Impacts of Saltwater Intrusion on Drinking Water

A Major Qualifying Project submitted to the Faculty of Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
degree of Bachelor of Science

March 21, 2022

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Submitted to:
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Abstract

Coastal erosion and saltwater intrusion caused by climate change have significantly impacted the freshwater quality in coastal cities like Dania Beach, Florida. Our team identified water supply issues in Dania Beach by researching the city's water quality and water treatment processes and forecasting population growth and water demand through 2050. Long-term management plan options were analyzed and ranked based on technical feasibility, water quality, cost, and space required. If saltwater intrusion continues to impact Dania Beach, our team recommends purchasing additional raw water from Broward County's regional wellfield because it incurs no capital cost and the wellfield has excess capacity. An alternative is purchasing treated water with a marginal cost increase.

Executive Summary

Within the last century, the threat of climate change and severity of its impacts have been seen across the globe. Climate change is known as the long-term transformation of Earth's climate patterns and is caused by gases in the atmosphere that trap heat, known as greenhouse gases (National Geographic Society, 2019-a). Human activity in the last two centuries has significantly contributed to greenhouse gases in the atmosphere. As a result of this increase over recent years, the Earth's climate has been undergoing significant change. Climate change has caused a global temperature rise, extreme weather events, sea level rise, wildfires, droughts, and impacts on coastal regions. These impacts have affected the environment and put a strain on resources worldwide.

Climate change has significantly impacted water sources, with sources in coastal regions particularly facing these effects. Rising sea levels have caused coastal erosion and saltwater to contaminate water sources. Frequent intense weather events lead to coastal flooding and erosion, causing saltwater to contaminate water sources as well. Both sea level changes and storm events result in the movement of the saltwater-freshwater interface inland, causing the contamination of fresh water sources. This process is referred to as saltwater intrusion. As a result of saltwater intrusion, the quality of water in drinking water sources, such as surface water or aquifers, can suffer. If the salinity in water is too high, issues in water treatment and distribution can occur. To prevent issues in public water supply, coastal communities need to adapt to climate change impacts and become better equipped with handling saltwater intrusion.

Because Florida is a peninsula, water resources across the state have been impacted by saltwater intrusion. Dania Beach, a coastal city in Florida, has specifically seen impacts from saltwater intrusion in its aquifer and well system. The goal of this Major Qualifying Project was to identify problems in water quality and supply in Dania Beach, Florida caused by saltwater intrusion and create a long-term management plan to address these problems. To identify problems with the drinking water system in Dania Beach, information on the city and it's water system was obtained, including data received from correspondence with Frederick Bloetscher, Ph.D., P.E., a consultant who has worked with the Dania Beach water utility. Then, population and water demand projections were calculated. Finally, long-term management plans were identified, analyzed, and ranked based on cost, technical feasibility, water quality, and space.

Using the ranking, the most appropriate long-term management plan for Dania Beach's water utility was chosen.

Dania Beach's water supply system is supplied by two different entities. The City of Dania Beach Water Utility serves 60% of the city, and Broward County Water and Wastewater Service (WWS) serves 40% of the city. The wells that provide service to the city's water utility have been significantly impacted by saltwater intrusion, with four wells being taken out of service permanently as a result. The two remaining wells are temporarily offline, with capacity limited due to saltwater intrusion once brought back online. Water demand from the City of Dania Beach's Water Utility in 2020 is approximately 2.33 MGD, with the water utility serving 19,406 people. In 2050, the projected population will be 26,273 with a water demand of 3.15 MGD. Five options were considered for a long-term water supply plan: (1) using surface water instead of groundwater, (2) constructing wells further from the ocean, (3) purchasing additional water from a nearby system, (4) constructing and operating a desalinating plant in Dania Beach, and (5) utilizing wetlands in Dania Beach. The highest-ranking management plan option was purchasing additional water from a nearby system, as it was the most cost effective and technically feasible.

It is recommended that Dania Beach purchase additional water from Broward County regional wellfield if the city's wells are shut off due to saltwater intrusion or cannot meet demand. Dania Beach's water treatment plants currently receive water from Broward County's regional wellfield, and the raw water is treated to meet state and federal standards. Purchasing additional water from this source would not incur additional capital cost, making it the most cost-effective option. This wellfield has excess capacity, making purchasing water from it feasible well into the future. An alternative is purchasing water from Broward County WWS. This would result in a marginal increase in costs and may impact distribution system water quality.

Acknowledgments

Our team would like to give a special thanks to Jeanine Dudle, Ph.D., P.E., for providing guidance, instruction, and encouragement in designing and completing this project. Dr. Dudle's information and instruction were invaluable in our process of designing a long-term management plan for the City of Dania Beach's water supply. We would also like to Frederick Bloetscher, Ph.D., P.E., for his valuable information and impacts on our research. Dr. Bloetscher provided our team with vital data from the City of Dania Beach Water Utility, helping us be successful in our project.

Authorship Page

The front matter, Chapter 1, Chapter 2, and Chapter 4 are a result of equal contribution of all authors. Chapter 3 was worked on by each author, and Sections 3.1, 3.2, and 3.3 are the result of equal contributions of all authors. Natalie primarily contributed to Sections 3.4.1, 3.4.2, and 3.4.3; Kaelyn primarily contributed to 3.4.4; and Caroline primarily contributed to Section 3.4.5. Each author helped one another research and revise these sections as needed.

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Chapter One: Introduction and Background

This chapter introduces this project and provides an overview of anthropogenic climate change and its impacts, including extreme weather events, sea level rise, saltwater intrusion wildfires, drought, aquifer depletion, and coastal habitat destruction. An emphasis is put on aquifers (Section 1.3) and saltwater intrusion (Section 1.4), as they directly relate to Dania Beach's water supply.

1.1 Climate Change

The long-term transformation of Earth's climate patterns is known as climate change (National Geographic Society, 2019-a). Climate and weather, while related, have important distinctions. Weather is the state of the atmosphere at any given time (i.e. rainy, cloudy, sunny) whereas climate is defined by a region's average weather patterns over time (National Geographic Society, 2019-a). Similarly, global warming and climate change, while related, also have important distinctions. Global warming refers to the long-term heating of the Earth's climate, whereas climate change is the shift in climate patterns as a result of rising temperatures (NASA, n.d.-a).

The following sections discuss the causes of climate change, the history of climate change studies, and examples of negative environmental events that occur as a result of the changing climate system.

1.1.1 Causes of Climate Change

Global warming is related to the greenhouse effect, which is the process by which the Earth is warmed by the sun and kept at a livable temperature. A portion of radiation from the sun is reflected back into space, while some radiation remains trapped by naturally occurring greenhouse gasses in Earth's atmosphere (NASA, n.d.-a). This natural process has intensified due to increased greenhouse gas emissions from human activity. Since the human population relies heavily on natural gas as fuel, there has been an increase in carbon dioxide (CO_2), water vapor (H_2O), chlorofluorocarbons (CFCs), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere (Ahmed, 2020). Excess greenhouse gas emissions unevenly trap solar radiation in the atmosphere and cause irregularities in global climate patterns. Since 1901, the global surface temperature has increased an average of 0.17ºF per decade (USEPA, n.d.-a). As a result, weather patterns have become significantly more severe and unpredictable (National Geographic Society, n.d.-a). For example, hurricanes, wildfires, and droughts have all increased in number and intensity across the globe. Glaciers and ice sheets are melting, raising the overall sea level (NASA, n.d.-b). Saltwater intrusion has also become an issue along coastal areas (Horton, 2019).

