolidated shore, and open water (figure 1). The refuge's barrier island feature more ecosystems such as large sand dunes, maritime forests, freshwater marshes, ponds, and ocean beach. The mission of BBNWR is “to serve as a breeding ground and as an inviolate sanctuary for migratory birds, to conserve and protect other wildlife including endangered and threatened species and wetlands.” (Brandwein et al., 2010). The waters within BBNWR are defined as an oligohaline estuary, nearly fresh, ranging in 0-3 ppt of salinity. BBNWR is a wind driven tidal system, this means that salinity is regulated by how far north water from the Albemarle and Currituck sound is pushed into BBNWR. Water can only travel into the Albemarle and Currituck sound through the Oregon inlet which is in North Carolina, 96.6 km south of BBNWR (Brandwein et al., 2010).

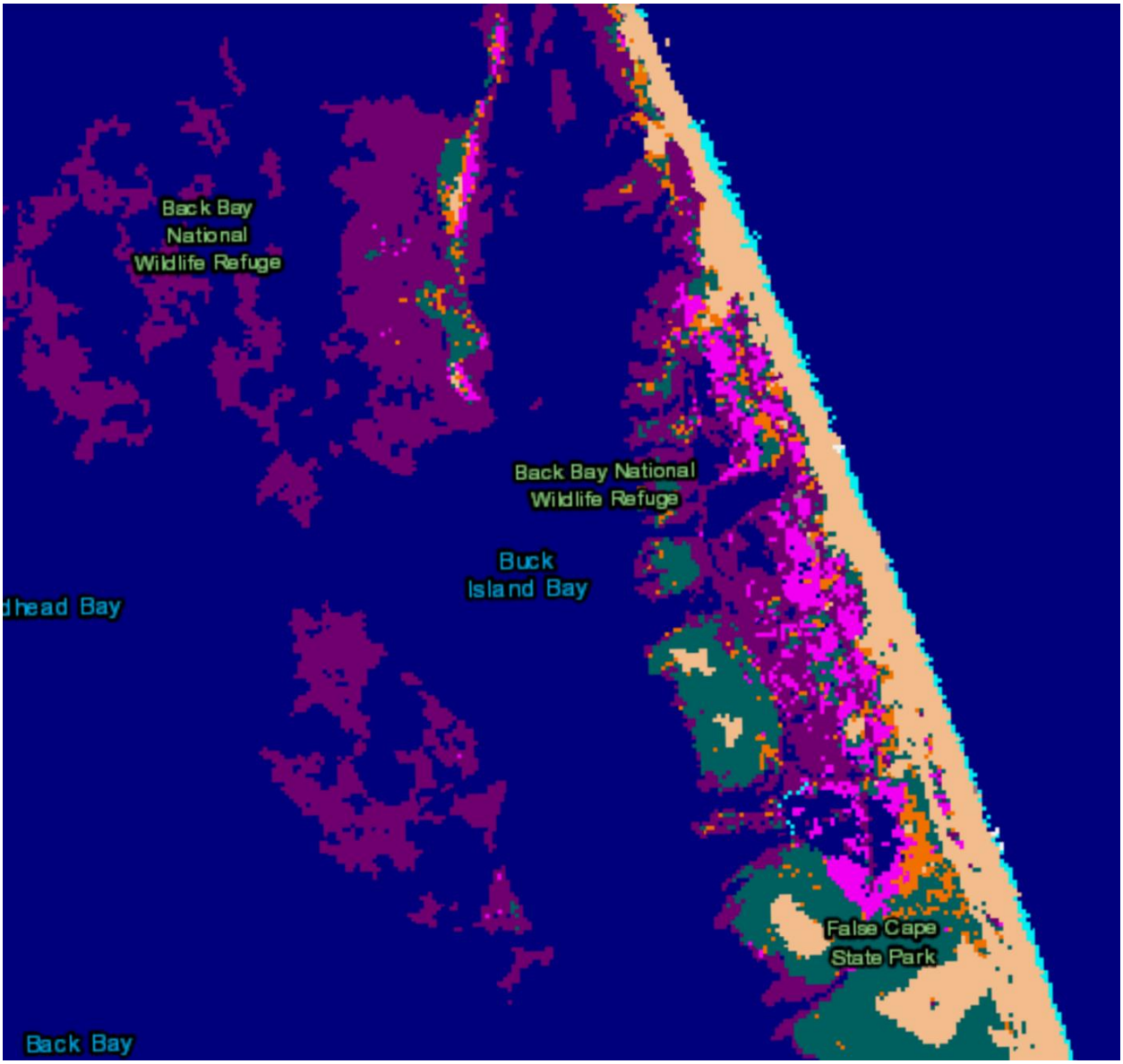

Figure 1. *BBNWR ecosystems; upland (tan), freshwater forested wetlands (green), freshwater shrub wetlands (orange), freshwater emergent wetland (light pink), brackish/transitional marsh (dark pink), saltwater marsh (purple), unconsolidated shore (light blue), and water (dark blue). Image created with the NOAA Sea Level Rise Viewer (2020).*

In the 1970's the Back Bay National Refuge impoundments were created; in the spring and summer the refuge draws down the impoundment water levels to expose mud flats for the migrating shore birds, in the fall and winter the water is raised to feed the wintering water fowl, this is a primary component of the refuge and its purpose The impoundments are filled using a system of nineteen man made waterways that are strategically placed throughout the refuge that control the water flow from the Albemarle and Currituck sound into the refuge; only three waterways are directly connected to the Albemarle and Currituck sound. These waterways also control the water height of the twelve pools (Brandwein et al., 2010). Waterfowl rely on the

freshwater marsh habitat of Back Bay and impoundments on the refuge for food. Within Back Bay there are multiple species of submerged aquatic vegetation (SAV), small invertebrates live within the SAV beds and feed the waterfowl that inhabit the refuge. It has been observed that a low SAV habitat is not suitable for the migrating waterfowl (Morton and Kane, 1994) although a high SAV habitat means a high wintering waterfowl population. For the last half century, the waterfowl population in BBNWR have been declining because of the reduction in SAV beds due to poor water quality, this means that the waterfowl are shifting to northward habitats in the Atlantic Flyway (Brandwein et al., 2010).

Global climate change is one of the most well recorded driving forces behind current long-term sea-level rise around the world (Sweet et al, 2017). In the last century global sea levels have risen 0.17 cm a year on average, within the past few decades it has increased to 0.32 cm a year on average, almost doubling its original rate, it is projected that future rates will be even higher than background rates (Smallegan et al, 2017). Within the United States, sea level rise in Hampton Roads is considered one of the fastest and most impactful with the average rate being 0.46 cm a year (NOAA, 2019). Sea level rise is not the only thing BBNWR is threatened by, significant storms storm surges causing dune breaches, like the Ashe Wednesday storm in 1962, also pose an ongoing threat to barrier islands like Back Bay. Barrier islands are a type of dune system parallel to a main part of the coast, they are prone to move landward or seaward due to over wash, also called roll-over, depending on the capacity of the sediment bank the island has (Titus et al, 2009). When an over wash event occurs, sediments are moved and deposited on the backside of the barrier island and held in place by marshes, this process moves the barrier island landward. It is predicted that in the future BBNWR will see a total transition from freshwater ecosystems to saltwater ecosystems due to these threats (NOAA, 2020). This report will be focused on the system vulnerabilities and threats within BBNWR and what the best strategy may be to support the ecosystem in the transition from a freshwater marsh to saltwater marsh due to sea level rise while upholding the mission of the refuge.

Decision Making

BBNWR does not make decisions only based on the interest of this refuge but also the equities it's partners. Back Bay is a part of the Atlantic Coast Joint Venture Program, it is also included and recognized by the Albemarle-Pamlico National Estuarine System, a system that spans 2,601.3 square meters encompassing the watershed of the Albemarle and Currituck sound, Partners in Flight: Mid-Atlantic Coastal Plain Bird Conservation plan with their mission "keeping common birds commons and helping species at risk though voluntary partnerships" (Brandwein et al., 2010). The refuge also works closely with other government services such as the Army Corps of Engineers, Virginia Beach department of Game and Inland Fisheries, Virginia Department of Conservation and Recreation, the City of Virginia Beach Department of Parks and Recreation, North Carolina Department of Environmental and Natural Resources, and Division of Marine Fisheries, North Carolina Fish & Wildlife Department (Brandwein et al., 2010). Other than government agencies BBNWR also works with NGOS like, the Virginia ECO-tourism Association, Back Bay Restoration Foundation, False Cape State Park, Virginia

Beach and Cape hennery chapters of the Audubon Society, Elizabeth City State University, East Carolina University, Ducks Unlimited, and Delta Waterfowl non-governmental organization. These groups and agencies have been involved with inventorying and understanding SAV bed trends and how better management of these SAV beds will affect migrating bird populations on the refuge (Brandwein et al., 2010). Although not all these groups will have a final say in what happens to BBNWR they can offer their opinions on how the refuge should approach the threat of strong storm surges and global sea level rise.

