MATTAMUSKEET NATIONAL WILDLIFE REFUGE: THE THREATS THE LAKE AND THE SURROUNDING COMMUNITIES FACE

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The System

Mattamuskeet National Wildlife Refuge (NWR) protects and conserves migratory birds and other wildlife resources. The foundation of the refuge is Lake Mattamuskeet, a freshwater lake that requires severe restoration efforts. The lake is a primary source of freshwater for local farmers that use it on their agricultural lands. It is also a high economic driver during peak seasons and directly benefits Hyde County. When developing successful restoration strategies, understanding the system of the lake and its' biological and economic value is critical.

Threats

Three human-originated factors are discussed as specific threats that are impacting, and expected to further impact, the living and nonliving factors associated with Mattamuskeet NWR: land use, socio-economic activities, and sea level rise. High eutrophic levels are frequent in response to agricultural runoff. Changes in climate and sea level rise can result in permanent and increased flooding, salinity changes, and other coastal hazards. Successful mitigation strategies can be achieved by understanding how the threats affect Lake Mattamuskeet.

Weaknesses

Within the lake, several factors vulnerable. Water quality is a variable within the refuge that can directly constitute threats. The biological system of freshwater wildlife and the human system of local economy both have numerous vulnerabilities, but do not change much over time. However, if it were not for the change in land use, socio-economic activity, sea level rise, and climate change; the vulnerabilities associated with the freshwater wildlife and local economy would not be as threatened. Agricultural runoff has proved to be rich in phosphate and nitrogen that accumulates in the lake, preventing the freshwater levels from thriving. This runoff forces algal blooms that can block sunlight from reaching the lake bed causing severe vegetation die offs. With sea level rising, Hyde County's crop production could face an increased risk of salt intrusion from coastal flooding and increased storms. Higher sea levels will also cause the tide gates along the canals from the Sound to the lake to stay closed, leaving limited options for draining.

Possible Futures

Three scenarios are developed discussing how changes in eutrophic levels can affect the economy. Increased or continued levels of pollution from agricultural runoff can lead to dead zones. With loss of biodiversity, revenue in relation to hunting, fishing, and wildlife observation will decline. Reducing the amount of nutrient input could allow for the system to gradually

improve from current quality, giving aquatic vegetation the opportunity to live successfully allowing for economic profit. Disrupting the input of nutrients into the lake from agricultural lands allows the lake's quality to recuperate and assist in an influx of tourism. This will also allow in the future investment of new tourism furthering economic benefits.

Other areas with water quality problems like the Chesapeake Bay, Lake Apopka, and Grand Lake St. Marys have had outcomes that can aid in making a plan for Lake Mattamuskeet. In Virginia, 80% of the tidal Chesapeake Bay is partially or fully impaired by toxic contaminants. With the direct efforts of the local community, new targets for nutrient reduction have been met (Chesapeake Bay Program, 2017). With restoration underway, 2009 benefits reached up to $504 billion from the Bay's ecological services (Chesapeake Bay Program, 2017). Lake Apopka located in Florida contains toxic algal blooms similar to Mattamuskeet. By constructing a filtration zone and the state's participation in the buyout of farms along its perimeter, water quality has improved, and aquatic vegetation has begun to recover. This restoration has salvaged the economy, creating hundreds of jobs and millions in economic revenue. One unsuccessful area with issues resembling those of Lake Mattamuskeet is Grand Lake St. Marys located in Ohio. A revenue of almost $50 million was lost, advisory signs to prompt the avoidance of contact with water, and large fish die offs were soon to follow the severe algal blooms. With toxic algae, exceptional amounts of cropland, and low lake depth, this lake can portray a likely future for Mattamuskeet if efforts are not made.

Three different scenarios have been conducted by the Union of Concerned Scientists in 2017 projecting the outcomes of Hyde County due to sea level rise. These different scenarios are based on the rate of carbon emissions globally. If carbon emissions drastically slow down, Hyde County is likely to see 2 feet (0.5 m) of sea level rise in the community by 2035, leaving as least 10% of the county flooded. If carbon emissions continue at the rate they are today, Hyde County is likely to see 4 feet (1.2 m) of sea level rise by 2030, leaving at least 20% of the county flooded and inevitable salt water intrusion on local farms and in Lake Mattamuskeet. If carbon emissions continue to increase throughout the century, Hyde County is facing up to 6.5 feet (2 m) in sea level rise, causing at least 40% of the county to be flooded, and most of the agricultural land and Lake Mattamuskeet likely to be lost due to salt water intrusion.

Decision Making

In order to change the future of the lake's ecology, support from Hyde County's government, farmers, residents, tourists, North Carolina Coastal Federation, North Carolina Wildlife Resources Commission, and the U.S. Fish and Wildlife Service is imperative. Participation in the restoration process of these stakeholders could help limit nutrient input thus recovering freshwater and vegetation numbers in the lake. However, all funding and regulations are passed through the officials in the U.S. Department of Interior.

Alternatives

Options to address the hazards include the restoration and re-opening of the Mattamuskeet Lodge, developing an agricultural management plan, and the opening of the gates that reach the surrounding canals. The Lodge's opening can create revenue and programs for guests to become informed and involved with the lake. Creating an agricultural management plan can give local farmers an opportunity to learn how to practice alternative farming techniques and how these practices are beneficial to the lake. The final option discussed involves the opening the gates to gradually transition salt water into the lakes ecosystem. Increasing salinity would not only aid in the removal of excess nutrients, but also help local wildlife adapt to the salinity changes that could inevitably happen to the area.

Proposal

In summary, this paper provides three mitigation options to help with the lakes quality and overall economy in Hyde County. The opening of the Lodge will help aid in community outreach and economic growth. Creating a regulation based on nutrient loading is also crucial in controlling fertilizer input. Opening the gates gives the ecosystem the opportunity to adapt to levels of salinity. By doing so this will aid in the removal of eutrophication as well as adapt native species to higher salinity levels to mitigate the occurrence of sea level rise. It is the authors' hope that these recommendations are taken into serious consideration.

1 Introduction

1.1 Mattamuskeet National Wildlife Refuge

Kayla Berger, Lena Midgette

Established in 1934, Mattamuskeet National Wildlife Refuge (NWR) located in Hyde County, North Carolina, currently owns 50,180 acres of land, ranging between forests, open water, wetlands, and crop lands (Fish and Wildlife Service, 2017; see Figure 1.1). Because this

refuge is located along the Atlantic Flyway, a popular migrating route for birds along the eastern coast of North America and the Appalachian Mountains, Mattamuskeet NWR is an important stopover site for many migrant birds. Waterfowl, such as Northern Pintails (*Anas acuta*) and Green-wing Teals (*Anas carolinensis*), are the most commonly found birds on the refuge during the winter season and contribute to the high volume of waterfowl hunting activities that take place from November-February annually (Fish and Wildlife Service, 2017). Receiving an average of 200,000 birds annually, waterfowl stop at the refuge to feed on the underwater grass beds, also known as submerged aquatic vegetation (SAV) and other emergent wetland plants along the lakeshore (North Carolina Coastal Federation, 2017). The refuge maintains 2,505 acres of waterfowl impoundments surrounding the lake using "moist soil techniques", this keeps the soil moist throughout the summer to promote growth of native wetland plants that are vital food for waterfowl in the winter (North Carolina Coastal Federation). While the refuge is known for its wintering waterfowl, it also supports species of shorebirds, wading birds, and birds of prey. Large wildlife like American Black Bears (*Ursus americanus*) and White-tailed Deer (*Odocoileus virginianus*) also live within the mixed habitat of open water, marsh, forests, and wetlands of the refuge (North Carolina Coastal Federation, 2017).

Eco-tourism, hunting, and fishing practices are economically beneficial to the refuge and Hyde County. For example, these activities brought in 32,750 visitors between October 1st, 2015- September 30th, 2016 and profiting roughly $3.7 billion to the Albemarle-Pamlico watershed (Dabson, 2016).

1.2 Lake Mattamuskeet

Kayla Berger, Lena Midgette

The centerpiece of the refuge is Lake Mattamuskeet, which encompasses 40,000 of the 50,000 acres, and was once considered the largest natural lake in North Carolina (Fish and Wildlife Service, 2017). The lake originally engulfed 120,000 acres of land before local farmers decided to drain the lake for additional agricultural space. The plan was to dredge 87 miles of navigable canals and build a steam-powered pumping plant to drain the lake waters to the Pamlico Sound (Dabson, 2016). The draining project was eventually abandoned due to the practice becoming impractical and too expensive (Fish and Wildlife Service, 2017). Because of

these landscape modifications, the lake is no longer considered to be “natural” today (North Carolina Coastal Federation, 2017).

The lakes shallow waters (average depth is 0.46 m) is what makes this body of water such a popular stopover site for many waterfowl due to easy access to SAV (North Carolina Coastal Federation). Other predatory animals rely on fish and other organisms in the lake. The most common fish include Black Crappie (*Pomoxis nigromaculatus*), Channel Catfish (*Ictalurus punctatus*), White Perch (*Morone americana*), Common Carp (*Cyprinus carpio*), and Largemouth Bass (*Micropterus salmoides*) (Dockendorf et al., 2014). The lakes fishery resources have also been recognized for their ecological, recreational, economic, and cultural importance (Dockendorf., 2014).

Lake Mattamuskeet is connected to the Pamlico Sound (see Figure 1.1) by four major canals (Main, Lake Landing, Waupoppin, and Rose Bay; Dockendorf et al., 2014). These canals are used as a drainage system to control water levels in the lake, with tide gates built at each canal to block salt water intrusion from the sound (Dockendorf et al., 2014). When the lake levels are higher than the sound, the gates open to drain the lake. When the sound levels are higher than the lake, the gates stay closed (Fish and Wildlife Service, 2017).