1.1.2 History of Climate Change Research

Scientists and researchers have been studying climate change and its impacts on the world since 1824 (Bolin, 2007). When climate change was less studied, the concept was not commonly recognized by the public. In the early 1800s, Joseph Fourier's philosophy on the Earth's climate brought forward the idea that the climate was determined by the heat balance between entering solar radiation and outgoing radiation. This concept was further explored by Claude Pouillet in 1837, and both scientists raised the hypothesis that the atmosphere acts as an absorbing layer for the outgoing radiation leaving the earth, causing the Earth's temperatures to rise as a result. This hypothesis was the first time the concept of greenhouse gasses was considered (Bolin, 2007). In 1856, Eunice Foote then discovered that carbon dioxide and water vapor retain heat after they are placed in sunlight, further supporting Fourier's and Pouillet's hypotheses (Thompson, 2019). In 1865, John Tyndall tested the heat absorption of gases, also finding that carbon dioxide and water vapor trap heat. From his research, Tyndall concluded that variations of carbon dioxide and water vapor concentrations may explain past climate variations (Bolin, 2007). By 1896, an article by Svante Arrhenius claimed that "We are evaporating our coal mines into the air...", and that this will impact the atmosphere and create a warmer planet, further contributing to the concept of climate change (University Corporation for Atmospheric Research, n.d.).

By the mid to late 1900s, climate change was taken more seriously by scientists, politicians, and the public. Beginning in 1950, measurements of the arctic ice in the ocean were taken, and results showed that the amount of ice was shrinking. By 1958, daily measurements of carbon dioxide in the air were being recorded at Mauna Loa in Hawaii (University Corporation for Atmospheric Research, n.d.). In the 1970s, climate change was widely recognized by the public, discussed on college campuses, and members of congress were beginning to address it (Hurt, 2017). In 1988, NASA climate scientist James Hansen discussed global warming before the senate energy and natural resources committee (University Corporation for Atmospheric Research, n.d.). In the same year, climate change was recognized by UN leaders with the formation of a UN panel on climate change (Childress, 2012). In 1992, scientists Stephen V. Smith and R.W. Buddemeier addressed the idea that carbon dioxide in the ocean can raise ocean acidity levels, which is problematic for ocean life. Scientist Joanie Kleypas at NCAR (National Center for Atmospheric Research) is continuing to research the impacts on ocean acidity and ocean life. In 2003, the IPCC (Intergovernmental Panel on Climate Change) reported that there is evidence that global warming in the last 50 years is due to human activities. The same year, a heat wave in Europe that resulted in over 30,000 deaths was attributed as an effect of climate change. Between 2007 and 2008, scientists recorded the impacts of climate change on polar regions of the Earth, finding that these regions are changing at a faster rate than other areas of the Earth (University Corporation for Atmospheric Research, n.d.). In 2011, a new branch of climate science that studies climate change's impact on extreme water was created and named "attribution research". Since its creation, this branch has been studied by the American Meteorological Society. By 2019, scientists and researchers discovered that biodiversity is dramatically decreasing, with roughly 1 million species facing extinction within decades if climate change progresses at its current rate (University Corporation for Atmospheric Research, n.d.). Currently, climate change is being focused on by scientists as they urge action to be taken to prevent its irreversible impacts.

1.2 Climate Change Impacts

Environmental impacts from climate change range from changing temperatures to increases in the frequency of extreme weather events. The following sections provide details on these impacts, which require communities to develop mitigation or adaptation strategies to preserve resources and quality of life.

1.2.1 Temperature Rise

Because temperatures worldwide are not rising by the same amount or at the same rate, the environmental and socio-economic impacts also vary dramatically. While the global temperature is likely to rise 1.5 degrees Celsius in the next five years, various latitudes experience the implications of this increase differently (United Nations, 2021). Polar amplification, for example, is a scientific phenomenon in which the areas at high latitudes experience an even greater temperature increase than the annual mean temperature increase of the globe (Cai *et al.*, 2016). Additionally, larger changes over lower latitudes come in the form of heatwave duration, which is projected to increase by 2–10 days/°C (Perkins-Kirkpatrick & Gibson, 2017). This leads to water scarcity in already dry areas being exacerbated (Sanderson *et al.*, 2011). At the same time, increased flooding in areas by the coast is also caused by higher temperatures. In areas that may be less developed, or have a history of conflict, climate change may escalate conflict over water, land, and food. For example, studies of the Middle East show that "climate change will have significant impacts to food security, disease prevalence, population distribution, and water availability in the Middle East," (Brown & Crawford, 2009). A similar phenomenon occurs in other regions like sub-Saharan Africa. There, "the increase of population growth leads to increased demand for natural resources which, in combination with regional exclusion from global trade, damages the climatic productivity of agriculture," (Mikhaylov *et al.*, 2020). Additionally, there are inequalities between countries that contribute significantly to greenhouse gas emissions and therefore to climate change.

1.2.2 Extreme Weather Events

The impact on weather patterns is not relegated to temperature increase alone. Extreme weather patterns involving major precipitation events including hurricanes can also be attributed to the rise in the global mean temperature. There is support for a hypothesis that increases in atmospheric and ocean temperatures due to climate change cause energy stored in the ocean to turn into wind, which causes intensified cyclone patterns (Battistoli *et al.*, n.d.). Scientists have determined that extreme weather events are inevitable, but the degree of severity is influenced by the changing climate (Woodward *et al.*, 2018). The media often reports on weather events as isolated events given the need for communities to prepare and respond. However, climate scientists note that "rainfall amounts in the heaviest downpours have increased by an average of 20 percent over the last century, a trend which is forecast to continue" (Battistoli *et al.*, n.d.).

A pattern of increased economic loss due to climate change and extreme weather events coincide. This implies that there is increasing damage due to these weather events. Specifically in the U.S., hurricane damages make up a significant amount of the insurance fund provided for global property damages. When a regression-based normalization method is applied to data, there is a linear trend that shows that the cost from hurricane and storm damage is increasing at a rate of $136 million U.S. dollars annually in the last century (Estrada *et al*., 2015). This trend provides a concrete example of how recent storms are increasing in intensity.

1.2.3 Sea Level Rise

Another critical impact of global warming is global sea level rise. The main reason why climate change influences sea levels to rise is that global warming causes solid water formerly trapped in polar ice to melt and contribute to the volume of the ocean (Lindsey, 2017). Projections for how much the sea level will continue to rise predict a global mean increase of 65 ± 12 cm by 2100 (Nerem *et al*., 2018).

A rising sea level means that damage from storm surges moves further inland, and the minor damage from nuisance flooding occurs more frequently (Lindsey, 2017). These issues may require people in vulnerable areas to relocate. Up to 180 million people globally are immediately at risk of migration due to sea level rise, and over 1 billion additional people are living in the lower-elevation coastal zone (Hauer, 2017). This introduces an issue not only for coastal communities, but also for landlocked cities that are not designed to accommodate millions of migrants. Mass migration due to sea level rise could place stress on access to potable water, which then further encourages salinity intrusion into groundwater sources (see Section 1.4).