Stakeholders	**Level of Governance**	**Use of Area**	**Decision Making Authority**
U.S. Fish and Wildlife Service	Government	Owns and maintains the refuge	Owns BBNWR so they have the final say
False Cape State Park	Government	Attached to the refuge, shares impoundment system	They have input for the refuge but not a final say in what happens
Army Corps of Engineers	Government	Helps maintain refuge	They have input for the refuge but not a final say in what happens
Virginia Beach and Cape hennery chapters of the Audubon Society	Non-Government	Monitor bird populations	They have bird data for the refuge but not a final say in what happens
Virginia Beach Department of Game and Inland Fisheries	Government	Issues hunting licenses that can be used on the refuge	They have input for the refuge but not a final say in what happens
City of Virginia Beach Department of Parks and Recreation	Government	Encourage tourism of BBNWR	They have tourist data for the refuge but not a final say in what happens
Partners in Flight	Non-Governmental	Monitor Atlantic flyway bird populations on the refuge and helping protect habitats	They have bird data for the refuge but not a final say in what happens
Ducks Unlimited	Non-Governmental	Monitor bird populations	They have bird data for the refuge but not a final say in what happens
Local NGOs	Non-Governmental	Interest in BBNWR	Care about what happens to BBNWR

			but do not have a say, can offer opinion
Farmers	Non-Governmental and Commercial	Concerned about the land changes the surrounding area will have	No say in what happens to BBNWR, can offer opinion

Table 1: *A list of primary stakeholders and other partners that influences decisions BBNWR makes.*

The Wicked Problem

How will BBNWR be able to maintain its refuge mission under the threats of seal level rise and strong storm surges? On average the water depth in Back Bay reaches 1.5 m but can fluctuate daily and average of 23 cm based on wind tides (Brandwein et al., 2010). Water flows north from the Albemarle and Currituck sound due to strong southern winds and feeds into Back Bay. A wind tidal system determines the water level in that region based on the season, if waters from the Albemarle and Currituck sound show an increase in salinity this would bring in more salinity to BBNWR. Low elevation of the dune system on the seaward side of BBNWR and the impoundment system on the bay side of BBNWR as well as a narrow barrier island structure also increase the probability of saltwater intrusion, whether that be though a dune breach due to severe storms, or inundation caused by sea level rise which both could cause not only an increase of salinity but also a loss of land within the refuge. Most importantly an increase in the salinity of BBNWR would decrease the SAV beds therefore lowering the food source for migrating birds shown in the conceptual model (figure 2). Conceptual models are used to represent specific systems and what would happen if a system were to undergo specific changes. This conceptual model gives three levels of outcomes for BBNWR, the first ending with a decrease in wintering waterfowl, the second ending with a decrease in shore bird populations and the third ending with BBNWR no longer being a habitable ecosystem for waterfowl.

During the spring and summer months the impoundments are drained to expose mud flats so that migrating shorebirds may feed, retrospectively during the fall and winter months the impoundments are raised to feed the wintering waterfowl (Brandwein et al., 2010). BBNWR is the northern most limit for southern species of plants to thrive and the southernmost limit for northern species of plants to thrive, making this a very delicate ecosystem, this being said the five most dominant species of SAVs that inhabit Back Bay are cattails, needle rush, big cordgrass, salt meadow hay and switchgrass. Although it has been seen that a common reed, Phragmites, has also increased in volume between the inventory done in 1977 and 1990 observations making it one of the more dominant plant species found at BBNWR (Priest and Dewing, 1991). There is a direct correlation between the decline of SAVs and the decline of waterfowl that use BBNWR as a habitat within the Atlantic Flyway (figure 3). Diving ducks, the greater snow geese, the Canada goose, and tundra swans have all shown a statistically significant declining trend since 1954. Dabbling ducks however have only seen to be declining since 1980. These declines in waterfowl directly correlate with declining SAV bed trends seen in figure 3

(Settle and Schwab, 1991). It would be desirable for BBNWR to maintain its waterfowl populations while being threatened with sea level rise and strong storm surges.

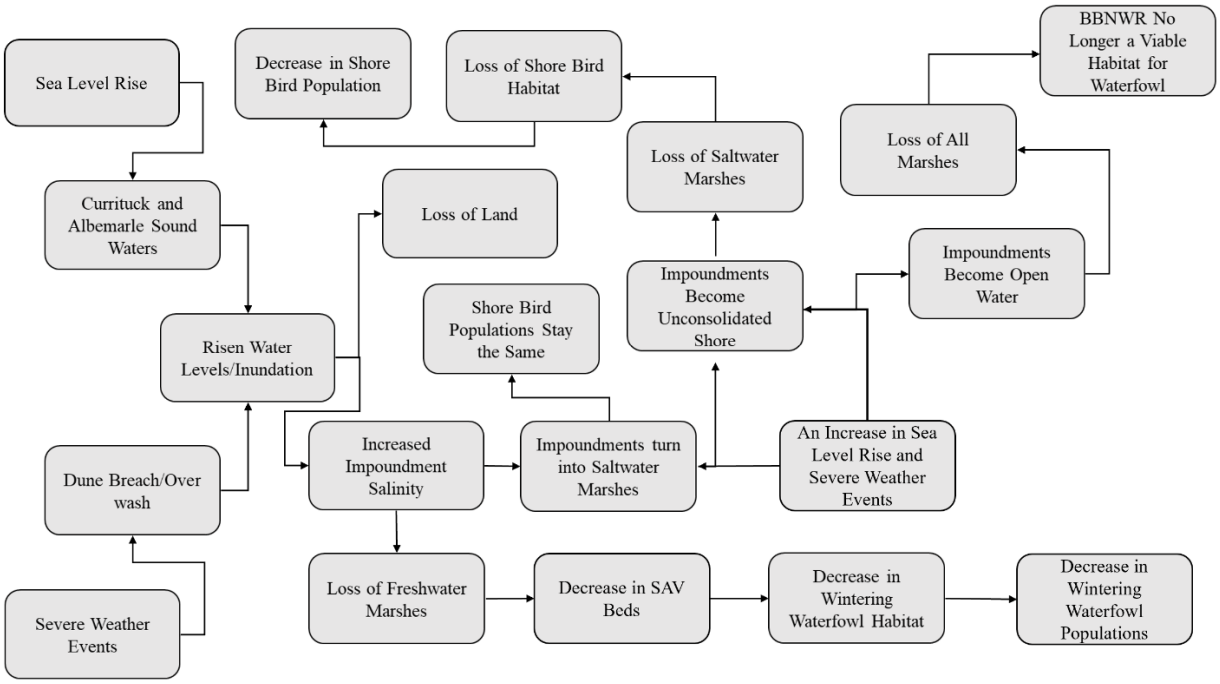

Figure 2. *Conceptual model for the potential impacts of sea level rise and storm surges on the ecosystems, SAV beds, and migrating bird populations in BBNWR.*