Figure 1.1 Map overview of Mattamuskeet National Wildlife Refuge and surrounding areas. *Google Earth, 2018.*

Figure 1.2 Zoomed image of focused system: Lake Mattamuskeet, Mattamuskeet National Wildlife Refuge. *Google Earth, 2018.*

1.3 The Challenge

Kayla Berger

Eutrophication occurs when too much nutrients are loaded in to a body of water, typically through runoff from surrounding land (Chislock et al., 2013). Nitrogen and Phosphorus from fertilizer runoff create harmful algal blooms in the lake, which kills the SAV. Fish and Wildlife Service (2017) officially reported zero SAV in Lake Mattamuskeet. The loss of SAV in Lake Mattamuskeet leaves oxygen levels low and depletes important habitat for fish and wildlife (Fish

and Wildlife Service, 2017). As sea level is continuing to rise in the Pamlico Sound, the tide gates are not draining the lake as efficiently, leaving limited options to drain polluted waters. Increase in global temperature and climate is also causing an increase in precipitation, which increases the rate of runoff and lake flooding (Butcher et al., 2015). If the ecological services provided by the lake are lost, Hyde County could face negative economic impacts (Dockendorf et a., 2014). U.S. Fish and Wildlife Service and Mattamuskeet National Wildlife Refuge managers held a public meeting on November 7th, 2017 to discuss a watershed restoration plan for the lake. They insisted to the public that these problems are not simple solutions, could take 20+ years, and are not likely to harm other local industries.

Goal Statement Provided by U.S. Fish and Wildlife Service (2017): "Protect the way of life in Hyde County, including opportunities for fisherman, hunters, and other recreational users, promoting tourism, and enhancing agricultural and commercial fishing interests by supporting thriving populations of fish, waterfowl, and other wildlife."

Achieving the objectives expressed in the goal statement requires an effort to change the current trajectory of the lake, which will lead to increasing eutrophication with significant impacts on wildlife and the socioeconomic environment. In this report, we first consider the problems that pose threats to the lake and NWR (Section 2) and discuss the vulnerabilities of the lake (Section 3). In Section 4, foresight is developed for the future of the lake where possible options are created (Section 5) based on these different scenarios. The final section (Section 6) discusses the various recommendations for this system based on what is currently known.

2 The Problems

2.1 Land Use and Socio-economic Activities

Lena Midgette

Surrounding the rim of the lake are many farms, businesses, schools, and residences. Nearby farming communities use their lands to yield crops of corn, grain, soybeans, and other vegetables. According to the 2012 North Carolina Census of Agriculture, there are approximately 158 farms in Hyde County covering an average of 107,559 acres of land (USDA, 2012). Figure 2.1 shows that 77.3% of the land is used for crops producing $133,411,000 in total for market value of products sold in this census (USDA, 2012). Hyde County's large amount of agriculture connects almost directly to the lake by wetlands and environmental processes through its close

proximity (see Figure 2.2). In developed countries, such as the United States, heavy use of animal manure and commercial fertilizers for agriculture are the main causes of eutrophication. Runoff from large agricultural fields enter bodies of water through irrigation practices and precipitation (National Geographic, 2011). Eutrophication occurs when a body of water contains too many nutrients of phosphorus and nitrogen. Normal levels of nutrients feed the growth of organisms like blue-green algae or cyanobacteria, but excess nutrients cause bacteria to grow excessively and can be harmful to the environment (National Geographic, 2011). The process of eutrophication can cause severe impacts on the environment, like rapid and excessive growth of algae and phytoplankton on the water's surface called algal blooms. These blooms can also lead to the death of marine mammals and shore birds that rely on the ecosystem for food. These blooms prevent sunlight from penetrating the water's surface. Beneath the surface, algal blooms also prevent organisms from absorbing oxygen. Sunlight is key for SAV which manufacture their own nutrients from sunlight, water, and carbon dioxide (National Geographic, 2011).

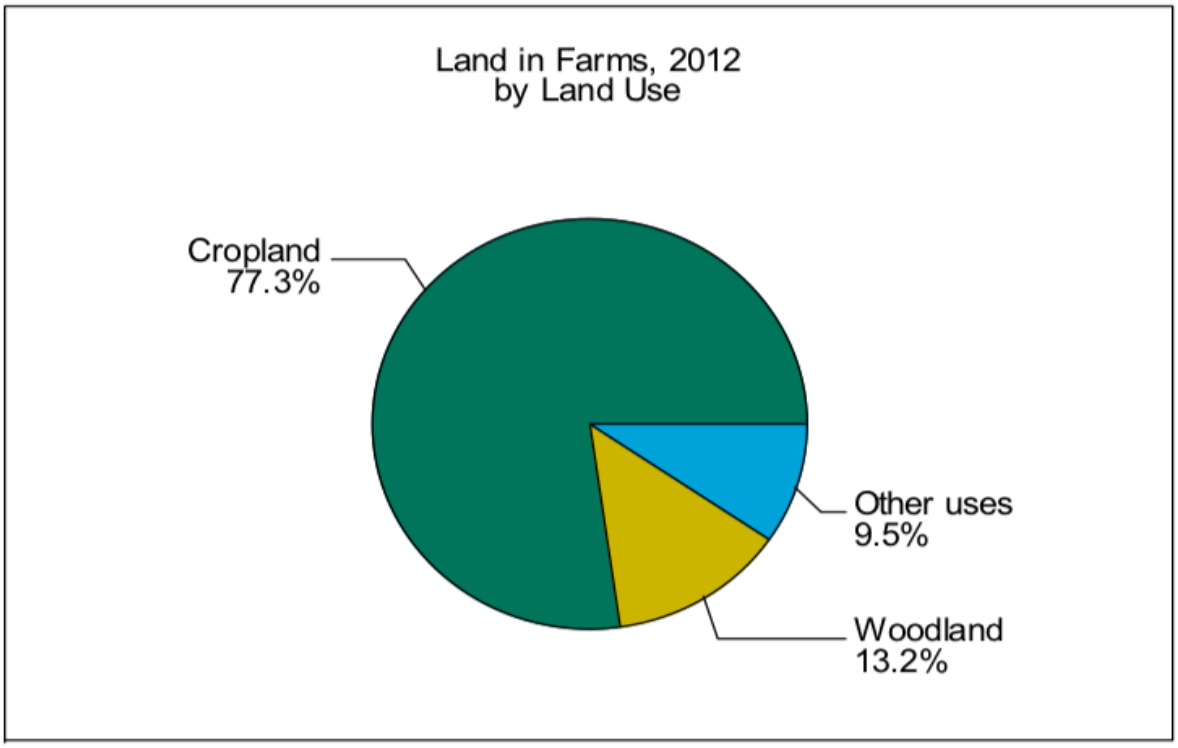

Figure 2.1 This graph shows the amount of land used for farming according to the 2012 Hyde County, North Carolina census. From *USDA (2012).*

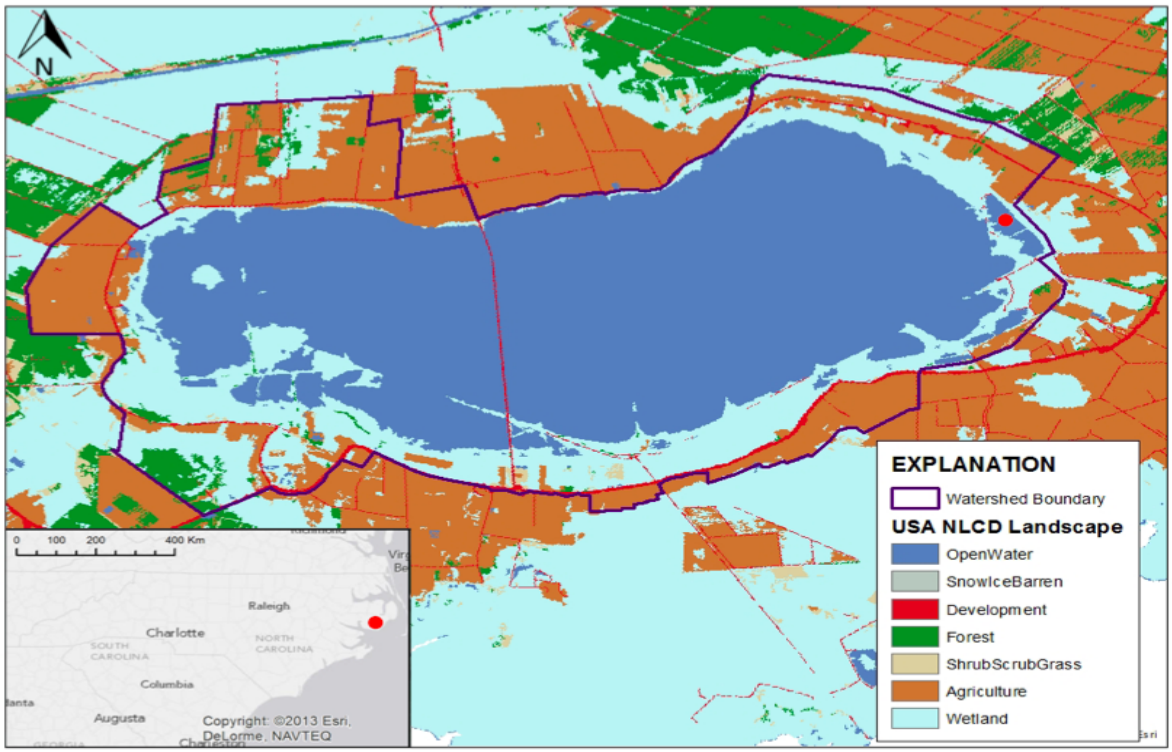

Figure 2.2 Map of the Lake Mattamuskeet watershed showing land cover. From *Winton (2016).*

2.2 Sea Level Rise

Kayla Berger

2.2.1 Climate Change

Climate change at regional and global scales has resulted in significant shifts of time-series trends and patterns of long term weather and hydrological observations, including maximum and minimum air temperatures, snow accumulation, snow to precipitation ratios, snowmelt timing, and stream runoff (Hansen et al., 2006). By now, many scientists have come to agreeance that the main driver of climate change is the expansion of the "greenhouse effect," caused by an exceeding rate of greenhouse gas emissions such as carbon and methane (NASA, 2018). NASA (2018) states that current carbon dioxide levels in the air are the highest in 650,000 years, with 408 ppm currently. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), global greenhouse gas (GHG) emissions will continue to increase over the next few decades and continued GHG emissions at or above the current rates could cause further warming and induce changes in the global climate system during the 21st century (IPCC, 2007). As the planet is currently 1.8°C warmer than it was in 1880 (NASA, 2018) and is projected to

rise further, this will cause an increase in surface temperatures and a decrease in ice cover (see Figure 2.3; Butcher et al., 2015).