Sea level rise has a significant impact on populations' living situations. In fact, 80% of the world's largest cities are located in coastal areas (Lindsey, 2017). If cities were not designed with a buffer for an increase in sea level, rising water levels can dramatically affect the structural integrity of public structures. These include roads, bridges, subways, water supplies, oil and gas wells, power plants, sewage treatment plants, and landfills. (Lindsey, 2017). In the U.S., it is acknowledged that sea level rise is inevitable and irreversible at this point, and federal planning is needed "not only for long-range planning, but also for emergency preparedness and other short-term considerations" (Hall *et al*., 2019).

1.2.4 Increased Wildfires

Another natural event that has increased in both number and intensity due to climate change is wildfires. Wildfires are large-scale destructive fires, especially in a wilderness or a rural area. Wildfires are typically naturally occurring and vital to the health of ecosystems in different areas across the globe, but in recent years, both the number and severity of these fires has dramatically increased. Data shows an increase of millions of acres destroyed by wildfires from 1980 to 2020 (Insurance Information Institute, 2021). This increased frequency and intensity of wildfires is due to both human activity and the environment becoming hotter and drier because of climate change, causing soil to become dry and temperatures to rise. As human activities that spark wildfires occur and climate change creates ideal conditions for wildfires, the likelihood of numerous wildfires sweeping across land is high (USEPA, n.d.-c; Union of Concerned Scientists, 2011).

Wildfires cause between hundreds of thousands to over a million acres of land in the United States to burn each year, destroying entire communities and claiming the lives of people and wildlife. In 2020, it was estimated that 58,950 wildfires occurred in the United States, burning 10.1 million acres. These wildfires were most severe in California, with six of the top twenty largest wildfires in the state's history occurring in that year. An estimated 4.3 million acres of land in California were burned, 10,500 structures were damaged or destroyed, and 33 people were killed (Insurance Information Institute, 2021). Due to the frequency and intensity of wildfires in California, California Department of Forestry and Fire Protection leaders raised the point that there is no wildfire season anymore, as they fight fires that sweep across the land year-round (Union of Concerned Scientists, 2011). The destruction that wildfires have caused in California is an unfortunate example of the effects that climate change can have on the environment.

1.2.5 Drought

Climate change affects the hydrological cycle immensely and has led to an overall increase of natural disasters. Droughts are among the most destructive natural disasters as they have severe effects on the environment, economy, poverty, and community health (The World Bank, 2012). They are one of the most expensive natural disasters to recover from (Grillakis *et al.*, 2019). It is estimated that droughts cause an average of $9 billion of losses per year in damages related to crop failure, diminished food supplies, decrease in dairy production, and land damages (NOAA, n.d.).

Droughts are more likely to occur when temperatures are higher as elevated temperatures promote higher evaporation rates from the soil (NOAA, n.d.). Droughts pose a significant threat to agricultural communities as global warming continues to progress. Crop failures are inevitable in a drought and have the potential to impact countries across the globe (The World Bank, 2012). For example, in 2012, prices for maize and soybeans reached an unprecedented high in the summer due to a large number of droughts in both the United States and Eastern Europe. The World Bank organization reported that global food prices increased by 10% and in response, food insecurity rates increased as well (The World Bank, 2012).

Another anticipated risk during droughts is that hydroelectric power may become inaccessible. The demand for electricity increases with temperature as people are inclined to want to use AC units and fans to keep their living areas cool. This demand, however, puts stress on the electrical supply grid because the water used to produce electricity evaporates in drought conditions (Eaton, 2012).

1.2.6 Impacts on Coastal Environments

As described previously, climate change results in sea level rise and an increase in the frequency and severity of extreme weather events, such as hurricanes, floods, and tropical storms. A byproduct of these impacts is an increase in coastal erosion, which results in receding shorelines and coastal habitat destruction. Damage to constructed facilities such as homes, roads, and wastewater treatment facilities (which are sited proximate to surface waters) also occurs.

Sea level changes and storm events also lead to movement of the saltwater-freshwater interface inland. Saltwater encroachment can contaminate surface water sources, turning them brackish. Encroachment also impacts aquifer recharge, eventually leading to saltwater intrusion in subsurface water sources. Saltwater intrusion is defined as the process where sea water infiltrates coastal groundwater systems, resulting in seawater mixing with the coastal freshwater supply (Prince Edward Island, 2011). Details on saltwater intrusion are provided in Section 1.4.

1.3 Aquifers

An aquifer is defined as a subsurface, permeable geological formation that can economically provide a usable amount of water. Water in an aquifer is stored in and moves through open spaces called pores in the subsurface materials. There is a higher quantity of groundwater in humid climates where there is porous or fractured bedrock with ample space for precipitation to be stored. Aquifers are typically composed of gravel, sandstone, and sedimentary conglomerates. Highly fractured rock materials are also common, including limestone (National Geographic Society, 2019-b). Aquifers are classified as either unconfined or confined. Unconfined aquifers form below a permeable layer of soil. In contrast, confined aquifers reside underneath an impermeable layer of clay or rock (National Geographic Society, 2019-b).

The ability of subsurface materials to provide water can be measured several ways. First, porosity measures the amount of water contained per unit volume in an aquifer. It is expressed as a ratio of the volume of voids (the space between sediment) to the total volume of the system. This provides information on what the available water storage volume is in the aquifer (Bedient *et al*., 2013). Second, hydraulic conductivity is "a measure of the ability of porous media to transmit water" (Bedient *et al*., 2013). This ability defines how well water can travel through an aquifer and depends on various physical factors, including the soil pore geometry and the density and viscosity of the fluid. Hydraulic conductivity, denoted by the symbol K, ranges from 10^{2} m/s (for gravels and cobbles with a high porosity) to 10^{11} m/s (for solid clays or unfractured rock), which is a significant range (Preene, 2014). Lastly, safe yield is defined as the maximum amount of groundwater that can be withdrawn from an aquifer for use without exceeding long-term recharge or impacting the aquifer's integrity. It is important to calculate the safe yield during the projected driest period to ensure that the rate of extraction never exceeds the rate of sufficient replenishment (Alberta WaterPortal, 2012).

1.3.1 Aquifer Systems

Traditionally, aquifers are located using a series of drilled test holes. At each sample site, the soils are analyzed and a layered map is created. However, drilling is costly and time consuming, so holes are usually only drilled every three to six miles. This means that it may take months or even years to collect enough data for a rough estimate of the shape of an aquifer

(Hotchman, 2015). Newer technologies such as satellite imaging and ground penetrating radar can map aquifers more efficiently (Blanchfield, 2021). For example, a tool called SkyTEM is a way to measure aquifers electronically. It consists of “a global positioning system, lasers, loggers, and a computer strapped to a giant hexagon-shaped frame... [made of] nonconductive fiberglass and wood” (Hotchman, 2015). This rig is pulled by a helicopter that flies 100 ft from the ground along a predetermined grid-like path. The system then sends electromagnetic waves into the ground every nine feet to a depth of 900 feet to determine the composition of the ground below. The end product is a detailed three-dimensional image of the area’s geology. This type of radar system is more efficient and accurate than the traditional method of methodically sampling the soil. Detailed results can be acquired in the span of weeks rather than years.

Aquifers are found globally, and because of their underground nature, can be relatively large. For example, “the Guarani aquifer in South America... covers roughly the same area as France, Spain, and England combined [and] provides drinking water to about 15 million people in four different countries” (Lerner & Lerner, 2003). Mapping these aquifers is especially important in specific countries to determine the availability of groundwater for the nation. In the U.S., the principal aquifers (those which provide potable water) are mapped by the United States Geological Survey (USGS). This map can be seen in Figure 1.

Figure 1: Map of all the major aquifers in the United States with key (USGS, n.d.-a).