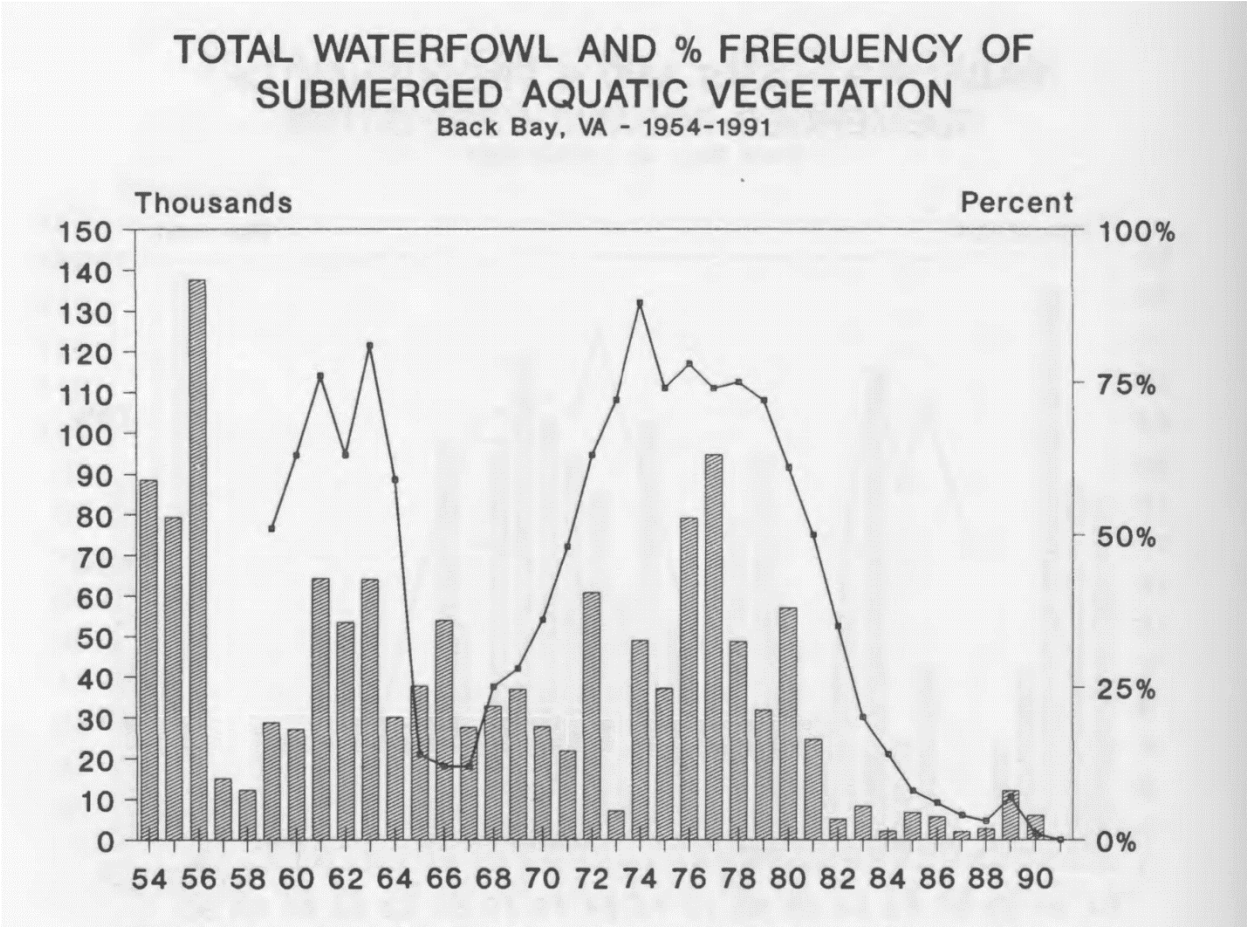

Figure 3. *Total number of waterfowl and the percent of frequency of submerged aquatic vegetation through the years 1954-1990. From Settle and Schwab (1991).*

System Vulnerabilities and Fragilities

Significant sea level rise may take years to inundate the entirety of BBNWR, although extreme weather events that cause inundation are an immediate problem for the refuge. With BBNWR being on a barrier island there are two responses to sea level rise, morphologic and ecological evolution a dynamic response where initial land cover type is maintained or a transition to another non submerged land cover type, or inundation a static response which occurs in areas where land cannot accommodate or adapt to water level increases and then become submerged or inundated (Lentz et al, 2015). In the worst-case scenario sea level rise is projected to reach 2.4 m by 2100, this will completely wipe away the refuges impoundment system seen in figure 4. NOAA projections demonstrate that with 0.3 m of sea level rise some of the impoundments will remain a freshwater marsh, the first level of outcomes demonstrated by the conceptual model, with 0.9 m of sea level rise most of the impoundments will transition to a saltwater marsh, the second level of outcomes demonstrated by the conceptual model, and with 1.2 m of sea level rise BBNWR's impoundment system will become completely inundated with salt water, the third level of outcomes demonstrated by the conceptual model (NOAA 2020).

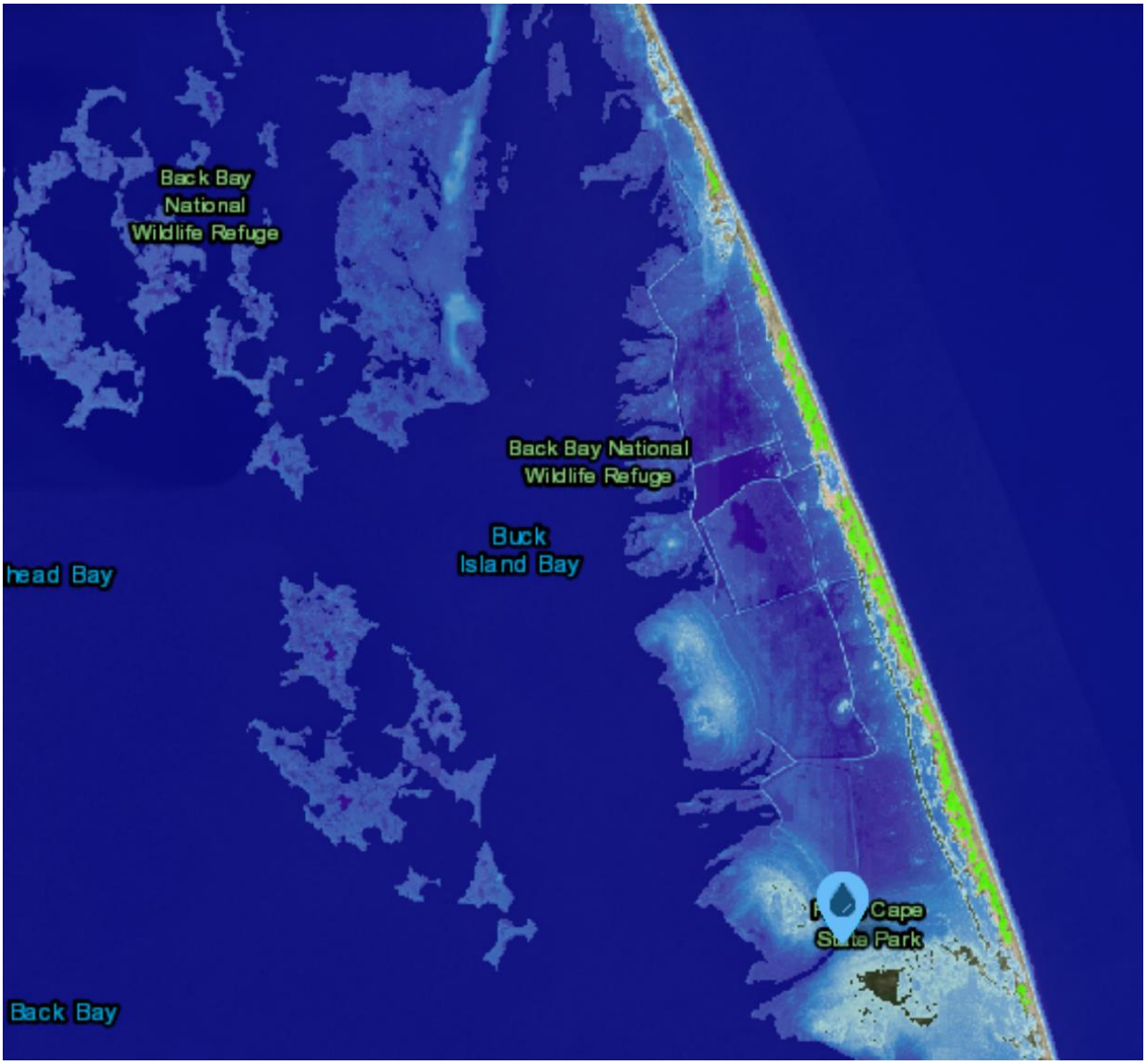

Figure 4. *Impact of a 2.4 m sea level rise on Back Bay. This sea level rise results in complete inundation of the impoundment system on the refuge making it inhabitable for migrating waterfowl. Image created with the NOAA Sea Level Rise Viewer (2020).*

SAVs stabilize soils and reduce shoreline erosion, there were two periods of high SAVs at BBNWR, the first being between 1958-1963 and the second being the year 1973. There were also two years of low SAVs on the refuge, the first being between the years 1964-1966 and the second being the year 1990. These years correlate with when salt water was being pumped into Back Bay but the City of Virginia Beach (Schwab et al, 1991). SAVs have demonstrated that they are highly sensitive to saltwater environments, dying off between 3.0 ppt and 5.0 ppt. (Norman and Southwick, 1991). SAVs cannot survive a sudden high volume of salinity, this was

also seen not only by pumping saltwater into Back Bay but by the Ashe Wednesday Storm in 1962 (Schwab et al, 1991). The differences between freshwater marsh habitats and saltwater marsh habitats are quite drastic, therefore only certain birds along the Atlantic Flyway can inhabit BBNWR. Within the east coast of the United States freshwater marshes are dominated by freshwater plants while saltwater marshes are composed of only a few estuarine and marine plant species. Freshwater marshes have twenty to forty species of plants growing intertidally with over one hundred species of plants growing where water is flooding somewhat frequently, saltwater marshes however have an average of ten plant species growing in regularly flooded areas of the marsh and thirty to forty plant species growing in monthly flooded areas of the marsh. Lower freshwater marshes tend to be more erodible because of the lowered biomass of plant roots, less plant litter is produced in the winter and spring therefore they become finer particles, although freshwater marshes are found to have on average 35% of organic content within their sediments while saltwater marshes are found to have 15% on average (Odum, 1988).