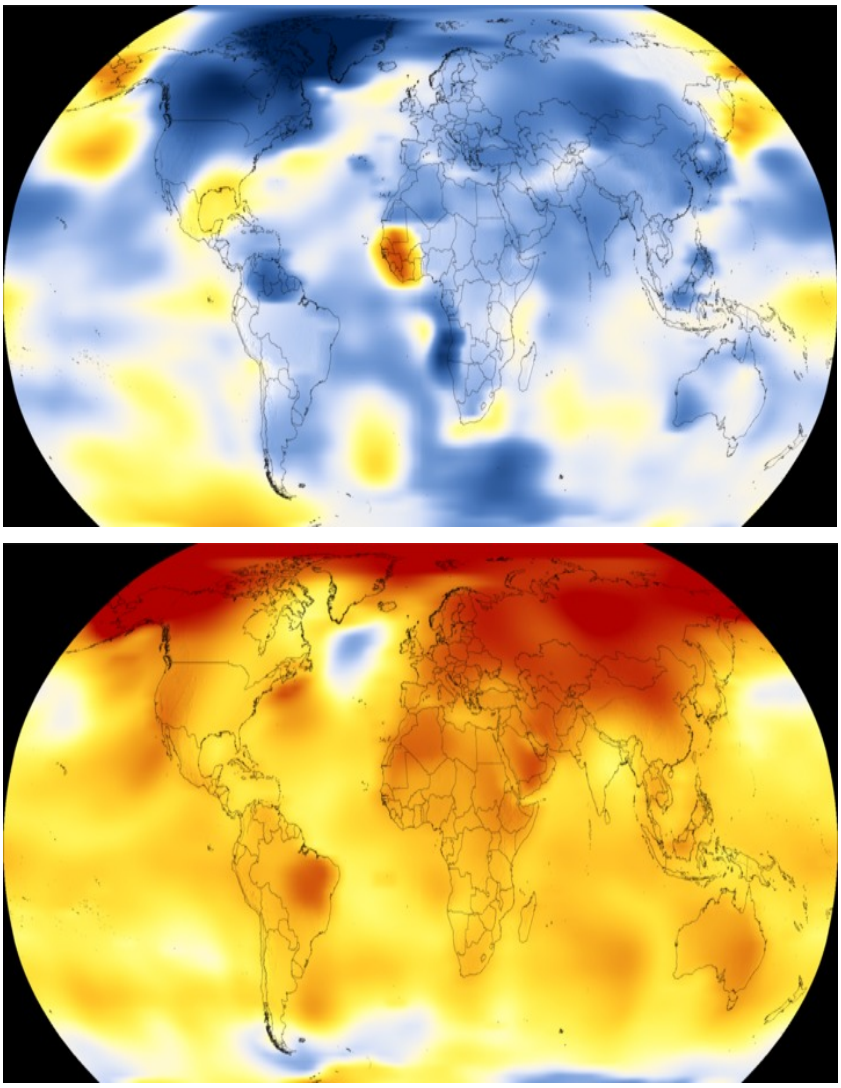

Figure 2.3 Visual representation of the global temperature difference between 1884 (top) to 2017 (bottom). Each picture represents a five-year time series average. Blue represents areas that were below average, red/orange areas represent temperatures above average. From *NASA/GISS (2018)*.

2.1.2 Ice Caps

According to tide gauge records, global sea level rose at a rate of 1.8 mm/yr in the twentieth century, with most of the rise being due to thermal expansion and melting of glaciers from climate change (Zhang et al., 2011). IPCC (2007) projected that global sea level would rise up to 0.6 m by 2100 but stated that any accelerated melting of the ice sheets had not been considered in this estimate. Recent studies have found that IPCC (2007) may have greatly underestimated the rate of sea level rise (SLR) due to the continued acceleration of the melting

Antarctic and Greenland ice sheets (Zhang et al., 2011). The rate of melting ice caps is subject to change depending on the rate of GHG emissions (Butcher et al., 2015). Because of this, Vermeer and Rahmstorf (2009) created an updated equation to get a more accurate representation of SLR rate. This extended method derived an updated SLR global projection of 3.4 mm/yr and 0.7-1.9 m of SLR by 2100 (Vermeer and Rahmstorf, 2009).

2.1.3 Local Rate of Sea Level Rise

Coastal ecosystems are the foundation for the quality of life and economies of many people across the globe, and sea level rise may substantially change these ecosystems by increasing dry-land loss due to submergence and erosion (Geselbracht et al., 2015). These systems are heavily influenced by a variety of factors such as tectonic setting, climate conditions, relative sea-level change, storm frequency and intensity, sediment supply and flux, and the antecedent geology (Zeremba et al., 2016). The local sea level is rising at a rate of 2 mm/yr in the Pamlico Sound (see Figure 2.4; Estuaries, 2010). The Pamlico Sound system is isolated from the Atlantic Ocean by a wave-dominated barrier island chain, the Outer Banks (Zeremba et al., 2016). Because of the Outer Banks working as a barrier, tides are small (0.1 m or less; Zeremba et al., 2016). However, it is currently being projected that the Sound will eventually become a Bay-like estuary due to the Outer Banks breaking up from water pressure (North Carolina Coastal Federation, 2017). Because Lake Mattamuskeet is directly connected to the Pamlico Sound, coastal hazards associated with SLR factors, such as permanent inundation, salinity changes, and an increase in coastal flooding need to be taken in to consideration when determining the outlook of this lake and refuge.

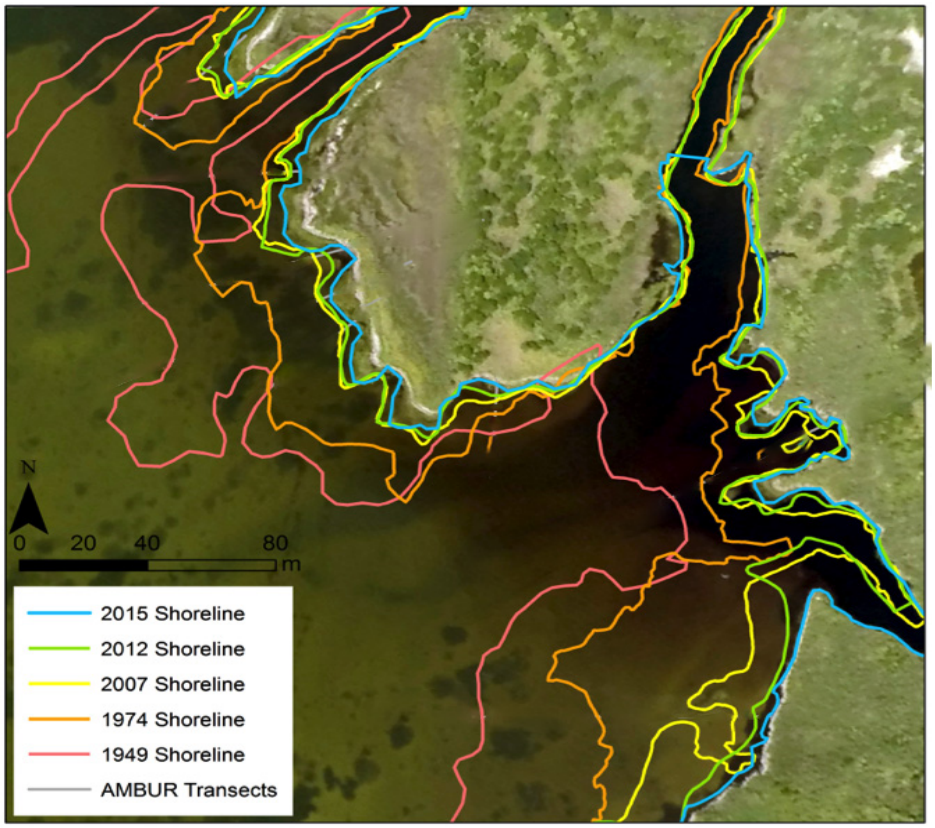

Figure 2.4 Shoreline erosion in the Pamlico Sound. *UNC Coastal Studies Institute, 2016*.

3 Vulnerabilities from the Problems

3.1 Water Quality and Freshwater Wildlife

3.1.1 Land Use and Socio-economic Activities

Lena Midgette

Lake Mattamuskeet is shallow and connects to several canals throughout Hyde County. Mitigating local water-quality problems is complicated because of the lake's large surface area, extensive shoreline, and shallow depth (Winton, 2016). The lake is highly dependent on freshwater to maintain salinity levels suitable for sustaining a large array of ecological communities such as SAV, marshes, open water, and wetlands. Historically, fresh water was delivered to Lake Mattamuskeet by a natural flow of precipitation. Since the first attempt to drain the lake for farming in 1773, both the lake and adjacent lands have been transformed (North Carolina Coastal Federation 2017). Canals, ditches, and gates have altered the amount of freshwater input and the overall quality of the lake.