The largest aquifer in the U.S. is the Ogallala Aquifer (Mandler, 2017), or the High Plains Aquifer, which extends under eight states from Texas to South Dakota (see Figure 2). This aquifer alone supplies the U.S. with one third of the water used for irrigation of agricultural land. As of 2010, 65% of fresh groundwater was being pumped for irrigation, with the highest consumption rates coming from Kansas. Kansas draws 80% of its fresh water from groundwater aquifers. Due to rapid depletion of this aquifer for irrigation purposes, the water level in the Ogallala has decreased by over 100 feet in some areas (Talon LPE, 2021). This is not only an issue for those local to the Ogallala. Without this aquifer, over $20 billion in food and material goods that are shipped all over the country would be lost (Talon LPE, 2021).

Figure 2: Map of the Ogallala Aquifer which spans across eight states in the U.S. (Colorado Ogallala Aquifer Initiative, n.d.).

1.3.2 Aquifer Recharge

The rate by which aquifers replenish themselves is called recharge (USGS, n.d.-b). Keeping a balance of input and outputs in the hydrologic cycle is very important because precipitation is the main method by which aquifers are recharged. In a typical watershed, the hydrological cycle includes inflow from rain, groundwater flow, and infiltration from nearby water bodies, as shown in Figure 3.

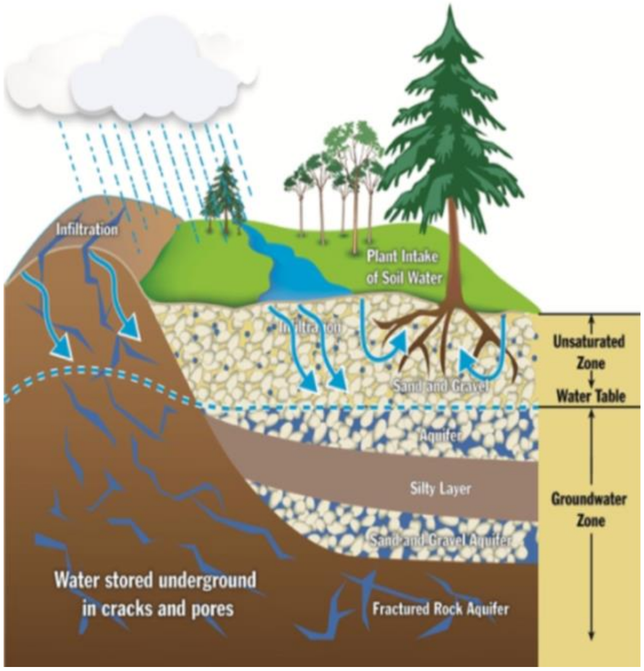


Figure 3: A diagram that shows aspects of the hydrological cycle from rain, groundwater flow, and infiltration (Luxem, 2017).

There is also an outflow of water through evaporation, transpiration, runoff, and demand. The change in storage for an aquifer in steady state conditions is represented by a conservation of mass equation, as shown below:

$$(P + I + G_{in}) - (E + O + D + G_{out}) = \Delta S$$

In this equation, there are three inflow terms (where P represents precipitation, I is infiltration, and G_{in} is groundwater flow into the system) and four outflow terms (E is evaporation, O is outflow, D is demand, and G_{out} is groundwater flow out of the system), and ΔS is the change in storage over time. Ideally, for a steady state condition, the inflow and outflow values would be equal, resulting in no change in aquifer storage over time. If there is an imbalance in the system, it is likely that there is either an oversaturation or depletion of the aquifer. This equation demonstrates that decreased precipitation in one area has the potential to contribute to the water level of an aquifer miles away.

As described in Section 1.3.4, humans pump water out of aquifers for use in industry, agriculture, and domestic uses. When water is used at a rate higher than the recharge rate, aquifers become depleted unless water is artificially introduced to offset the demand. This can be done by redirecting water across land areas using rivers, canals, irrigation basins, or sprinkler systems. A long-term planning approach to maintaining aquifer levels is called aquifer storage and recovery. This involves storing water in wells that can be pumped into aquifers during dry periods (USGS, n.d.-b).

1.3.3 Groundwater Wells

There are a variety of purposes that communities utilize groundwater for, as detailed in Section 1.3.4. The most common way to access groundwater is through drilling a well and pumping the groundwater up to the surface. There are three main types of wells depending on the method that is used to dig them (Waller, 1982).

The simplest type of well is a dug well. These are constructed manually using hand tools or equipment such as a backhoe. In order to use this method, the ground must be relatively soft, and the water table must be shallow. These wells expose a large surface area of the aquifer and are used to reach water trapped in less permeable materials like very fine sand, silt, or clay. Typically, dug wells are only 10 to 30 feet deep (EPA, n.d.-d). This shallow depth combined with an exposed surface area makes them at a higher risk for contamination, and they are very susceptible to changes in drought conditions (Waller, 1982).

A second type of well is a driven well. They are created by driving a pipe into the ground. This pipe has a relatively small diameter of about 2 inches (IDPH, 2011) and usually has a screen to filter out the soft soil. Driven wells tend to be 30 to 50 feet deep and are used in areas with thick sand and gravel deposits (USEPA, n.d.-e). Similar to dug wells, these work best for relatively shallow water (water table within 15 feet of the surface) and are at high risk for contamination (Waller, 1982. USEPA, n.d.-d).

The third commonly used method of creating wells is drilling. Drilled wells require a drilling rig to penetrate approximately 100-400 feet below the surface into fractured bedrock

(USEPA, n.d.-f). The rig utilizes rotary drill bits to break down rock and make room for a pump that pushes water to the surface. Drilled wells are commonly used for both private properties and public water supplies. A basic structure of a drilled well includes a well casing, cap and screen, as well as a pitless adaptor and a pump. Well casings are tube-like in shape and keep the integrity of the surrounding soil. They also act as a barrier to prevent dirt and contaminants from entering the water. Well screens and caps attach to the top and bottom of the well casing, respectively, and act to keep the water free from debris. However, well caps also include a valve to control the pressure of the well casing. The pitless adapter allows the casing to descend past the frost line and maintain a seal.

Finally, there are two types of pumps that are commonly used to transport water. Jet pumps are used for dug wells with a depth of less than 25 feet. They utilize suction to pump the water. For deeper wells, like driven or drilled wells, submersible pumps are used. This pump is placed within the well casing and connects to power above ground (Waller, 1982).

1.3.4 Groundwater Use in the U.S.

In the United States, an estimated 322 billion gallons of water was used per day (Bgal/d) in 2015. Freshwater accounts for 281 Bgal/d of water used, and saltwater accounts for 41 Bgal/d. Within recent years, water withdrawal rates have decreased compared to previous years. For example, water withdrawal rates were 9% less in 2015 than in 2010 (Dieter *et al.*, 2018). Water is primarily withdrawn from surface water or groundwater sources. Surface water is found in any water body that is located on the Earth's surface (National Geographic Society, 2019-c). Groundwater found in aquifers below the Earth's surface represents about thirty percent of the world's freshwater (USGS, n.d.-c.; International Groundwater Resource Assessment Centre, 2014).