The bird populations within BBNWR depend on these SAVs to have a stable habitat, however they also depend on the recurring fish populations that inhabit the bay and impoundments within the refuge. With BBNWR being defined as an oligohaline estuary the fish community is dominated by estuarine and marine species. Data from Odum (1988) suggest that marine and brackish water fish species are better suited to exploit the lower salinity conditions in an oligohaline estuary than an almost completely freshwater conditions in a tidal freshwater estuary. Alternatively, freshwater species were shown to have difficulty penetrating higher salinity waters. These observations were consistent with Deaton & Greenberg's conclusions that the most severe changes within ionic ratios, would possibly be a limiting factor to invading species, they would occur within the range of 0-2 ppt salinity rather than in the range between 5-8 ppt salinity (Odum, 1988). Within BBNWR a total of forty-eight species of fish were collected in 1952, this included nineteen freshwater species, twenty-three fresh/brackish species, and six marine species this study confirmed that Back Bay was an oligohaline estuary (Southwick and Norman, 1991). Based on a survey performed by The Cornell Lab of Ornithology several species of heron such as King Rails, Least Bitterns, and the American Bittern make BBNWR their home year round and rely on the refuge for breeding in the summer months as well as a safe nesting habitat. The King Rails and American Bittern require a freshwater marsh for its habitat, the tall grasses and reeds are used as a safe cover although they cannot survive in a saltwater marsh environment, these species of birds feed primarily at low tide so they require plant coverage and shallow water (Scribner et al., 2017). Alternatively, the Least Bittern hunts for its food in deeper waters utilizing reed stalks as ladder so that the bird does not go below the water level (CU, 2015). These species of birds' vulnerability are not unilateral, because of this some species of birds will be affected by sea level rise before others, and some will adapt to a higher seal level before having to abandon its habitat. American Black Ducks visit the refuge in the winter to use the freshwater marsh for its habitat, but it has been seen that they can nest in saltwater marshes (Scribner et al., 2017). Dabbing ducks, Canadian Geese, and Tundra Swans prefer a freshwater marsh habitat while species like diving ducks, mergansers, snow geese, and clapper rails, prefer saltwater marshes (Odum, 1988).

Hazards and Threats

BBNWR is threatened with not only sea level rise and strong storm surges but with the hazards that are associated with these; inundation, salinification, erosion, over wash, and accretion of sediments (Clough and Larson, 2009). The Ashe Wednesday Storm of 1962 has been the most significant storm surge BBNWR has seen, several dune system breach points occurred at Little Island Park, south of Bodie Island located in False Cape State Park, and along the North Carolina and Virginia border. The Ashe Wednesday Strom had a storm surge over 2.4 m to the relative mean of low water level around Little Island Park, along with a storm surge of 2.2 m at Sewell's Point NOAA tidal gauge (Ambrosen and McDaniel, 1962). Since the Ashe Wednesday Storm of 1962 the mean water level at BBNWR has risen 0.3 m due to sea level rise, resulting in the baseline low water level no longer being 2.1 m but 1.8 m (Titus et al. 2009). There are two responses barrier islands can exhibit during a storm surge, the first being a swash regime, water will flow up the dune system and create erosion on the foreshore but there will be a complete storm recover and the sand will eventually return to its normal resting place. The second response is called an over wash regime, this is where water flows over the dune system and causes erosion on both sides of the dune, the Ashe Wednesday Storm was an over wash regime (Sallenger, 2000). Storm surges breaching the barrier island like the Ashe Wednesday Storm will result in a rapid transition from a freshwater ecosystem to a saltwater ecosystem within BBNWR. Alternatively, sea level rise on the back barrier would not only bring a slower onset of salt water into the refuge but would also lead to the reduction and narrowing of impoundment and dune structures, meaning a loss of freshwater marsh habitat. However, sea level rise only seen on the back barriers of the island will be a slower transition from a freshwater ecosystem to a saltwater ecosystem. A sudden spike of salinity within Back Bay would create inhabitable conditions for SAV beds as well as disabling freshwater fish eggs, often resulting in a lower survival rate to adulthood (Schwab et al, 1991). Another effect of sudden saltwater intrusion into the bay would be the inability for the Back Bay impoundment system to share water with the bay, doing so would decrease the SAV population therefore decreasing the migrating bird population within BBNWR (Karlov et al., 2017). Alternatively if there were to be a dune barrier breach, Back Bay would become a lunar tidal system rather that a wind tidal system, meaning that the refuge would have to rely on annual rainfall to fill the impoundments on the refuge rather than the wind tides that are currently pushing water into the refuge (Giacomangeli et al., 2017).

Inundation of BBNWR will make it exceedingly difficult for SAV beds to stabilize and grow, SAV beds do not thrive in waters with a high turbidity rate or deep waters. High turbidity waters inhibit water to penetrate SAV beds at the bottom of Back Bay, as a result this leads to reduced germination of SAVs. Inundation will also prevent the drainage of the freshwater impoundments within the refuge to the bay and cause moist soil plants to decrease their germination and seedling periods, therefore decreasing SAV populations (Fredrickson and Taylor, 1982). If BBNWR were a saltwater marsh, it is likely that migrating shorebirds would become the dominant species on the refuge because they would then be able to inhabit both the seaside of the dune system and the newly transitioned saltwater marsh impoundment system (Giacomangeli et al., 2017). Relative to the year 2000, global sea level rise is expected to rise

0.1-0.2 m by the year 2030, then 0.2-0.4 m by the year 2050 demonstrated in figure 5, and 0.3-1.3 m by the year 2100 demonstrated in figure 6 (Sweet et al, 2017). Combining global sea level rise scenarios from NOAA and the principle that the Back Bay region is experiencing a doubled rate of sea level rise compared to other regions around the world it can be concluded that BBNWR will be inundated beyond a freshwater marsh ecosystem function by the year 2050 (Karlov et al., 2017). Future scenarios have little effect on the projected global sea level rise within the first half of the century, although they begin to significantly affect the second half of the century. New scientific data regarding the Antarctic ice sheet stability shows that with high emission scenarios global sea level rise could exceed 2.4 m by the year 2100 demonstrated again in figure 4 (Sweet et a, 2017). In the last three decades it has been observed that Artic land and sea ice loss continues and in most cases is accelerating, there is a degree of certainty that Alaska glacier has lost a significant amount of mass within the last 50 years, from the year 1984 it has been observed that the annual average mass of ice loss is greater than the previous year based on gravitational data from satellites. The average loss of ice mass form Greenland was 269 Gt per year between the years 2002 and 2016. It has also been observed that the annual average artic sea ice has decreased in extent from 3.5% to 4.1% per decade since the 1980s, as a result becoming thinner between 1.3-2.3 m and beginning to melt on average 15 more days per year. It has been calculated that with artic wide ice loss expected to continue it is highly likely that by the year 2040 there will be sea ice free summers, with this increasing the background rates of sea level rise (Taylor et al, 2017).