The canals' close proximity to agricultural land leads to phosphate and nitrogen runoff to accumulate within them and this makes the lake highly vulnerable to eutrophication. Toxic algal blooms have been monitored that include the algae cylindrospermopsin, in which the lake was found to have some of the highest concentrations in the country, almost reaching the federal limits for recreational contact (North Carolina Coastal Federation, 2017). The increase of nutrient and sediment loading pushes an increase of cyanobacteria and eutrophic conditions (see Figure 3.1). The growth of algae prevents sunlight from reaching the lakebed. As SAV is lost from the lake, previous sediments that were held together become loose and get forced into the water column and prevent light penetration. With this cycle persisting, measurable declines in SAV have been observed (see Figure 3.2) within the lake over time (North Carolina Coastal Federation, 2017). Furthermore, light retention reduces SAV growth thus leading to SAV death (North Carolina Coastal Federation, 2017). As SAV is a biological base for water quality, this places the entire lake and its inhabitants at risk to any further anthropogenic activities that would

further input excessive nutrients.

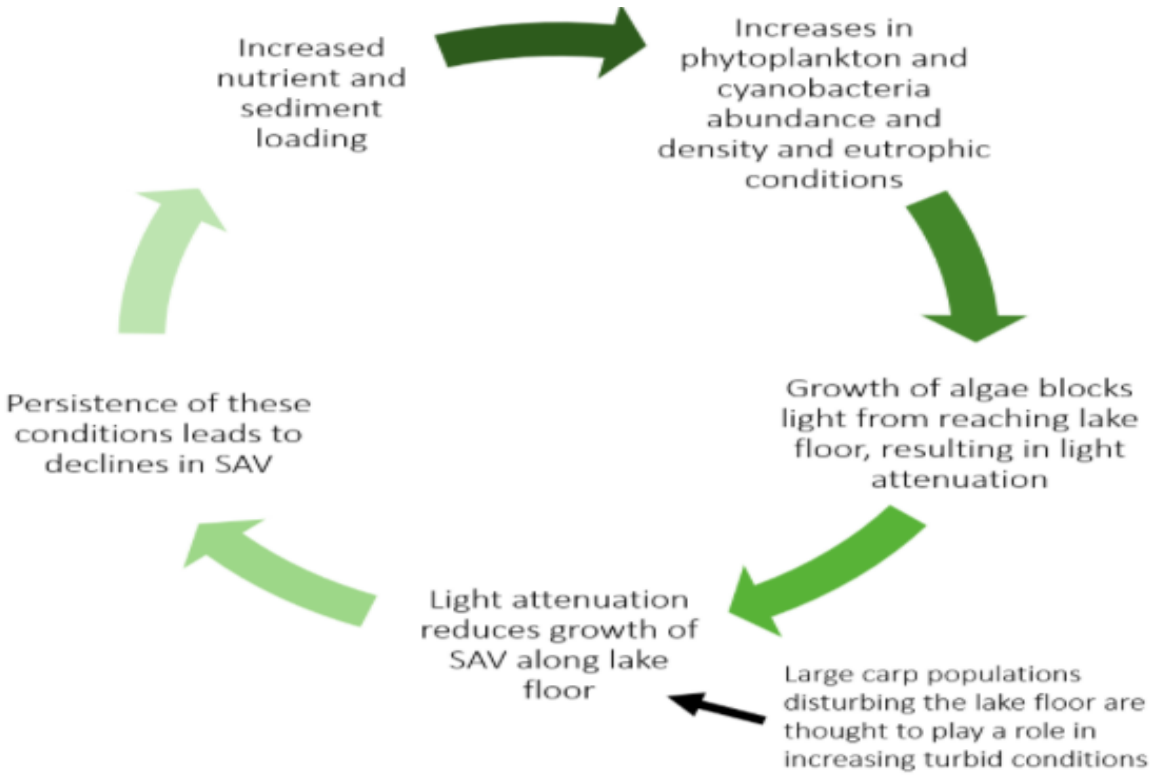

Figure 3.1 This illustration shows the positive feedback cycle of impacts within Lake Mattamuskeet. From *North Carolina Coastal Federation (2017).*

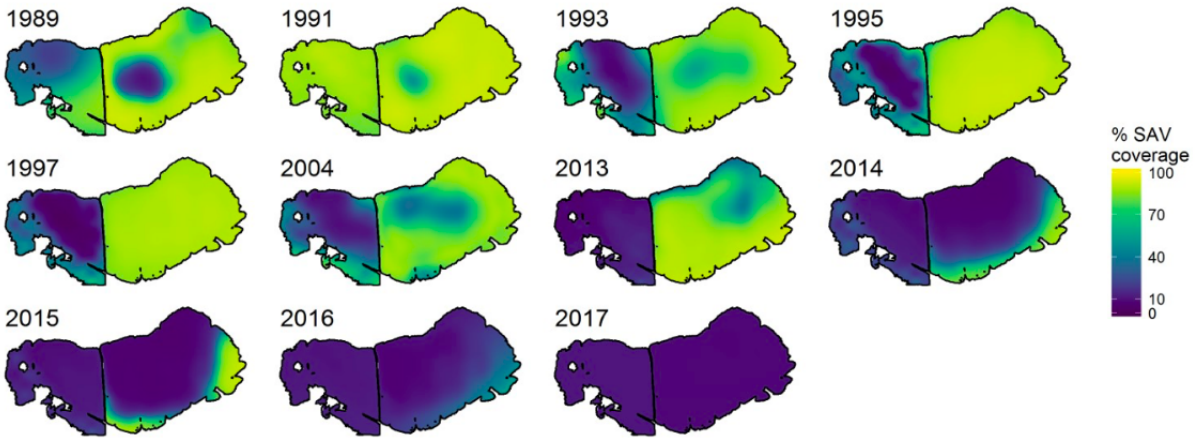

Figure 3.2 Maps displaying percentage of SAV within Lake Mattamuskeet. Darker colors indicate low coverage, while lighter colors indicate high coverage. From *North Carolina Coastal Federation (2017)*.

3.1.2 Climate Change and Sea Level Rise

Kayla Berger

Meteorology is the driving force for lake internal heating, cooling, mixing, and circulation (Sahoo et al., 2012). Warming of surface waters has led to an increasing strength of thermal stratification, which leads to reduced mixing (Butcher et al., 2015). When lakes fail to completely mix, the bottom sediments are not replenished with dissolved oxygen, creating hypoxic conditions for oxygen relying organisms (Sahoo et al., 2012). Therefore, warming-induced changes in lake thermal and mixing regimes present risks to water quality and ecosystem services provided by U.S. lakes and reservoirs such as Lake Mattamuskeet (Butcher et al., 2015). Figure 3.2 shows that SAV died off faster on the west side of the lake than on the east side. When considering the depths of the lake (see Figure 3.3), the faster die-off on the west side could have been due to less mixing of the deeper water, creating a more hypoxic environment than the shallower regions of the lake.

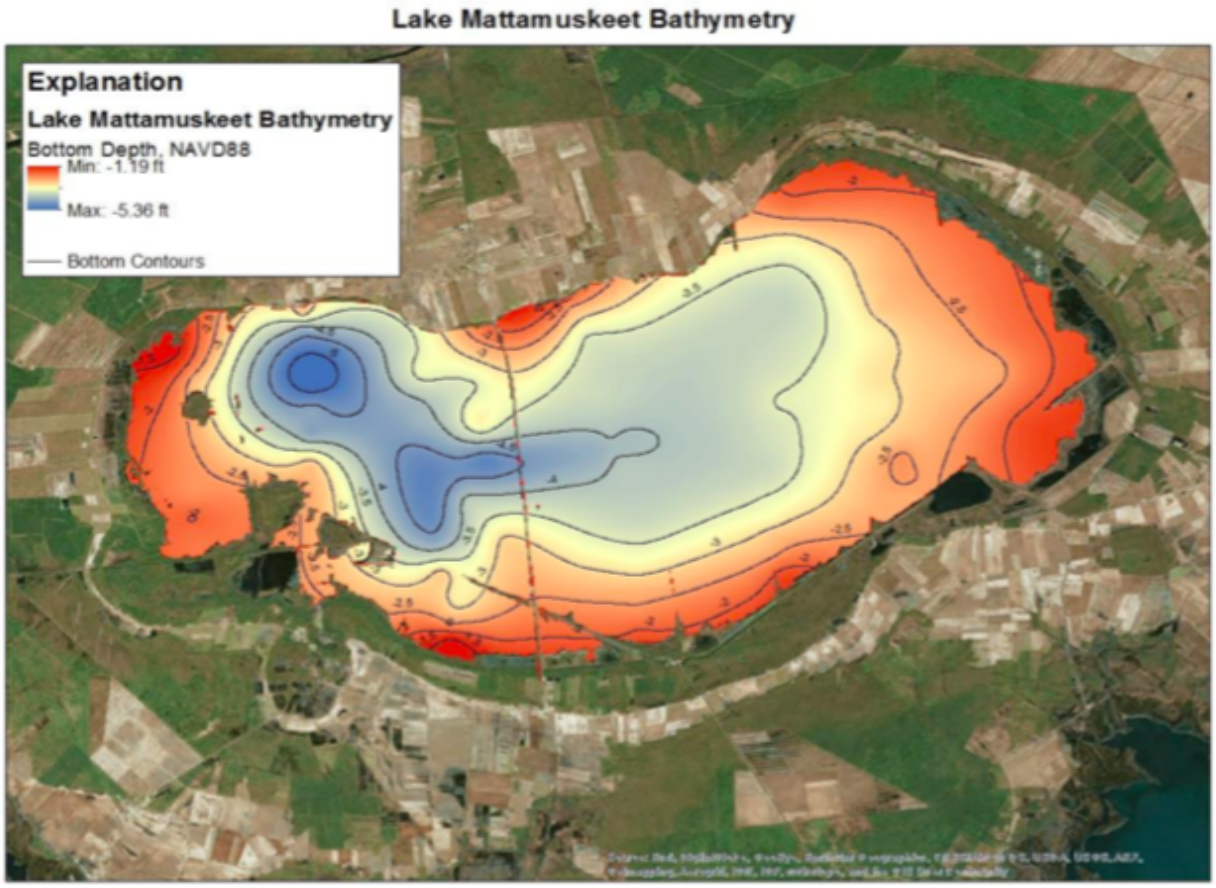

Figure 3.3 The bathymetry in Lake Mattamuskeet. Blue indicates deepest depths, red indicates the shallowest depths. From *U.S. Fish and Wildlife (2017).*

Also, continued climate change will affect a lake's water level, internal nutrient loading, external nutrient loading, nutrient cycling, food web characteristics, fish habitat, and other factors associated with lake limnology (Sahoo et al., 2012). As the GHG rate of emissions continues to increase, this will cause certain areas of the globe to experience heavier rains, or extreme droughts (NCA, 2014). The National Climate Assessment (2014) done by the U.S. Global Change Research Program projects a 10-20% increase in precipitation in northeastern North Carolina by 2070 compared to precipitation rates in 1990. An increase in precipitation could lead to increased flooding in Lake Mattamuskeet and increased runoff from surrounding lands (Dwight et al., 2011).