In the U.S., water is used for thermoelectric power, irrigation, public supply, industrial purposes, aquaculture, mining, and livestock, with thermoelectric power and irrigation using the most water compared to all other categories (Dieter *et al.*, 2018). Thermoelectric power and irrigation both use saltwater and freshwater, which is withdrawn from surface water and groundwater (Dieter *et al.*, 2018; Centers for Disease Control and Prevention, n.d.-a). In 2015, 133 Bgal/d were withdrawn for thermoelectric power, and 118 Bgal/d were withdrawn for irrigation use. Public water supply is sourced from both groundwater and surface water, and 39

Bgal/d were withdrawn for public supply in 2015 (Dieter *et al.*, 2018, National Research Council, 1982). Industrial processes use freshwater sourced from surface water and groundwater, and in 2015, 14.8 Bgal/day were withdrawn for industrial use (Centers for Disease Control and Prevention, n.d.-a; Dieter *et al*., 2018). Aquaculture uses both saltwater and freshwater, and the freshwater for this industry is sourced from both surface water and groundwater. In 2015, 7.55 Bgal/d was withdrawn for aquaculture. Mining uses both surface water and groundwater, with some of the water from both sources being freshwater and saltwater. In 2015, 4 Bgal/d were withdrawn for mining. Livestock uses both groundwater and surface water as well, with 2 Bgal/d being withdrawn for livestock in 2015 (Dieter *et al.*, 2018).

Public water systems provide the public with treated water for human consumption. In public water systems, treated water is pumped through networks of pipes to a minimum of 15 service connections or serves a minimum of 25 people for 60 days out of the year (USEPA, n.d.-g). In the U.S., there are roughly 148,000 public water systems that act as a resource to provide cities, towns, communities, and residents with water. Public water systems withdraw water from both surface water and groundwater sources. Community water systems are public systems that supply water to the same population year-round, and in the U.S., 32% of community water systems are supplied by groundwater, and 68% of these systems are supplied by surface water (USEPA, 2008). Non-transient non-community water systems are public systems that supply the same population for at least 6 months per year. In the U.S., 87% of non-transient non-community water systems get water from groundwater and 13% of these systems get water from surface water (USEPA, 2008). Transient non-community water systems are public water systems that provide water to places where people do not stay for long periods of time. In the U.S., 81% of transient non-community water systems withdraw water from groundwater sources and 19% of these systems withdraw water from surface water sources (USEPA, 2008). Large public water systems supply urban areas and typically source their water from surface water, and smaller public water systems typically supply rural areas with water sourced from groundwater (Centers for Disease Control and Prevention, n.d.-b). This is because it is easier for cities and urban areas to take water from surface water, treat it, and supply it to the public than provide groundwater to the entire city's or urban area's population.

To provide groundwater to any population, water must be removed from the ground through wells. In a city or urban area with a high population, a large public water system would need access to hundreds of wells to provide water to its population (Sensorex, 2021). Smaller public water systems tend to use groundwater because it is more cost effective and less complicated than surface water due to surface water treatment regulations (Sensorex, 2021). Surface water typically must be treated through a water treatment system since it is likely to contain pollution and sediments. However, groundwater is typically safe to drink without treatment because as water travels through aquifers, the soil and sediment it travels through filters out contaminants. Because of this natural filtration, most groundwaters are not required to go through a treatment process (Centers for Disease Control and Prevention, n.d.-c; Sensorex, 2021). Due to these treatment regulations and because small public water systems do not require hundreds of wells to gather groundwater, it is more cost effective and less complicated for groundwater to be used as a water source for small public water systems in rural areas.

While public water systems supply water to numerous people in the U.S., 13% of the population does not rely on public water systems for their drinking water (Dieter *et al.*, 2018). The majority of the population that does not rely on public water systems are located in rural areas. Over ninety percent of the rural populations that do not get water delivered to them through county water, city water, or a private water company use groundwater as their drinking water source (USGS, n.d.-c). This water source typically comes from private wells, which are located on or near the property they supply water to (USEPA, n.d.-i.).

1.3.5 Climate Change Impacts on Aquifers

Climate change has caused rising global temperatures, seawater rise, and increased water demand, all of which can negatively impact aquifer useability. These effects of climate change impact the ability of aquifers to provide a sustainable source of water, as they typically cause a decrease in aquifer recharge rates and can lead to saltwater intrusion. Impacts of saltwater intrusion on aquifers and groundwater are discussed in Section 1.4. Evidence from scientific research has shown that as global temperatures climb, the supply of freshwater in aquifers will slowly decline. For example, a team of researchers in central Nebraska studied the effects of rising global temperatures on aquifer recharge rates by utilizing a Crops Simulation Model (CROPSIM). This model combines mathematical representations of physiological processes that play a factor in crop growth and development into a format that can be used to predict the outcome of crop, soil, and weather scenarios (Hunt & Pararajasingham, 1995). This model allowed the team to estimate aquifer recharge rates by studying the climate in Nebraska and measuring the recharge rate through use of physical and chemical tracer methods on site in the Platte River Basin in central Nebraska. Results from the model showed that if temperatures rise by a small margin (1ºC), there are no indications that recharge rates will change between 1999 to 2050. However, if temperatures rise over 2.4ºC, by 2050 there will be a "...25% and 15% increase in median annual evapotranspiration and irrigation demand and decreases in future diffuse recharge by 53% and 98% and irrigation recharge by 47% and 29% at the eastern and western sites, respectively" (Lauffenburger *et al.*, 2018).

Seawater rise also impacts aquifers, as rising seawater levels decrease the availability of freshwater in aquifers. This impact occurs when seawater enters the aquifer, causing the salt concentration in the freshwater to rise. This process is known as saltwater intrusion and is discussed in depth in Section 1.4.

Increased water demand is another issue that impacts aquifers. As a result of increased water demand, it has been shown that in recent years, more water is being removed from aquifers than before. Between 1950 and 2015, the amount of groundwater withdrawn in the U.S. has increased by roughly one half (USGS, n.d.-d; USGS, n.d.-e). If water is removed from aquifers at a faster rate than the aquifer can be recharged as a result of groundwater overuse, the water table level can decrease and water levels in surface waters can also decline. Due to excessive consumption, the Worldwatch Institute has reported water table drops on every continent in the world since 1999 (Blanchfield, 2011).

In arid environments, the decreased amount of moisture prevents precipitation from quickly replacing any water that is transported out of the aquifer. In the case of these aquifers, 'fossil water', which has accumulated over thousands of years or more, is being removed faster than it can be replenished, resulting in groundwater depletion. The recharge rate is "only of the order of one thirty-second of an inch (1 mm) per year," however the water level has been "decreasing by as much as 3.2 feet (1 m) per year in intensively utilized zones," (Blanchfield, 2011). Therefore, in dry environments, aquifers may become a non-renewable resource (Blanchfield, 2011). In addition, groundwater depletion can also cause ground subsidence, which is the loss of support below the ground. When too much water is removed from aquifers, the soil is less supported by materials and water underground. This issue can cause the ground to collapse as soil compacts, creating large voids in the ground (USGS, n.d.-f).

1.3.6 Coastal Impacts on Groundwater

Groundwater near coastal areas is at a higher risk of contamination due to impacts of climate change that include sea-level rise, changes in rainfall, and groundwater withdrawal rates, as previously described in Section 1.2. Along coastlines, saltwater and groundwater are separated by the seaward movement of groundwater and a transition zone where freshwater and saltwater mix (Bradford, n.d.). When sea-levels rise and changes in precipitation levels occur, saltwater is likely to enter the groundwater, reducing the availability of freshwater for coastal regions as a result (Bradford, n.d.). This same impact occurs when too much water is extracted from aquifers, resulting in saltwater entering the groundwater as a means of recharging the aquifer (Huizer *et al.*, 2018). If too much saltwater gets into the groundwater, the groundwater's salt concentration can become too high for human use and consumption (Bradford, n.d.).