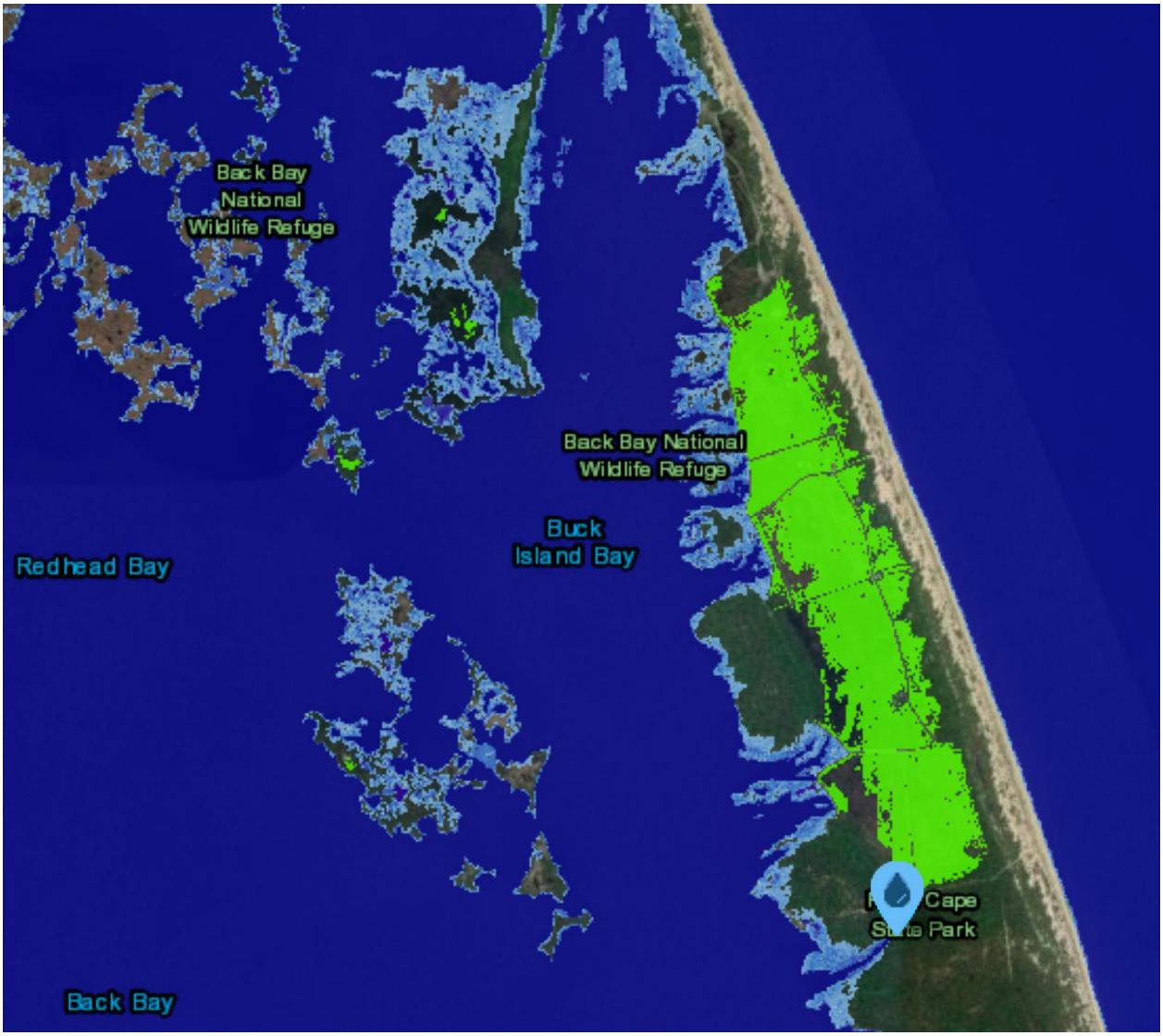

Figure 5. *Impact of a 0.3 m sea level rise on Back Bay. This sea level rise results in little inundation of the impoundment system on the refuge making it habitable for migrating waterfowl. Image created with the NOAA Sea Level Rise Viewer (2020).*

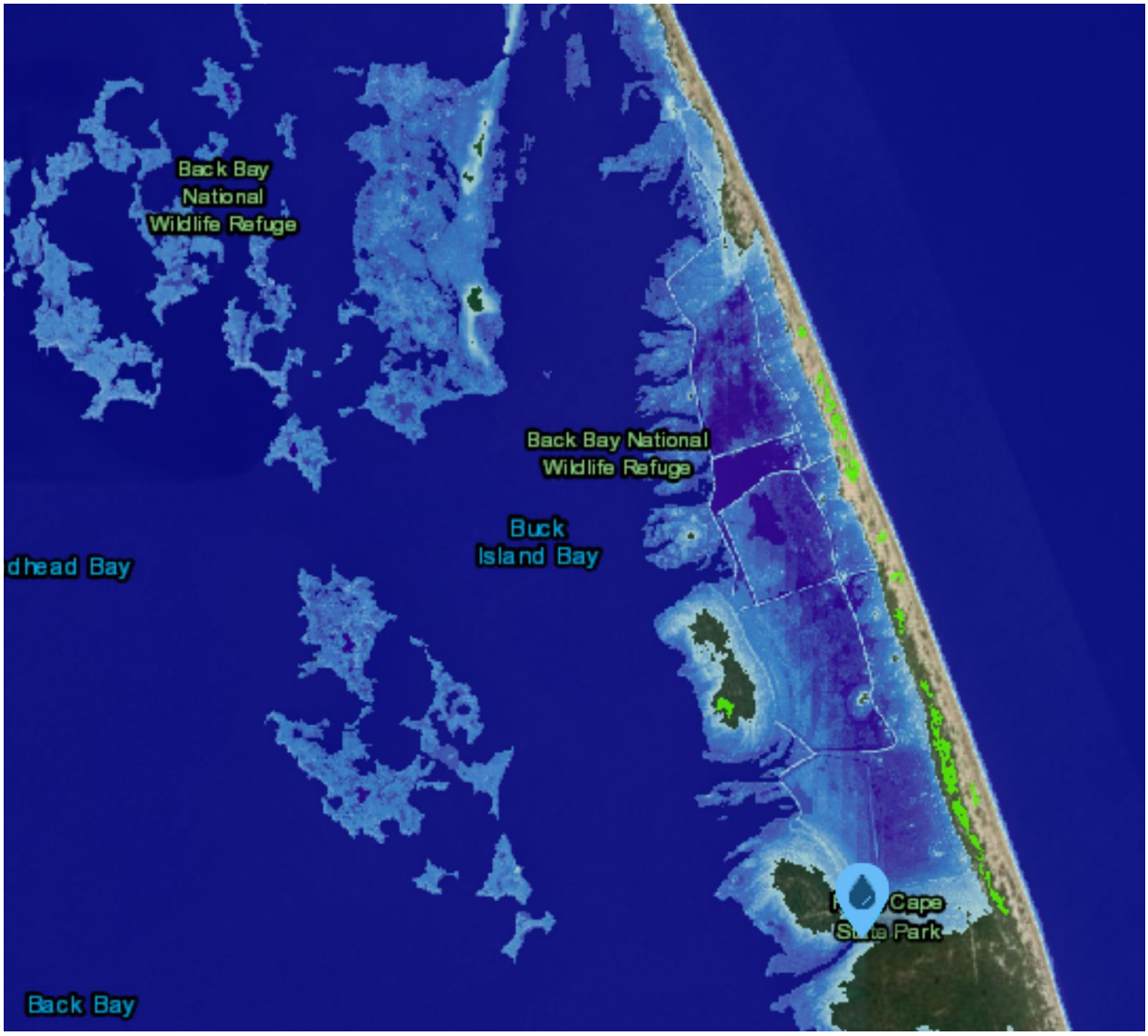

Figure 6. *Impact of a 1.2 m sea level rise on Back Bay. This sea level rise results in complete inundation of the impoundment system on the refuge making it inhabitable for migrating waterfowl. Image created with the NOAA Sea Level Rise Viewer (2020).*

Foresight and Possible Futures

According to Sweet (2017) by the year 2030 sea level is expected to rise 0.1-0.2 m, considering that the rate of sea level rise in Back Bay is double the global prediction it is safe to assume that sea level will rise 0.2-0.4 m by the year 2030. Looking at projections from NOAA's marsh migration model with 0.3 m of sea level rise (figure 7) it is shown that most of BBNWRs marsh will become saltwater marsh with the northern most impoundments becoming slightly inundated. This being considered migrating wintering waterfowl will only be able to utilize less than half of the refuge, while migrating shorebirds will still be able to utilize the refuge. By the year 2050 sea level rise is expected to rise 0.2-0.4 m according to Sweet (2017), looking at the

values of sea level rise doubled it is projected that within Back Bay sea level will rise 0.4-0.8 m. Using NOAA's marsh migration model with 0.6 m of sea level rise (figure 8) BBNWR's impoundment system will become a total saltwater marsh ecosystem with most of the impoundment being unconsolidated shore and open water. By the year 2050 migrating wintering waterfowl will no longer be able to inhabit BBNWR and will have to travel to False Cape State Park to feed and breed, alternatively the refuge will be completely inhabited by migrating shore birds. Finally, by the year 2100 Sweet (2017) predicts that sea level will rise 0.3-1.3 m, doubling this prediction, Back Bay will experience a sea level rise anywhere from 0.6-2.6 m. Taking the average of this prediction and using NOAA's marsh migration model looking at 1.5 m of sea level rise (figure 9) BBNWR will be completely inundated with saltwater, erasing the impoundment system from the refuge, turning the back side of the dune system into unconsolidated shore. This means that by 2050 the prediction for migrating wintering waterfowl is that they will no longer be able to inhabit BBNWR, however with 1.5 m of sea level rise, False Cape State Park would then be turned into a brackish/saltwater marsh while taking away part of its own land coverage. A small percentage of migrating wintering waterfowl would be able to inhabit False State Cape Park while migrating shorebirds would be able to use the entirety of the park and only the small remaining dune system of BBNWR. Including the high emission scenarios by Sweet (2017) it is projected that sea level rise could exceed 2.4 m, according to NOAA's marsh migration model (figure 10) this would mean that all of BBNWR would become open water, while False Cape State Park turns into primarily unconsolidated shore, open water, and a small portion of saltwater marsh. Therefore, migrating wintering waterfowl would no longer be able to inhabit BBNWR or False Cape State Park. With this amount of unconsolidated shore and water it is also unlikely that migrating shorebirds would also use this habitat for breeding and feeding grounds.