As the lake could experience rain flooding from increased precipitation, draining excess water could become an issue due to SLR. When the Sound water levels are higher than the lake levels, the four tide gates connected to the lake do not open (Fish and Wildlife Service, 2017). Because of this, the gates are closed more often and longer, causing these tide gates to not drain

lake waters as efficiently as before (North Carolina Wildlife, 2017). As this problem will become increasingly challenging to the system due to sea level continuing to rise in the Pamlico Sound, polluted lake waters will have limited draining flow, impacting the water quality negatively and degrading the vulnerable ecosystem.

The continuously closed gates also pose a threat to blue crabs (*Callinectes sapidus*). As most blue crabs reside in the Albemarle-Pamlico region, many blue crabs use the canal system to migrate into lower salinity waters during their juvenile years to molt (North Carolina Environmental Quality, 2017). If the gates do not open, this will hinder the migration route for the blue crab.

3.2 Local Economy

3.2.1 Land Use and Socio-economic Activities

Lena Midgette

In 2013, visitors spent approximately $32 million within the tourism industry in Hyde County (North Carolina Department of Commerce, 2018). The refuge provides many recreational opportunities for fishermen, wildlife photographers, and bird watchers. Bird enthusiasts visit year-round but visit more heavily during the migratory season to observe the many different bird species. Loss of SAV from eutrophication could eventually cause a decrease in waterfowl stopovers during wintering season. Hunting and fishing are economically important to local businesses, both directly as the local population spends money and indirectly as an attraction that draws fishermen from outside Hyde County (U.S. Fish and Wildlife Service, 2008). Environmental degradation in Lake Mattamuskeet has reduced the viability of valuable fishery spawning grounds and habitat quality for many wildlife species. Recently, because of the nutrient influx, the refuge has increased its efforts to remove the canals of silt, which provides deep water refuge for fish during dry seasons and spawning habitat. In 2004, East Carolina University conducted a study for the U.S. Fish and Wildlife Service, surveying 1,675 visitors to eight national wildlife refuges in eastern North Carolina and southeastern Virginia (U.S. Fish and Wildlife Service, 2008). The study concluded that fishing was the number one primary activity, this was followed by bird/wildlife watching and hunting (U.S. Fish and Wildlife Service, 2008). Mattamuskeet NWR provides economic goods and services to the local community by supplying

recreational opportunities for the locals and tourists. If the centerpiece of this refuge dies, due to the large influx of nutrient loading, this will hinder the economic benefits of Hyde County.

3.2.2 Climate Change and Sea Level Rise

Kayla Berger

As Hyde County brings in hundreds of millions of dollars from crop production, salt water intrusion could greatly impact the local economy by disturbing this production due to inundation (USDA, 2012). SLR can also impact the local economy due to salt intrusion into the lake, which is a primary source of water for many local farmers (USGS, 2018). Salt water intrusion can alter the lakes ecology, creating an unsuitable environment for organisms with low salinity tolerance. If salinity levels increase to a point that turns the lake into an estuarine system, freshwater wildlife living on the edge of their physiological tolerance to salinity are not expected to survive (Pearlstine et al., 2010).

Blue Crabs have historically been North Carolina's most valuable commercial fishery, harvesting over 27 million pounds and profiting $26 million annually from 2008-2017 (North Carolina Environmental Quality, 2017). The Albemarle and Pamlico sounds are the two largest producers of blue crabs, accounting for over 90% of the total landings and dockside value since 2007. If the tide gates interfere with the migration routes for the blue crabs due to water levels being too high, the population of blue crabs will begin to decline, causing a negative impact on the local economy.

4 Future Scenarios

4.1 Land Use and Socio-economic Activities

Lena Midgette

Because Lake Mattamuskeet is economically beneficial to the community, nutrient loading plays a role that can directly affect the county. Three scenarios have been developed discussing how changes in eutrophic levels can alter the economy. The first is a business as usual scenario. If high nutrient runoff from agricultural fertilizers continues or escalates, it could eventually lead to hypoxic conditions. Hypoxia events typically follow algal blooms and occur when algae and other organisms die from lack of oxygen. The cyanobacteria are decomposed by bacteria, this decomposition process uses up most of the oxygen within the ecosystem and

creates dead zones in which most aquatic species are unable to survive (National Geographic, 2011). Runoff is an environmental threat but also negatively impacts the economy. Agricultural businesses lose millions of dollars to runoff each year (National Geographic, 2012). The degradation of the lake's overall biological diversity could hinder the tourism industry within Hyde county. During the migrating season waterfowl could be unable to use the lake as a stopover site. This could force a decline in hunting and wildlife observation which accounts for one the largest sources of revenue during the winter months and peak visitor season for Hyde County (North Carolina Wildlife Resources Commission, 2017).

The second scenario would be for landowners to reduce the amount of nutrient input that is being transported into Lake Mattamuskeet. Although this scenario does not completely terminate the accelerated eutrophication process, it could allow the ecosystem to slowly recuperate from previous harmful levels. The slow increase in water quality could support the replanting of SAV allowing numbers to rise and economic input to flow.

The scenario that could prove to be the most beneficial to the lakes ecosystem involves completely dissolving the use of harmful chemicals on nearby agricultural lands. This scenario would greatly reduce nutrient input into the watershed by means of agricultural lands. It forces the least amount of stress on current wildlife and allows tourism to flourish. New income could become be available from the influx of recreational activities. For every 10% increase in tourism, a spending of $600,000 will go directly into Hyde County's economy, developing 40 jobs, and increasing local and state taxes (North Carolina Wildlife Resources Commission, 2017). Although it generated $33.54 million in 2015, tourism is a relatively undeveloped part of the county's economy (North Carolina Wildlife Resources Commission, 2017). With a better water quality, investment in new tourism infrastructure and recreation for visitors may be able to increase the economic resources to a new extent.

4.1.1 Successful Example: Lake Apopka

Lena Midgette

Florida's fourth-largest lake, 20,000-acre Lake Apopka is fed by a natural spring, rainfall, and stormwater runoff (St. Johns River Water Management District, 2018). This freshwater area contains chronic cyanobacteria blooms (EPA, 2010) similar to those in Lake Mattamuskeet. Strategies such as the marsh flow-way, shad harvesting, and shoreline were reviewed, debated,

and endorsed as the best plan to clean up Lake Apopka (Friends of Lake Apopka, 2016). The Lake Apopka Marsh Flow-Way is a constructed wetland, designed to remove phosphorus, algae, and suspended material in the water by filtering the water pumped through it from Lake Apopka (St. Johns River Water Management District, 2018). The system covers approximately 760 acres and contains four individual wetland cells, in addition to levees, canals, and ditches (St. Johns River Water Management District, 2018). As inflowing lake water passes through the marsh flow-way's emergent vegetation, the water's flow rate slows and suspended particles that contain phosphorus and other nutrients, settle out of the water column. The buildup of organic substances and settled decayed wetland vegetation, form new organic materials and overlay native soils. Retention time of lake water within this flow-way system ranges from two to seven days in the wetland (St. Johns River Water Management District, 2018).

In 1991, a broad-based citizens group known as The Friends of Lake Apopka (FOLA) organized, advocating the restoration of the lake. This group appealed to the agricultural community to change their farming practices and sought public support to restore the lake. FOLA endorsed the Lake Apopka Restoration Act of 1996 set phosphorus criteria for the lake, giving the state's public agency; St. Johns River Water Management District (SJRWMD), the legal authority to set a phosphorus output limitation and in 2003 passed a phosphorus limitation rule. In 1996, up to $26 million was guaranteed by federal government under the Department of Agriculture Natural Resources Conservation Service 2 (NRCS2) Program (Friends of Lake Apopka, 2016). In 1998, soon after FOLA endorsed the restoration act in the Florida Legislature, the states SJRWMD spent over $113 million to buy out the muck farms, leading to the end of farming and pesticide applications. In 2003, phase 1 of The Marsh Flow-Way began operation and treated about 50% of the lake's volume of water (Friends of Lake Apopka, 2016). Enforcing the removal of phosphorus from the lake, reducing the volume of water pumped from another property, and treating all discharges to inactivate phosphorus, have prompted phosphorus concentrations in the lake to decline significantly (St. Johns River Water Management District, 2018).

The improved water quality provides conditions which are allowing native submerged plants to recolonize on the lake bed and help the recovery of the lake's quality (St. Johns River Water Management District, 2018). Preliminary studies estimate an initial annual economic input to local communities to be $20-30 million along with the creation of 400 jobs (Lake Apopka

National Wildlife Refuge Coalition, 2013). The recreational opportunities bring tens of thousands of new customers requiring supplies and lodging. These customers are critical components of an improving economy and expanding employment.