1.4 Saltwater Intrusion

Freshwater naturally moves seaward, which prevents saltwater from moving into freshwater aquifers. As denoted by the dotted line in Figure 4, there is a naturally occurring interface (often found near the coast or below the surface of the ground) where saltwater and freshwater mix called the zone of dispersion or the zone of transition (USGS, n.d.-g). Reduction in the amount of freshwater interferes with the zone of dispersion and allows for the movement of seawater into freshwater aquifers. This movement of seawater can be affected by climate change and by pumping water from a groundwater well (Lenntech, 2021).

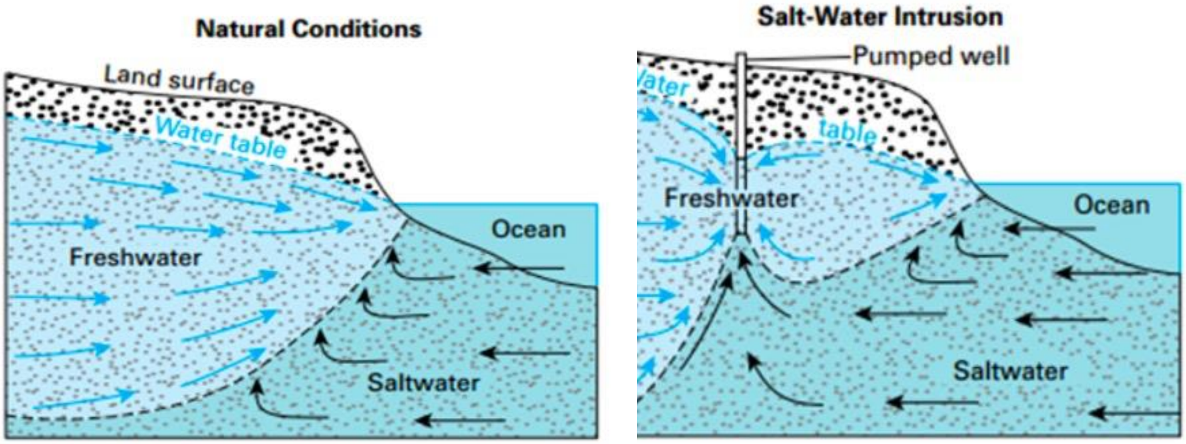


Figure 4: Diagram of how depletion of freshwater from excessive pumping causes saltwater to infiltrate the freshwater zones (USGS, n.d. -g).

1.4.1 Impacts of Sea Level Rise on Saltwater Intrusion

Climate change exacerbates saltwater intrusion through sea level rise, flooding, and droughts. This section focuses on the impacts of sea level rise. Sea level rise, while not the greatest contributor to saltwater infiltration, has an effect on coastal aquifers. One measured effect is that of the rising sea level on the zone of dispersion. Specifically in the eastern part of the Atlantic Coastal Plain, a finite difference model supported the finding that the position of the zone of dispersion interface is affected by sea level rise (Meisler *et al.*, 1984). This impact on the zone of dispersion could cause a disruption in the purity of a freshwater aquifer, especially in the distant future (Chang *et al.*, 2011).

When sea levels rise, saltwater encroaches inland and moves closer to coastal aquifers. This movement results from the change in freshwater and saltwater pressure gradients, which can be caused by sea level rise, and is also impacted by decreased aquifer recharge and over pumping of aquifers (Prince Edward Island Department of Environment Labour and Justice, 2011). Saltwater intrusion due to sea level rise has been seen throughout coastal areas of the U.S., with Florida being drastically impacted. Because Florida is a peninsula, the state is particularly impacted by sea level rise. Time-lapse maps illustrate that sea level rise could cause southern Florida to be submerged in water over time if the issue is not dealt with. It is also predicted that estuaries will become further extensions of the ocean instead of acting as protective barriers to the mainland (Machado, n.d.). Due to this rate of sea level rise, saltwater intrusion has already impacted groundwater in Florida’s coastal aquifers and caused groundwater to increase in salinity. Unfortunately, these impacts are expected to increase in severity over time as sea levels continue to rise and over pumping of aquifers occurs in the state. As a result, Floridians could lose their access to freshwater wells as the issue progresses. In Miami-Dade County, three public water supply well fields have already closed due to saltwater intrusion, with two of these public water supply well fields shutting down permanently (Machado, n.d.). It was found that saltwater intrusion in Miami-Dade County resulted from saltwater seeping from canals into groundwater and the encroachment of seawater inland along coastal aquifers, both of which have resulted from low water levels in aquifers (Machado, n.d.). Through further mapping and modeling, it has been shown that the movement of saltwater will cause the driving pressure for seawater to move inland through either coastal aquifers or through canals that exit to the ocean. These maps and models also led scientists to the conclusion that this movement is expected to increase during high tide events or during storm surges (Machado, n.d.).

1.4.2. Impacts of Flooding on Saltwater Intrusion

Flooding has been impacting groundwater quality over recent years because climate change causes sea level rise and a higher intensity and frequency of severe storms. Coastal regions see high levels of flooding specifically caused by storm surges and sea level rise, resulting in coastal surface water sources and aquifers facing issues in water quality. As coastal flooding occurs more frequently, an increased volume of saltwater is introduced into coastal aquifers and surface water sources (Mahmoodzadeh and Karamouz, 2017). Studies done on public health issues after Hurricane Katrina and Hurricane Rita proved that storm surges contaminated freshwater aquifers, and studies done in the northern Cook Islands two years after a category 5 cyclone showed atoll freshwater lenses (surface water sources) took between 11 to 26 months to recover. An additional study showed that moderate storms impact groundwater flow and water transport in coastal systems. This study showed that the occurrence of a tropical storm 2000 m south of a Georgia salt marsh caused the marsh's creek water to move more than 25 m from the creek bank at depths greater than 5 m (Mahmoodzadeh and Karamouz, 2017).

1.4.3 Impacts of Droughts on Saltwater Intrusion

As droughts occur worldwide with increased intensity and duration, the levels of groundwater in aquifers in affected areas have decreased. This decrease in groundwater is caused by both a lack of rain during droughts and the removal of water from aquifers faster than it can be recharged. During droughts, aquifers are recharged much slower because there is no rainwater seeping into the ground and entering into aquifers (USGS, n.d.-h). Because of this issue, aquifers by the coast can be recharged with saltwater during droughts.

The occurrence of saltwater intrusion in aquifers has increased significantly in the U.S. due to droughts occurring across the country. Saltwater intrusion caused by droughts has been an issue in California since 1946. In 1946, the first documented report of saltwater intrusion in the state was sent out from a farming center in the Salinas Valley (Walton, 2019). Orange County in California took actions to counteract saltwater intrusion in 1976, when a facility was built that injected treated wastewater into the nearby aquifer, forming a freshwater barrier against the ocean as a result (Walton, 2019). This action proved effective up until California recently faced a four-year-long drought. Because of the effects of the drought on California's aquifers, along with the agriculture industry over pumping groundwater, the California Department of Water Resources designated groundwater basins in Soquel, the Pajaro Valley, and the Salinas Valley as critical in 2015 due to saltwater intrusion. In some areas of California, the saltwater boundary has moved more than 6 miles inland. In attempts to control this issue, tighter restrains on groundwater use have been put into place in the state (Walton, 2019).