It is highly unlikely that BBNWR will remain a freshwater marsh ecosystem in the future, rather it is very likely, BBNWR will become a saltwater marsh ecosystem. BBNWR is on course to transition from a freshwater marsh ecosystem to a saltwater marsh ecosystem due to the barrier island being inundated by strong storm surges and sea level rise, because of this if the barrier island were to be left to natural process, without refuge interference, the dune system of Back Bay would begin to slowly migrate westward merging with the low lying farmland of Pungo before becoming completely inundated by sea level rise. While sea level rise is likely to inundate BBNWW by 2050 and cause migrating wintering waterfowl to no longer inhabit the refuge, a strong storm surge could break the barrier dune system and inundate BBNWR before then, speeding up the sea level rise timeline while also making the refuge unhabitable for migrating wintering waterfowl. Since the Ashe Wednesday Storm of 1962 a storm surge would only need to reach the height of 1.8 m to over wash the barrier dune system of BBNWR (Titus et al. 2009). While sea level rise is not likely to reach a height of 1.8 m until 2100 a storm surge could easily breach the barrier dune system and inundate BBNWR before then. Therefore it would be in the best interest of refuge managers to facilitate a migration of the freshwater marsh ecosystem westward into the low-lying farmland of Pungo. While this migration will take time, it will be important to avoid a future where the dune barrier system of Back Bay can be breached by a strong storm surge.

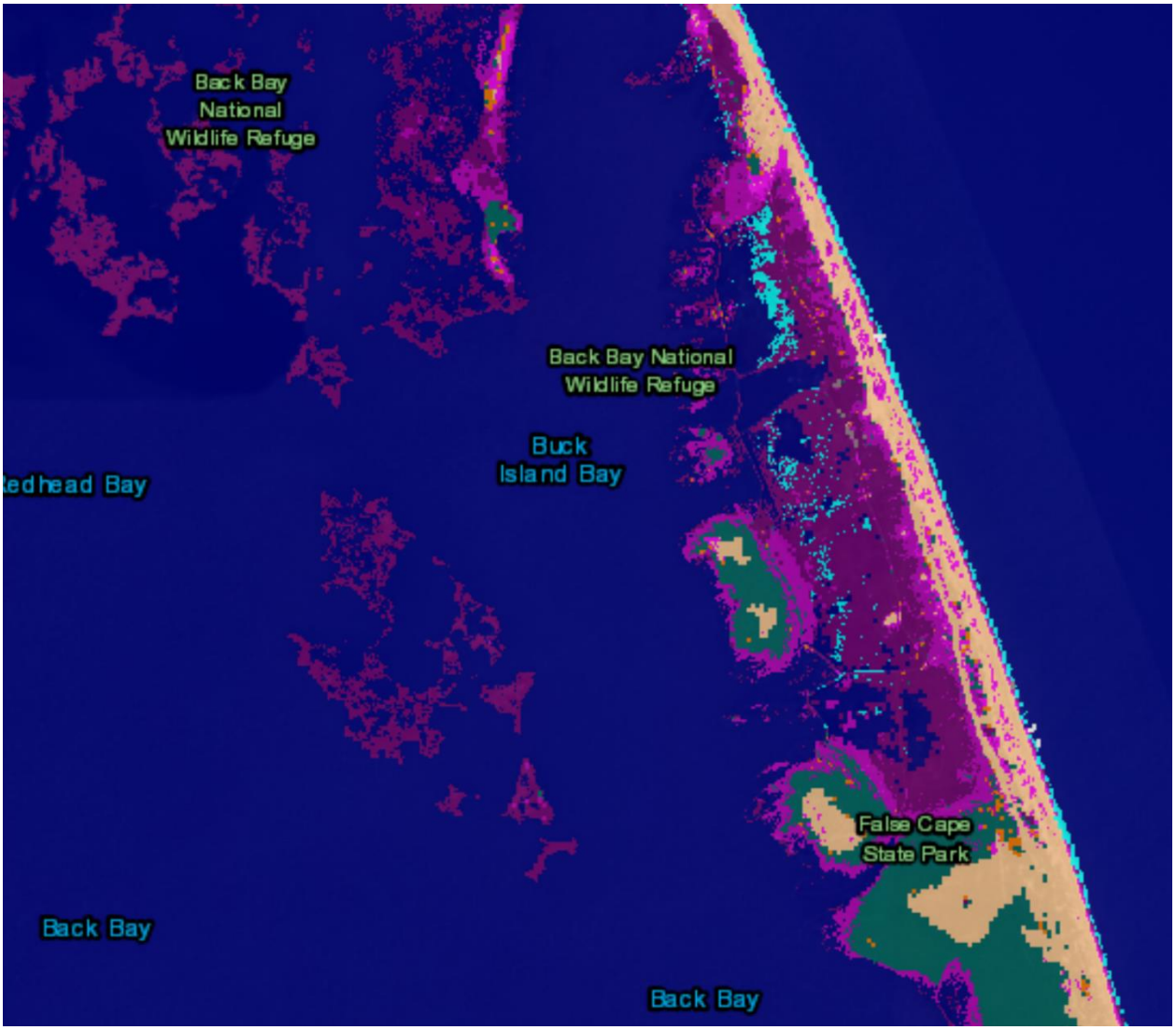

Figure 7. *Impact of a 0.3 m sea level rise on Back Bay. This sea level rise results in the impoundment system on the refuge becoming saltwater marsh and partial inundation of the northern impoundments. Image created with the NOAA Sea Level Rise Viewer (2020).*

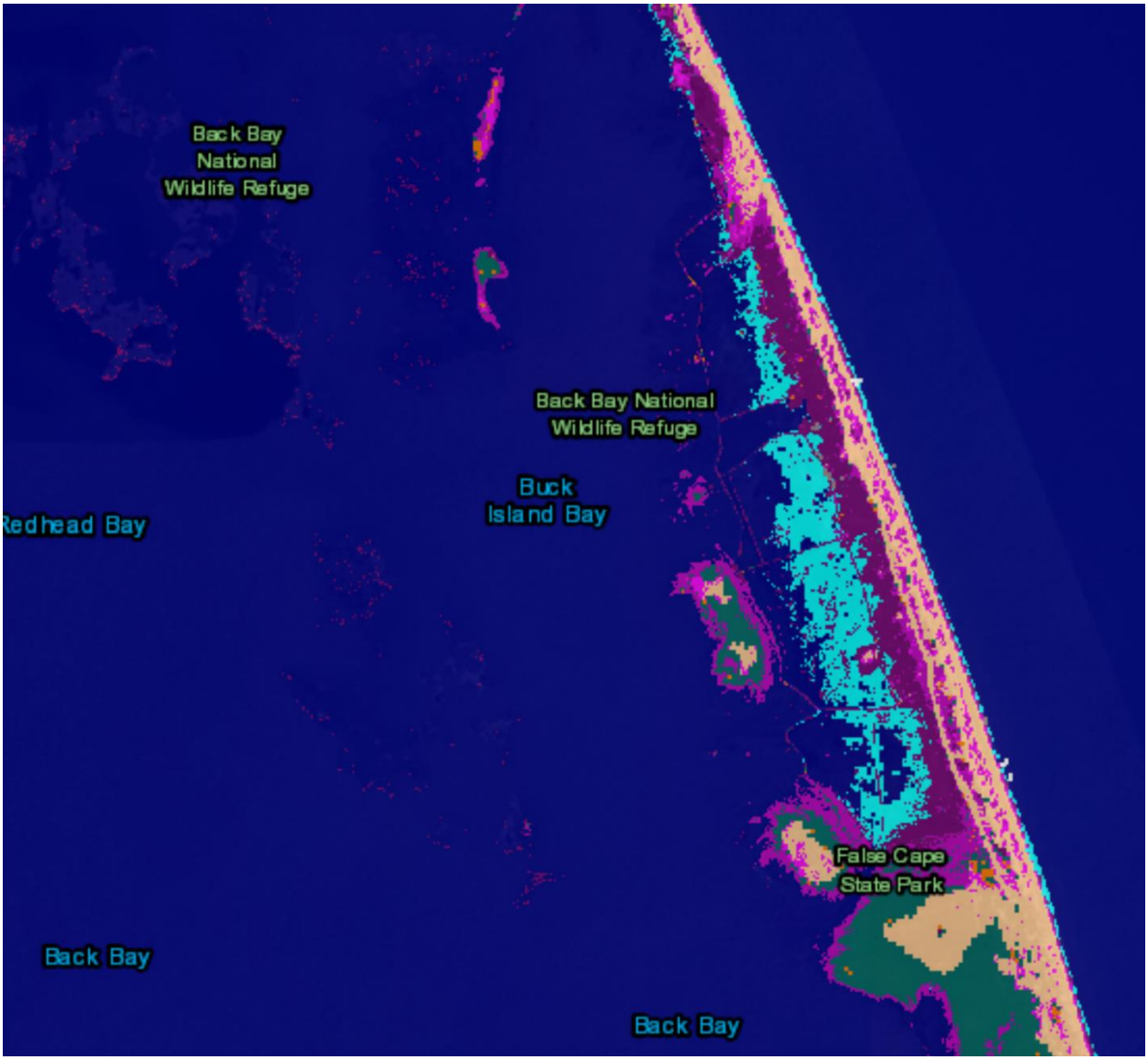

Figure 8. *Impact of a 0.6 m sea level rise on Back Bay. This sea level rise results in the impoundment system on the refuge becoming saltwater marsh, primarily unconsolidated shore, and open water. Image created with the NOAA Sea Level Rise Viewer (2020).*