4.1.2 Unsuccessful Example: Grand Lake St. Marys

Lena Midgette

The Grand Lake Watershed, at 54,000 acres incompasses a 12,680-acre lake. Grand Lake St. Marys (GLSM) is the largest inland lake in Ohio. It is a shallow lake that averages five to seven feet deep and is the public drinking water supply for the city of Celina and the Village of St. Marys (EPA, 2015). It encompasses a large state park and has a large seasonal and year-round population living along its perimeter. In 2007 a national lake assessment study conducted by the EPA analyzed water quality for the cyanotoxin microcystin, which is produced by the cyanobacteria Microcystis. Microcystin is one cyanotoxin that is similar to the cylindrospermopsin contaminant that is found in Lake Mattamuskeet. Out of the 19 Ohio lakes that were sampled microcystin levels were found to highest in GLSM (Davenport & Drake, 2011). In addition to the microcystin, the lake is highly nutrient enriched (hyper-eutrophic) resulting from agricultural nutrient-rich runoff, failing home sewage systems, and internal nutrient loading (Davenport & Drake, 2011). Much like Hyde County, this communities land use accounts for 73% in cropland (Davenport, et al., 2010). The combination of shallow depth and high nutrient inputs contributes to a severely hyper-eutrophic condition and frequent fish kills. The 2009 samples showed levels of microcystin so high that advisory signs were posted warning people to avoid contact with the water. In 2010, a severe bloom of blue-green algae (see Figure 4.1) prompted recreation, human health, and fish consumption advisories to be placed on GSLM. Dead fish began to wash up on the shoreline and twenty-three cases of human illnesses and dog deaths potentially related to the algal toxins were reported (Davenport & Drake, 2011). The GSLM areas previously accounted for $158 million in annual economic activity in tourism and recreation, declining water quality and public health advisories have had drastic impacts on the area’s economy (EPA, 2015). An estimated $37-$47 million was lost in tourism revenues in 2009 and 2010 (EPA, 2015). The harmful algal blooms have caused several marinas, boat dealers, and other small businesses to close or witness a high reduction in revenue.

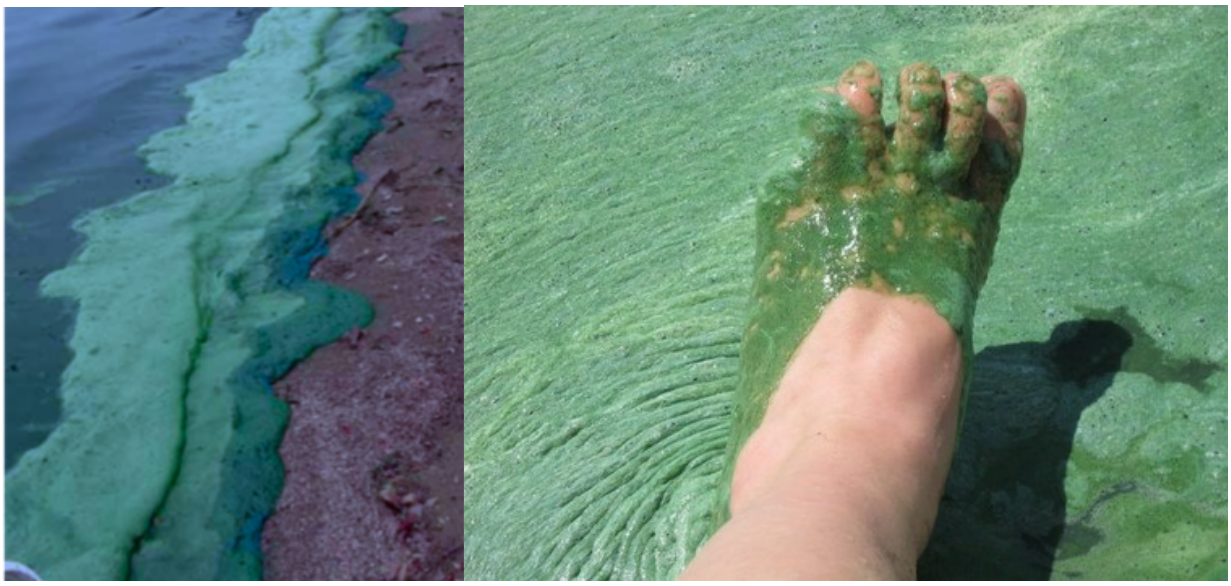

Figure 4.1. Pictures showing blue-green algae in Grand Lake St. Marys. *Davenport et al., 2010.*

4.2 Sea Level Rise

Kayla Berger

In 2017, the Union of Concerned Scientist (UCS) developed three different sea level rise scenarios for 20 different communities along the northeastern coast of North Carolina, including Hyde County and Mattamuskeet NWR. These three difference scenarios were assessed through the year 2100, and split into a low, medium, and high scenario (UCS, 2017). Each scenario is based on the rate of GHG emissions over the next 80 years. The first is a low foresight, representing the scenario that carbon emissions steeply decline, and climate warming is limited to less than 2℃, and only a 0.5 m (2 ft) sea level rise. This is the most ideal scenario with the least amount of impacts by climate change and sea level rise globally. It is being projected that Mattamuskeet NWR and 20 other coastal North Carolina communities could face at least 10% inundation by 2035 (UCS, 2017). For this analysis, inundation is defined as flooding that occurs 26 or more times per year (on average, once every other week) (UCS, 2017). If sea level were to rise just 0.5 m, Lake Mattamuskeet is likely to see significantly higher salinity levels due to intrusion of salt water from surrounding inundated lands (see Figure 4.2). Because this area is in a low elevation, local farmers are also likely to see intrusion of salt water on their agricultural land (North Carolina Coastal Federation, 2017).

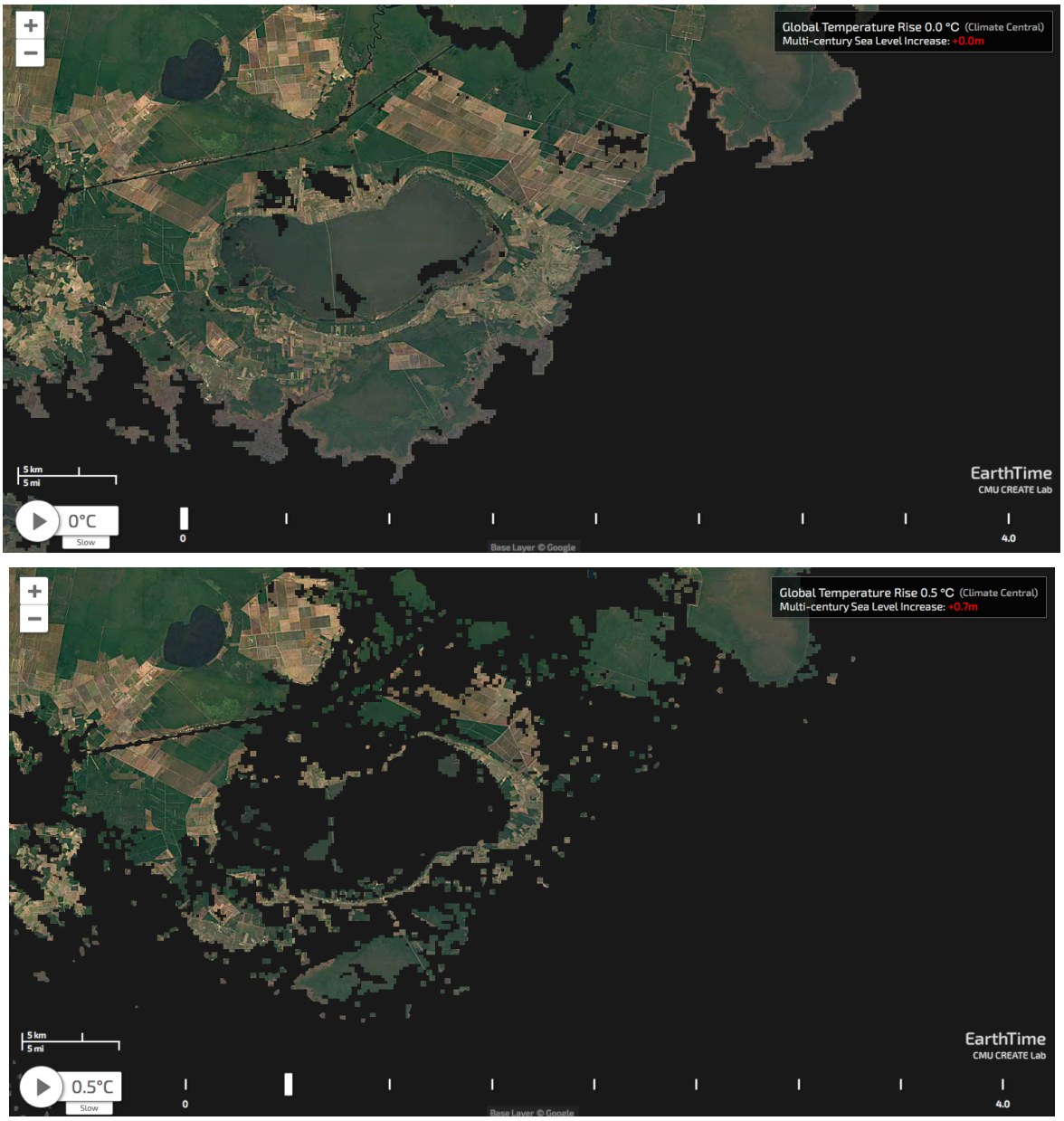

Figure 4.2 An overview look of Hyde County and Mattamuskeet NWR in 2018 (Top), and a future scenario at what this area could look like with a 0.7 m increase in SLR (Bottom). Variation of error in terrain data should be considered. *Earth Time, 2018.*

In an intermediate scenario, carbon emissions peak around 2050, which projects sea level to rise about 1.2 m (4 ft) (UCS, 2017). If this scenario were to happen, Hyde County could face at least 20% inundation by 2030. If local sea level were to rise over 1 m, Lake Mattamuskeet is likely to see a significant amount of salt water intrusion. This system would likely work its way out of a freshwater system towards an estuarine system (North Carolina Coastal Federation, 2015).