1.4.4 Impacts of Groundwater Pumping on Saltwater Intrusion

Without interference from populations pumping the water for use, rainfall is typically enough to recharge underground aquifers. However, with climate change causing increased demand for water, there is not enough water left in the hydrologic cycle to sustain increased usage. Freshwater, in this case, is being removed from aquifers at a greater rate than precipitation can replace it. Over drawing from freshwater sources is the main contributing factor to saltwater intrusion. An increased demand for water without consideration of the water budget of an area leaves aquifers nationwide unsuitable for use. For example, "in May County, New Jersey, more than 120 water supply wells have been abandoned because of saltwater contamination" (Chang *et al.*, 2011).

1.4.5 Impacts of Saltwater Intrusion

The intrusion of saltwater into otherwise fresh water sources reduces its productive and consumptive value (Safi *et al.*, 2018). This is especially a problem when the country depends heavily on the ability to use these aquifers. "In the US alone, it is estimated that freshwater aquifers along the Atlantic coast supply drinking water to 30 million residents living in coastal towns located from Maine to Florida" (Chang *et al.*, 2011). Loss of reliable access to a safe fresh water source has a significant impact on many people. Not only are the people who previously relied on the water source affected by this loss, but this may put stress on nearby aquifers, leading to a depletion of freshwater there, too.

Another significant issue is the structural integrity of buildings in areas affected by saltwater intrusion. Saltwater is extremely corrosive, especially in regard to older, more porous concrete. A news report on CBS Miami in 2021 provided evidence that saltwater intrusion contributed to the condominium collapse at Champlain Towers South in Surfside, FL (DeFede, 2021; CBSMiami.com Team, 2021). This resulted in 98 deaths (Lawson, 2021). This is an environmental issue as well as an engineering and policy issue. Buildings in areas at risk of saltwater depletion should be engineered with this in mind and monitored more frequently for signs of environmental degradation.

1.4.6 Impacts of Saltwater Intrusion on Water Quality and Treatment

As discussed previously, the increase in frequency of saltwater intrusion into source water is due to seawater flooding and storm surges that deposit saltwater onto land, as well as removal of freshwater from aquifers faster than it can be recharged (The Ocean Portal Team, 2019). Fresh groundwater in areas along the Atlantic coast in general contains low levels (20 mg/L) of salt that are a negligible source of daily salt intake, as daily salt intake is recommended to be less than 2,300 mg per day (Hedge, 2019; American Heart Association, n.d.). The World Health Organization has set a guideline that drinking water must have less than 200 mg/L of sodium in order for it to have a freshwater taste (MyTapWater.org, n.d.). Ground-water wells impacted by saltwater intrusion contain elevated concentrations of salts and are sometimes unusable for this reason (Hedge, 2019). The severity of saltwater intrusion has accelerated in recent years and has had adverse financial effects on treatment plants that rely on groundwater as their primary source of drinking water (Hedge, 2019). As saltwater intrusion continues to accelerate, water treatment plants must be able to adapt their processes to accommodate changes in source water availability and quality. This may include the need to adjust the treatment processes themselves, such as adding a nanofiltration process or reverse-osmosis process, or find a new source of water all together if water reaches salt levels above the limit of 200 mg/L (USEPA, n.d.-b).

1.4.7 Strategies for Managing Saltwater Intrusion

Management of saltwater intrusion in an area poses many challenges (Safi *et al.*, 2018). Monitoring an area is the first step to determine the extent of the problem. Traditionally, sentinel wells are drilled in target areas to determine the composition of water within the area. This is expensive, however, and is limited to one small location. One relatively new method of monitoring is electrical resistivity tomography (ERT). This is done by transmitting voltage through pairs of electrodes that detect and differentiate between electrically conductive seawater and electrically resistive freshwater (Than, 2017). Methods to map areas at risk for saltwater intrusion allow for action to be taken towards management.

A second component of a management plan is prevention. The most effective method of preventing saltwater intrusion is to limit or stop groundwater withdrawals in wells proximate to seawater. It is important that this strategy is employed before wells become contaminated with salt water, as reducing well withdrawals is not expected to reverse effects after saltwater intrusion has already occurred (Safi *et al.*, 2018). This requires proactive planning by the town to ensure that the annual water budget does not result in movement of the zone of dispersion.

A third aspect of a management plan is mitigation. This aspect involves "curtailing associated socio-economic burdens on coastal communities (impairment of water resources, damage to soil, plants and infrastructure, etc.)" (Safi *et al.*, 2018). Mitigating impacts of socio-economic burdens on coastal communities due to saltwater intrusion includes options such as constructing an additional water treatment plant that can treat saltwater, receiving water from another town or location that is not contaminated, and constructing infrastructure with saltwater intrusion in mind. Planning for the repercussions of saltwater intrusion vary dramatically on a case-by-case basis. Every situation is unique, but every town/city should have a plan for how to handle a saltwater intrusion event should it arise.

Lastly, if groundwater wells are contaminated due to saltwater intrusion, a community may need to adapt. This adaptation may include updating the water treatment process so it can handle and treat salty water. One method of adapting is adding membrane filtration to a treatment facility to remove salt. A reverse osmosis treatment plant, also known as a desalination plant, pushes water across a semipermeable membrane with pores sized at 0.0005 microns, leaving contaminants, like salts, behind the membrane and fresh water past the membrane (AchaWater.com, 2020). Nanofiltration is a similar membrane process that pushes water across a membrane with average pore sizes of 0.001 microns. Nanofiltration can filter out most salts, with an exception of sodium chloride (AchaWater.com, 2020). Because of the limitation that nanofiltration has, reverse osmosis is the better choice out of the two membrane filtration methods for treating water contaminated with salts.

One area in the United States that has been impacted by saltwater intrusion is Florida. Because Florida is a peninsula, water supply systems throughout the state have been significantly impacted by saltwater intrusion. Dania Beach, a city in Florida, has seen impacts from saltwater intrusion in its aquifer and well system. The goal of this Major Qualifying Project was to identify problems in water quality and supply in Dania Beach, Florida caused by saltwater intrusion and create a long-term management plan to address these problems. Chapter 2 shows the methods used to approach this goal, and Chapter 3 provides the results and analysis.

Chapter Two: Methods

The goal of this project was to identify problems in water quality and supply in Dania Beach, Florida caused by saltwater intrusion and create a long-term management plan to address these problems. This goal was achieved by researching background information on Dania Beach, forecasting population growth and water demand in Dania Beach, and researching Dania Beach's water quality and water treatment processes. Then, a list of long-term management plan options for Dania Beach's drinking water was created. These options were analyzed and ranked, and a management plan for Dania Beach was designed based on the highest-ranking option.

2.1 Dania Beach Background Information and Population Data

Background information on Dania Beach was gathered to provide context for this project. This information included location, climate, land area, and population. Data were obtained from the following official websites for the city of Dania Beach:

- Dania Beach (https://daniabeachfl.gov/245/About-Dania-Beach). The Dania Beach website contains the city's history, industries, tourist attractions, achievements, and services.
- Data USA (https://datausa.io/profile/geo/dania-beach-fl/). Data USA contains information about Dania Beach's population, diversity, economy, civics, housing and lifestyles, and health. The data are provided from 2000 to 2020, with the majority of the data falling between 2013 to 2019.
- Weather and Climate (https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,dania-beach-florida-us,United-States-of-America). Weather and Climate contains information about Dania Beach's weather and climate, including graphs conveying specific data such as temperature and rainfall.
- World Population Review (https://worldpopulationreview.com/us-cities/dania-beach-fl-population). World Population Review provides population data at various scales, from continents to zip codes. The site contains population data from 1970 to the present day, including information on population growth rate, race, age, level of education, household type, rate of poverty, and the origin of citizens in the city. For Dania Beach, population data were available from 1940-2021.