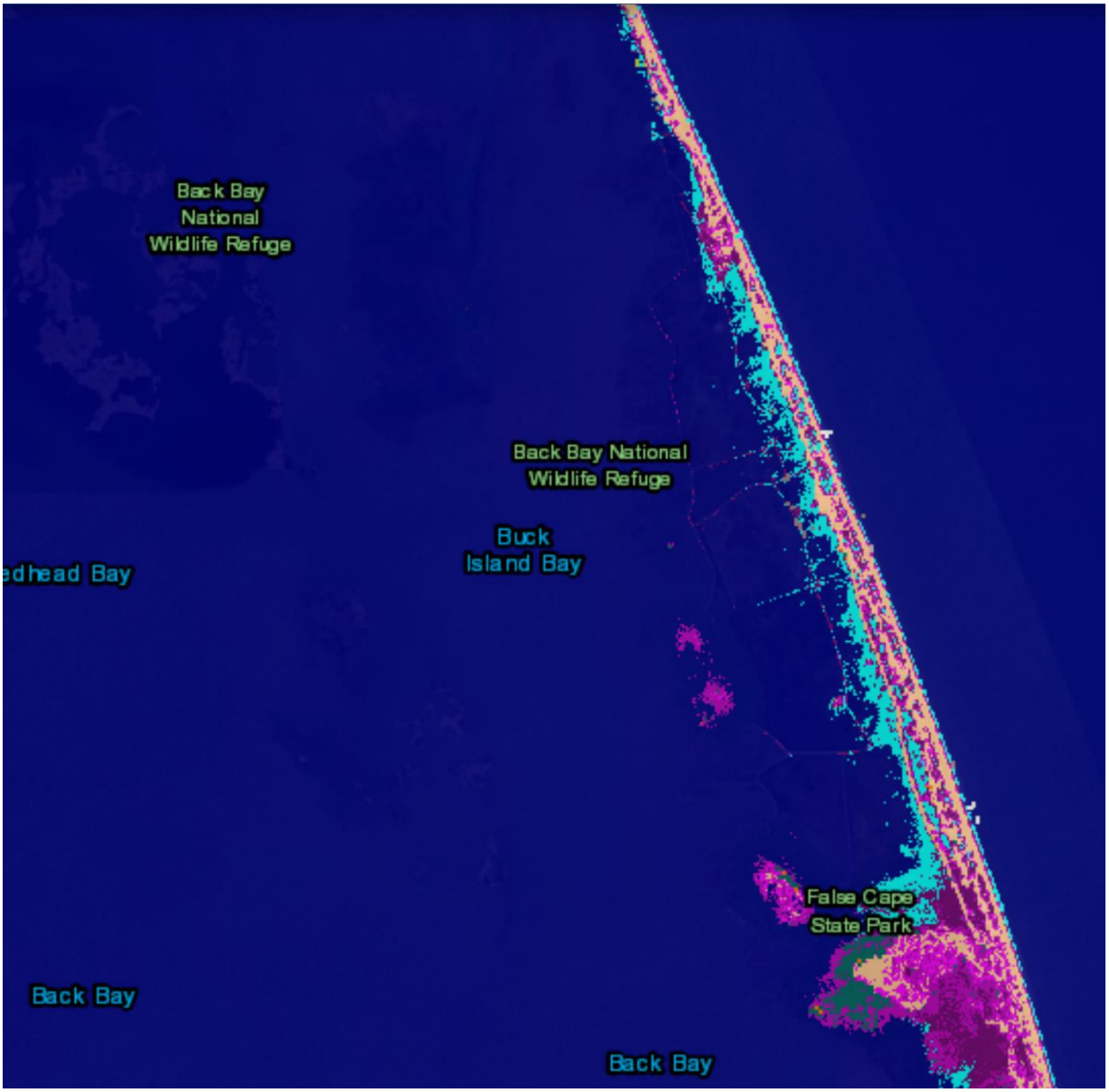

Figure 9. *Impact of a 1.5 m sea level rise of on Back Bay. This sea level rise results in the impoundment system on the refuge becoming unconsolidated shore completely inundated with saltwater. Image created with the NOAA Sea Level Rise Viewer (2020).*

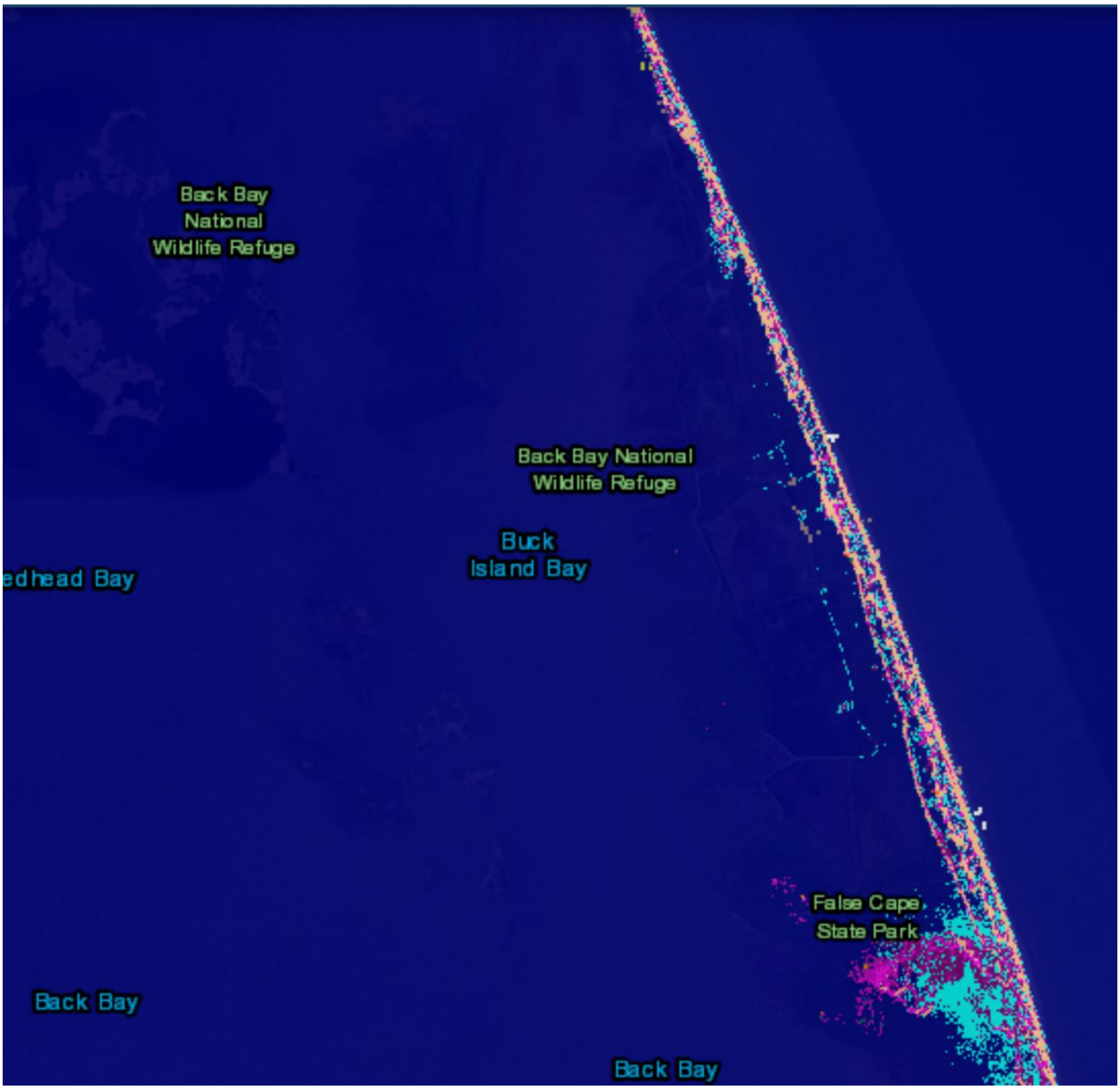

Figure 10. *Impact of a 2.4 m sea level rise on Back Bay. This sea level rise results in the impoundment system on the refuge becoming open water, while False Cape State Park becomes unconsolidated shore. Image created with the NOAA Sea Level Rise Viewer (2020).*