The highest scenario projected discusses the idea of GHG emissions continuously rising throughout the century. This would yield the highest amount of sea level rise endured, 2 m (6.5 ft). This amount of rise in sea level would create catastrophic impacts to the local community, projecting that Hyde County, Mattamuskeet, and 20 other coastal North Carolina communities could face no less than 40% inundation by 2060 (UCS, 2017; see Figure 4.3). According to the SLR algorithm by EarthTime (2018), all of Mattamuskeet NWR and most of Hyde County would be inundated by salt water, and the barrier island of the Outer Banks would no longer exist.

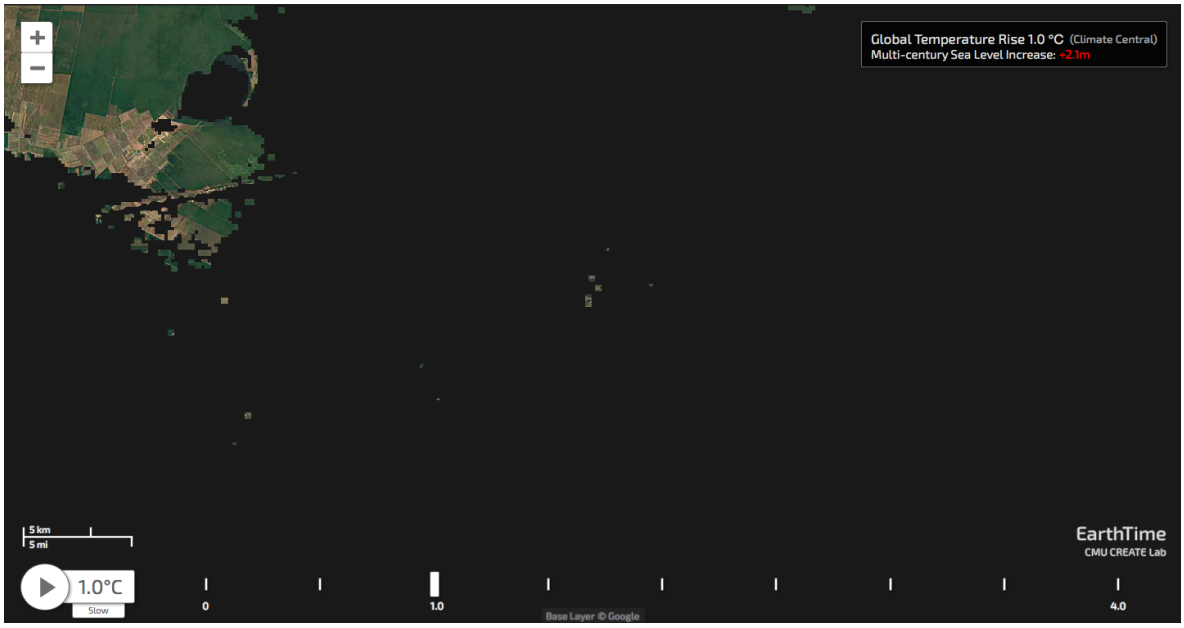

Figure 4.3 An overview look of Hyde County and Mattamuskeet NWR in 2018 (Top), and a future scenario at what this area could look like with a 2.1 m increase in SLR (Bottom). Variation of error in the terrain data should be considered. *Earth Time, 2018.*

5 Stakeholders

Kayla Berger

The relationships between Hyde County's stakeholder groups are vital to any future mitigation plans for Lake Mattamuskeet. All regulations and mitigations plans are passed and controlled by local Government and the U.S. Fish and Wildlife Service. The government officials who operate the Department of Interior have the control to change or enact regulations to the refuge. Propositions can be made about clean up or restoration plans, but if they are not passed by local officials and USFWS, they will not be put into action. Other partners who have contributed to the cleanup process of the lake are the N.C. Wildlife Resources Commission and the North Carolina Coastal Federation (Fish and Wildlife Service, 2018). These organizations have joined forces to conduct research and developed restoration recommendations and public outreach to the local community. Local businesses such as Hyde County Soil and Water are also important stakeholders for the lake and the refuge. They play a vital role in the amount of water uptake from the lake, as well as nutrient loading (Fish and Wildlife Service, 2018). Local residents and farmers are also playing crucial roles in what happens to the lake, as they are responsible for a large part of the nutrient pollution that has caused the SAV to die off. The majority of the nutrient loading comes from waterfowl impoundment owners and local agriculture (Fish and Wildlife Service, 2017). For the restoration process of the lake to be successful, all of these stakeholders must be in agreeance of the problem and on the same page of cooperation.

6 Possible Options

6.1 Restoring the Lodge

Kayla Berger

Mattamuskeet Lodge is an iconic building with great cultural and historical significance nationally, for the state of North Carolina, and for the community of Hyde County (Dabson, 2016). The reopening of the Lodge would restore its cultural significance and serve as a hub connecting people to the areas natural resources (North Carolina Wildlife Resource Commision,

2017). Re-opening the Lodge is currently projecting to cost $7.5 million with an economic benefit of $9.9 million on the local community (Dabson, 2016). Due to the amount of jobs that can come from the restoration, the County would also receive an additional $2.2 million in direct wages, $323,000 in the supply chain, and $223,000 in household spending (Dabson, 2016).

Restoring the Lodge would also bring an influx of guests to Mattamuskeet NWR, which would generate positive economic impacts on Hyde County (Dabson, 2016). For every 10% increase in tourism, $600,000 could be injected in to the local economy (Dabson, 2016). The economic boost to the local economy from restoring the Lodge could bring substantial financial support to lake restoration programs and any future damage costs from inundation.

6.2 Agricultural Management Plan

Lena Midgette

Addressing concerns in the regularly flooded communities and agricultural lands is vital in the development of watershed restoration (North Carolina Coastal Federation, 2017). Agricultural practices can be developed to place less nutrients in the system. Cover crops are primarily used to slow erosion, improve soil fertility, and soil quality. Advising agricultural communities to adopt no-till practices can be beneficial. Tilling helps to loosen dirt making it more effective to plant new seeds while aerating the soil. However, practicing no-till farming protects the soil as well as the environment. No-till reduces erosion and keeps carbon trapped in the soil. With this practice, soybeans have responded well, while corn does not (Sterling Land Company, 2018). Although economically, no-till farming can result in decrease profits. Hyde county's primary crop is corn for grain, while soybeans come in second (USDA, 2012).

Farming communities can also plant native vegetation to help with erosion and the prevention of excess nutrients from entering the lakes waterways from runoff (National Geographic, 2012). Riparian buffers are trees, shrubs, and other vegetation that grow next to waterways or areas of high eutrophic outputs. These living buffers slow runoff by trapping sediment and allowing nutrient rich water to be absorbed and stored in the leaves and limbs (Chesapeake Bay Program, 2018). Using the buffers as a management practice can reduce the number of nutrients before reaching the main water source.

As discussed with Lake Apopka, establishing groups and programs can become the best practice for making beneficial changes in the lake. Creating programs to educate farmers about

the effects of nutrient input and helping them transition to positive practices is key to the lake's survival. Another strategy to be developed for Mattamuskeet is the buyout of agricultural land within close range of the lake. As this was known to be an effective solution for Lake Apopka, halting farm production can lead to a decrease in eutrophication levels.

6.3 Tide Gates

Kayla Berger

As the tide gates are already showing to be not as efficient as they were before (North Carolina Wildlife, 2017), increasing sea level in the Pamlico Sound could lead to the gates being an ineffective way for keeping salt water out over time. According to the foresight projected for Hyde County, it is likely that the lake will inevitably transition to a brackish/estuarine ecosystem due to inundation (UCS, 2017; EarthTime, 2018). While the tide gates are a current solution to keeping salt water from mixing in with the freshwater system, further consideration should be made regarding the effectiveness and relevance of these gates to this system over time.

7 Recommendations

7.1 Re-open the Lodge

Lena Midgette

State investment of $7.5 million to complete the renovation could bring in approximately 64 construction related short-term jobs and $9.9 million impact in long-term economic benefits from Lodge operations (North Carolina Wildlife Resources Commission, 2017). The opening of the Lodge could create a new and anchor destination for tourists who seek experiences away from areas with a congested amount of people. The reopening of the Lodge can restore cultural significance and serve as a centerpoint between the public and the area's natural resources. After three years, the alterations and additions in the Lodge could generate over $2 million in revenues providing an additional boost of $900,000 into the economy (North Carolina Wildlife Resources Commission, 2017). Upon reopening of the Lodge, an opportunity for guests to participate in an environmental program will be available. This will give visitors and locals an opening to learn about the lakes vulnerabilities, while allowing them to assist with the issues. Within this program the participants will get firsthand knowledge and experiences on the lake and can help with

outreach in the local community. This program is a way for people to gain exposure to Lake Mattamuskeet's complications while also propagating the lake's story.

7.2 Create a TDML Regulation

Kayla Berger

7.2.1 Restoration Example: Chesapeake Bay

In the 1970s, The Chesapeake Bay was one of the first dead zones ever identified. This is due to high levels of eutrophication that were caused by urbanization and agriculture, depleting oxygen and creating a loss in SAV (National Geographic, 2011). Several plans have been in place since the 1980's to work on fixing this problem, with the Chesapeake Bay Program and the Clean Water Act service as the two major organizations (CBF, 2018).

After many years of public cooperation and regulations, the Chesapeake Bay Program (2018) have stated that there are now over 100,000 acres of grass beds in the Bay, the highest it's been in decades. This is, in large part, due to the substantial decrease in eutrophication from local regulations and anti-pollution programs (CBF, 2018). These programs, through the Clean Water Act, have set specific goals to have nutrient and sediment levels met by 2025, called the TMDL watershed (Total Maximum Daily Loads) (Paolisso, 2013). This TMDL plan creates a max amount of fertilizer use per square acre, controlling the level of pollution in runoff (Paolisso, 2015). Virginia and all other states along the watershed have enough anti-pollution measures in place to still meet their goals of having a completely restored bay by 2025 (CBF, 2018).

The Environmental Protection Agency (EPA) annual costs for clean air and water regulations from October 1999-September, 2009 ranged from $26-$29 billion, but benefits from the Chesapeake Bay such as commercial fishing and tourism ranged from $82-$533 billion, making a $56-$504 billion profit from the Bay's ecological services (Chesapeake Bay Foundation). If the ecological services provided by the Chesapeake Bay were lost, the local economy would have been significantly impacted in a negative way.

7.2.2 Recommendation for Hyde County

The restoration of the Chesapeake Bay would not be as successful without local regulations set in place along the watershed (CBF, 2017). To use this restoration story as a guide to restoration for the Lake, it is recommended that Hyde County create similar regulations

limiting fertilizer use per square acre of land. As seen in previous examples, this would significantly limit the amount of nutrient loading running in to local waters. Current plans to restore SAV in Lake Mattamuskeet will be less successful without eliminating the rate of nutrient runoff. As the biotic and abiotic factors associated with Lake Mattamuskeet bring significant benefits to the local economy (Dabson, 2016), Hyde County cannot afford to lose any ecological services from local pollution. Creating this regulation will also aid in farmers saving money on washed out fertilizer. By adjusting farmers to this new practice, it would be financially beneficial to their budget and help transition their livelihood into a more eco-conscious practice.

7.3 Open the Gates

Kayla Berger

Salinity levels have decreased over the last five years from 1 ppt to less than 0.5 ppt (USGS, 2018). As salinity is known to remove excess nutrients (Deegan et al., 2012), it could be beneficial to the lake to purposely open the gates to increase salinity to a higher, yet healthy, level. The faster nutrients and bacteria are killed off in the Lake, the faster restoration of grass beds can begin. Opening the gates to allow Sound water in could also aid in water flow, reducing lake flooding from precipitation. As pumping practices in to local wetlands are already put in place (Fish and Wildlife, 2018), the combination of increasing salinity and pumping practices could be sufficient enough to make changes to the lake's water quality.

Based on current foresight of Hyde County and Mattamuskeet NWR, it is projected that salt water intrusion could be inevitable due to SLR (EarthTime, 2018; UCS, 2017). Costs of gate renovation and upkeep may be unneeded and ineffective in keeping salt water out over time. Slow introduction to salt water could be an easier transition for all living factors associated with the ecosystem of the Lake and refuge as opposed to shocking the system with large levels of salinity at one time due to flooding and inundation. As the living organisms with low tolerance to salinity changes are already not expected to survive (Pearlstine et al., 2010), the focus should be shifted to create mitigation plans for species who are likely to adapt easier to changes in salinity, such as blue crabs.

References

Butcher, J., Nover, D., Johnson, T., and Clark, C. 2015. Sensitivity of lake thermal and mixing dynamics to climate change. Climatic Change. **129:** 295-305.

Canfield, D., Bachmann, R., Hoyer, M., 2000. Management alternative for Lake Apopka. *Lake and Reservoir Management.* 16:3, 205-221, DOI: 10.1080/07438140009353964 https://www.tandfonline.com/doi/pdf/10.1080/07438140009353964

Chesapeake Bay Program, 2018. Forest Buffers. https://www.chesapeakebay.net/issues/forest_buffers

Chesapeake Bay Program, 2017. Pollution. https://www.chesapeakebay.net/state/pollution

Chislock, M. F., Doster, E., Zitomer, R. A. & Wilson, A. E., 2013. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge* 4(4):10

Dabson, B. 2016. The economic development impact of renovating Mattamuskeet Lodge. North Carolina Wildlife Resources Commision.

Davenport, T. and W. Drake. 2011. EPA Commentary: Grand Lake St. Marys, Ohio – The Case for Source Water Protection: Nutrients and Algae Blooms. Lakeline, Fall 2011: 41-46.

Davenport, T., Gibson, R., and Mount, T., 2010. Implementing Grand Lake St. Marys Nutrient TMDL. Slide presentation.

Deegan, L., Johnson, D., Warren, R., Petterson, B., Fleegan, J., Fagherazzi, S., and Wollheim, W., 2012. Coastal eutrophication as a driver of salt marsh loss. Nature. 490: 388-392.

Dockendorf, K., Potoka, K., and Thomas, C., 2015. Lake Mattamuskeet Creel Survey. North Carolina Wildlife Resources Commision.

Dwight, R., Brinks, M., Caplan, J., and Semenza, J. 2011. Influence of variable precipitation on coastal water quality in southern California. Water Environment Research. **83:** 2121-2130.

EPA, 2010. Economic analysis of final water quality standards for nutrients for lakes and flowing waters in Florida. https://www.epa.gov/sites/production/files/2015-07/documents/florida-economic-anaylis-report.pdf

EPA, 2015. A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution. https://www.epa.gov/sites/production/files/2015-04/documents/nutrient-economics-report-2015.pdf

Friends of Lake Apopka, 2016. Lake Apopka Timeline. http://friendsoflakeapopka.wildapricot.org/timeline

Geselbracht, L., Freeman, K., Birch, A., Brenner, J., and Gordon, D. 2015. Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida's gulf coast: implications for adaptation planning. *PLoS ONE*. **10**.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D., Medina-Elizade, M., 2006. Global temperature change. Proceedings of the National Academy of Sciences of the USA. **103:**14288–14293.

Lake Apopka National Wildlife Refuge Coalition, 2013. Lake Apopka National Wildlife Refuge Preliminary Proposal: Lake and Orange Counties, Florida.

NASA, 2018. Global Climate Change. https://climate.nasa.gov/

National Climate Assessment. 2014. https://nca2014.globalchange.gov/

National Geographic, 2011. Dead Zone. https://www.nationalgeographic.org/encyclopedia/dead-zone/

National Geographic, 2012. Runoff. https://www.nationalgeographic.org/encyclopedia/runoff/?utm_source=BibblioRCM_Row

North Carolina Coastal Federation, 2017. Restoring the Lake Mattamuskeet Watershed. https://www.arcgis.com/apps/Cascade/index.html?appid=f488e9b4664140f88b2eba5e97de14c9

North Carolina Department of Commerce, 2018. Travel Economic Impact Model: Hyde County Statistics for year 2013. https://www.nccommerce.com/tourism/research/economic-impact/teim

North Carolina Wildlife Resources Commision, 2017. N.C. Wildlife Resources Commission's Report on Lake Mattamuskeet.

Paolisso. M., Trombley, J., R. Hood., and Sellner, K. 2013. Environmental models and public stakeholders in the Chesapeake Bay watershed. Estuaries and Coasts. **38:** 97-113.

Pearlstine, L., Pearlstine, E., and Aumen, N. 2010. A review of the ecological consequences and management implications of climate change for the Everglades. *Journal of the North American Benthological Society.* **29:** 1510-1526.

Sahoo, G., Schladow, S., Reuter, J., Coats, R., Dettinger, M., Riverson, J., Wolfe, B., and Costa-Cabral, M. 2011. The response of Lake Tahoe to climate change. Climatic Change. **116:** 71-95.

St. Johns River Water Management District, 2018. Lake Apopka. https://www.sjrwmd.com/waterways/lake-apopka/marsh-flow-way/

Sterling Land Company, 2018. Farm Tilling- till versus no-till. http://www.sterlinglandcompany.com/farm-tilling-till-versus-no-till/

Union of Concerned Scientists. 2017. When rising seas hit home: hard choices ahead for hundreds of US coastal communities. https://www.ucsusa.org/sites/default/files/attach/2017/07/when-rising-seas-hit-home-full-report.pdf

USDA, 2012. Hyde County, North Carolina. *Census of Agriculture.* https://www.agcensus.usda.gov/Publications/2012/Online_Resources/County_Profiles/North_Carolina/cp37095.pdf

USGS, 2018. Lake Mattamuskeet. https://nwis.waterdata.usgs.gov/usa/nwis/uv/?cb_00480=on&format=gif_default&site_no=0208458893&period=&begin_date=2012-07-03&end_date=2018-07-27

U.S. Fish and Wildlife Service, 2008. Mattamuskeet National Wildlife Refuge. Comprehensive Conservation Plan. 44-45.

U.S. Fish and Wildlife Service, 2017. Mattamuskeet National Wildlife Refuge. https://www.fws.gov/refuge/mattamuskeet/visitor_activities/hunting.html

U.S. Fish and Wildlife Service, 2017. Management Concerns at Mattamuskeet National Wildlife Refuge. Slide Presentation. https://www.nccoast.org/wp-content/uploads/2017/11/Nov-7-Water-quality-and-SAV-trends-MMoorman.pdf

Vermeer, M., and Rahmstorf, S. 2009. Global sea level linked to global temperature. National Academy of Sciences. **106:** 21527-21532.

Winton, S., 2016. The Effects of Organic Matter Amendments and Migratory Waterfowl on Greenhouse Gas and Nutrient Dynamics in Managed Coastal Plain Wetlands. *Duke University.*

Zaremba, N., Leorri, E., Mallinson, D., and Mitra, S. 2016. Controls on the stratigraphic framework and paleoenvironmental change within the Halocene estuarine system: Pamlico Sound, North Carolina. Marine Geology. **379.** DOI: 10.1016.

Zhang, K., Dittmar, J., Ross, M., and Bergh, C. 2011. Assessment of sea level rise impacts on human population and real property in the Florida Keys. Climatic Change. **107:** 129-146.