Interventions

BBNWR refuge managers should consider finding ways to slow down the transitions from a freshwater marsh ecosystem to a saltwater marsh ecosystem and help facilitate marsh migration across BBNWR into the low-lying farmlands of Pungo. Although refuge managers will not be able to slow the effects of sea level rise, they may be able to help prevent breaks in dune barrier system due to strong storm surges. There are several options BBNWR could partake in to reduce the chance of a break in the dune barrier system; stakeholders and refuge managers

could invest in building a sea wall, elevating the marsh and dune system, or if a breach were to occur, filling in the affected dune area immediately to stop a sudden inundation of saltwater. Alternatively, the stakeholders and refuge managers of Back Bay could choose to do nothing and let saltwater intrude into the freshwater marsh ecosystem of Back Bay over time in hopes of having the habitat adapt. With this approach it is expected that the refuge would see the migrating wintering waterfowl population finding another habitat rather quickly while the migrating shore bird population take over the newly saltwater marshes of Back Bay then abandon the habitat due to complete inundation of the refuge. Although refuge managers should consider the benefits of protecting BBNWR from sea level rise or a strong storm surge dune barrier breach and facilitate the Back Bay marsh ecosystem to migrate westward so that is can attach itself to the low lying farmlands of Pungo while adapting to the changes in water salinity as they increase from the Albemarle and Currituck sound.

Building a sea wall along the shoreline of BBNWR would be a costly option and would cause varying erosion as well as disrupt the ecosystem along Back Bay's dune system. Refuge managers and stakeholders would have to put in allocated resources and hours of manual labor to achieve the desired sea wall Back Bay would need, unfortunately building a sea wall is not a permanent solution to sea level rise and the wall would have to be up kept with the progression of sea level rise (Smallegan et al, 2017). As seen during the Ashe Wednesday storm of 1962 the dune system of Back Bay is breach-able and now has a lower threshold than before, this being said stakeholders and refuge managers could seek to fill in these storm breaches immediately so they cause less damage to the overall ecosystem of Back Bay rather than letting a breach continue unmonitored. This would require a dedicated team of workers that have the resources ready if a strong storm surge would occur, it also poses a hazardous work environment for those trying to fill a breach in Back Bay's dune system, which stakeholders and refuge managers would have to take into consideration if they choose to do this. Unfortunately, this does not change the outcome of sea level rise towards the refuge but could help mitigate immediate threats to the ecosystem of Back Bay. One of the most effective preventions against sea level rise BBNWR could take is building a buried sea wall within the dune system as well as elevating the physical dune, this would take many years of dune reconstruction and would be a very costly option, something stakeholders and refuge managers would have to take into consideration. Although this would prevent increased erosion from storm surges and sea level rise from the Atlantic Ocean, it would not prevent inundation within the back barrier of BBNWR as well as it would have to be rebuilt as sea level rise increased (Smallegan et al, 2017). If BBNWR seeks to combatant the salinity increase due to inundation within the impoundments the refuge managers could consider putting in pumps that filter in freshwater and filter out saltwater throughout the impoundment system, this would be a short term fix for BBNWR due to sea level rise completely inundating the impoundment system between the years 2050-2100.

Discussion and Conclusion

BBNWR is threatened with sea level rise and strong storm surges, with these threats comes inundation and ultimately an increase of salinity within the impoundments and the bay, as

well as the possibility of barrier dune breaches and a loss of habitable land on the refuge. As seen by the Ashe Wednesday Storm of 1962, the dune system around BBNWR can be breached by a storm surge causing an influx of saltwater into the refuge, damaging the SAV bed population and affecting the waterfowl habitat. Unfortunately, global sea level rise is not a reversible wicked problem and BBNWR will only see increased impacts of sea level rise as time goes on. If NOAA (2020) projections are accurate, BBNWR will be completely inundated with 1.5 m of sea level rise, this is when the refuge would no longer be able to serve as a saltwater marsh and become completely water, with only 0.3 m of sea level rise. BBNWR could expect all of their freshwater marshes to fully transform into saltwater marshes, with this losing their primary waterfowl habitat on the refuge. Unfortunately, because of sea level rise it is now easier for a storm surge to breach the barrier dune system because a storm surge would only have to exceed 1.8 m to do so, unlike the Ashe Wednesday Storm where a storm surge of 2.2 m was needed to breach the barrier dune system. The freshwater marsh ecosystems of BBNWR are extremely fragile, because Back Bay ranges in salinity from 0-3 ppt, an influx of saltwater would quickly alter the freshwater marsh ecosystem making it uninhabitable for most of the waterfowl species on the refuge, projected sea level rise makes salinity change unavoidable over time as the refuge becomes inundated. Data has shown that within BBNWR the majority of SAV beds thrive in freshwater marshes and are seen to have a high diversity within the marsh ecosystem. Waterfowl thrive off high diversity within SAV beds, using these beds for food and shelter within their migrating period. Therefore if BBNWR's impoundment system were to be suddenly inundated with saltwater either due to seal level rise or a storm surge causing a break in the barrier dune system, because it is currently a freshwater marsh ecosystem, the refuge would exhibit a decrease in the diversity and overall number of SAV beds, this leading to a decrease in the diversity and overall waterfowl population (Odum, 1988) that use BBNWR along the Atlantic Fly. The mission of BBNWR is to "serve as a breeding ground and as an inviolate sanctuary for migratory birds, to conserve and protect other wildlife including endangered and threatened species and wetlands" (Brandwein et al., 2010). Although BBNWR can still function as a resting place and habitat for migrating birds for a long time if refuge managers can prevent or combatant sudden dune barrier breaches, therefore giving the freshwater marsh ecosystem time to migrate westward. Unfortunately, when sea level rises several meters BBNWR will no longer exist but for the next 30 to 80 years BBNWR could still play an important role for the Atlantic Flyway.

Recommendations

BBNWR is a key breeding ground and sanctuary along the Atlantic flyway for migrating waterfowl, along with a habitat for many other threatened and endangered species. Its freshwater marsh ecosystem is vital for the migrating wintering waterfowl that inhabit Back Bay. Acknowledging that sea level rise as well as strong storm surges over time will increase inundation and salinity change on the refuge and permanently alter the freshwater marsh ecosystem of Back Bay. By the year 2050 with 0.6 m of sea level rise the freshwater marsh habitat of BBNWR is expected to become a saltwater marsh habitat. Although with a strong storm surge causing a breach in the dune barrier system would cause the refuge to be inundated

with salt water before sea level rise could reach 0.6 m. There are several ways BBNWR could adapt and combatant these threats. Refuge managers and stakeholders could implement a strategy to build sea walls underneath or behind the existing dune structures on the refuge as well as build up the height of the overall dune system and the outer impoundment barriers on the bay side of the refuge. This would be a short-term solution to sea level rise and may slow the impact of strong storm surges if dunes where to be built up several feet. A longer term solution that building a sea wall would be that U.S. Fish and Wildlife Service could consider buying land property in the low-lying farmlands of Pungo so that the current freshwater marsh ecosystem on the refuge could migrate west into this land, along with this expanding the area BBNWR managers oversee. This would be a moderate long-term goal given the degree of sea level rise within the region and how much land U.S. Fish and Wildlife Services is willing to buy to maintain the freshwater marsh ecosystem and the Atlantic Flyway habitat the refuge is a part of. Alternatively if the U.S. Fish and Wildlife Service were to agree to buy land west of the refuge in Pungo, refuge managers and stakeholders could begin to convert the now owned land in Pungo into the beginnings of a freshwater marsh ecosystem by planting freshwater SAV beds and introducing mudflats, therefore making it easier for the freshwater marshes located on what is currently BBNWR to migrate into Pungo and acclimate to its new geographical location. The mission of the U.S. Fish and Wildlife Service is to "work with others to conserve, protect and enhance fish, wildlife and plants and their habitats for the continuing benefit of the American people", it is my belief that this mission along with BBNWR's mission will still be supported if the above options are taken into consideration. It is my recommendation the U.S. Fish and Wildlife Service buy the low lying farm lands of Pungo for refuge managers and stakeholder to convert into new freshwater marsh ecosystems for the migration of the current freshwater marsh on the refuge, this not only preserves the migrating wintering waterfowl habitat but also does not try to fight the certainty of sea level rise. What was the old BBNWR will be transformed into a saltwater marsh ecosystem for the migrating shorebirds before transforming into unconsolidated shore and water. Once the saltwater marsh ecosystem is inundated completely it will also migrate west onto the low lying farmlands of Pungo, giving the existing freshwater marsh enough time to migrate further west, preserving both habitats, this of course cannot be done without public outreach from stakeholders and the help of Pungo's farmland owners.

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