2.2 Population and Water Demand Forecasting

Population forecasting for Dania Beach was completed to project the city's future water demands. Population forecasting methods most commonly used for determining water demand were found through an online search using the terms "population forecasting methods for water demand in towns". From this search, reliable sources (e.g., peer reviewed sources, sources published by universities, and scientific/educational journals and articles) were used to determine which population forecasting method was most applicable for a city like Dania Beach. Then, population data were projected from 2020 to the year 2050 using the selected method.

After completing the Dania Beach population forecasting calculations, the city's water demand forecast was completed for the population served by the City of Dania Beach Water Utility and the entire city of Dania Beach. Typically, demand is calculated through a simple equation as shown below:

Water Demand (gal/day) = Per Capita Demand (gal/day-person) x Population (persons)

Quantitative data on water usage from residential and commercial properties in Dania Beach was received from Frederick Bloetscher, Ph.D., P.E. Dr. Bloetscher is President of Public Utility Management and Planning Services, Inc. (PUMPS) in Hollywood, FL. PUMPS was formed in July 2000 and has dedicated itself to "providing services to water, sewer and stormwater utilities in the evaluation, planning and management of public utility systems" (Public Utility Management and Planning Services Inc., n.d.). He is also a Professor at Florida Atlantic University in Boca Raton, FL. He has worked extensively with the Dania Beach water system. While it is possible to calculate water demand using data from commercial establishments (e.g., restaurants, schools, theaters) and different types of residences (e.g., apartments, condominiums, single-family homes), the demand based on these more extensive calculations was found to be very similar to the demand calculated using only the average per capita value. Therefore, the equation presented above using the average per capita water demand value and overall population was used for water demand calculations.

2.3 Dania Beach Well System and Water Treatment Plants

Historical data on the Dania Beach water sources and treatment of those sources was obtained to determine current and potential future water supply issues. While the impacts of saltwater intrusion were the focus of this investigation, the data were reviewed to determine if any additional water quality and/or quantity challenges were faced. The data obtained included the following:

- Area of Dania Beach that receives service from the City of Dania Beach Water Utility
- Construction of wells in Dania Beach
- Type of well (monitoring or production), depth and capacity of each well, pumping rates of each production well, date range of well usage, date, and reason well was taken out of service, and (if applicable) changes and restrictions of well usage
- Contaminants in well water and parameters well water is tested for
- Design and operation of treatment plants
    - Design flow rate of treatment plants
    - Contaminants including chlorides, calcium, magnesium, organics, color, turbidity, and trihalomethanes
    - Customers served by treated water

The number of customers served by the City of Dania Beach Water Utility was found using the Dania Beach Public Services website (https://daniabeachfl.gov/publicservices), which contains information including the objectives of the public services and the number of residents served. The other data listed above were gathered from sources that were forwarded to the team by Frederick Bloetscher, Ph.D., P.E.

Information on the impact of saltwater intrusion on Dania Beach's wells was gathered from two documents provided by Dr. Bloetscher: (a) a document containing supporting information for renewal of the city's permit for water usage and (b) a document containing background information on the water utility. An interview was also conducted with Professor Bloetscher to attain additional information as needed that could not be found in the documents provided to the team. Lastly, information on the history of problems in the city caused by saltwater intrusion were obtained from one journal article and one editorial found through an internet search for “Dania Beach water treatment plant”.

- “Dania Beach Goes Gold with Nanofiltration Plant” (https://www.bluetoad.com/display_article.php?id=1491810&view=173183) This journal article describes the construction, design, and LEED certification process of Dania Beach’s nanofiltration plant.

- “This Nanofiltration Water Treatment Plant Boasts a 96% Recovery Rate” (https://www.tpomag.com/editorial/2017/07/this_nanofiltration_water_treatment_plant_boasts_a_96_recovery_rate). This editorial describes benefits of the nanofiltration water treatment plant’s construction, how the treatment process works, how the treated water from Dania Beach’s lime softening plant and their nanofiltration treatment plant are blended, and the LEED certification process.

2.4 Management Plan for Water Provision in Dania Beach

Long-term management plan options for sustainable water provision in Dania Beach were listed, researched, and ranked. The list of management plans was created by the team in a management plan brainstorming meeting after researching water quality issues in Dania Beach. The management plan options are listed below:

- Use surface water instead of groundwater
- Construct wells further from the ocean
- Purchase additional water from a nearby system
- Construct and operate a desalination plant in Dania Beach
- Utilize wetlands in Dania Beach

Research on each of the management plan options was then conducted. A brief overview of methods used for each management plan is provided in Table 1 with additional details incorporated into the results section.

Table 1: Methods for Management Plans

Management Plan Option	Evaluation Methods Used
Use surface water instead of groundwater	• Locate water source within appropriate distance of Dania Beach using Google Earth Pro measuring tool • Determine surface water treatment option by comparing surface water treatment systems in Florida • Estimate pipeline costs by researching cost of pipeline per mile • Distribute cost among population receiving water and estimate the increase in each household water bill
Construct wells further from ocean	• Distance of current wells from ocean determined using Google Earth Pro • Distance of furthest point in Dania Beach from ocean to the shoreline was determined using Google Earth Pro • Map of Dania Beach and Broward County saltwater intrusion line overlaid using Adobe Photoshop Mix
Purchase additional water from a nearby system	• Feasibility of purchasing water from Broward County, Miami-Dade County, and Fort Lauderdale were analyzed by comparing future treatment capacity of Dania Beach and each location's future water demand • Costs of purchasing water from each location were researched and compared • Additional treatment processes and pipe connections were investigated by estimating pipeline costs and distributing the cost among the population receiving water. From this distribution, the increase in each household's water bill was estimated
Construct and operate a desalination plant in Dania Beach	• Determined the level to which saltwater has intruded into the freshwater in the Biscayne Aquifer • Researched reverse osmosis desalination plants in Florida and California with similar characteristics to the treatment facilities Dania Beach o The Tampa Bay Plant o Robert W. Goldsworthy Desalter o City of Cape Coral RO Water Treatment Facility. • Performed a cost comparison for each plant in a table which included: o Approximate Capital Cost o Cost to Consumer ($/1000 gal) o Capacity (MGD) o Adjusted Capital Cost for 4.40 MGD Capacity o Primary Treatment Type o Population Served • Estimated total capital cost of the proposed desalination plant in Dania Beach based on the table of cost estimation
Utilize existing wetlands in Dania Beach	• Investigated the benefits of wetlands, specifically water storage • Identified contemporary wetlands in Dania Beach and Broward County using U.S. Fishing and Wildlife Service wetlands mapping tool • Researched the current uses of the two largest wetland systems • Determined if utilization of wetlands for drinking water storage was feasible

The five management plan options were then ranked according to the criteria shown below. Each option was ranked on a scale of 1 to 10 for each criterion, with 1 being the lowest ranking and 10 being the highest. For example, an option would be ranked low if it was costly and produced poor quality water, and high if it was technologically feasible and used little space. The rankings were color-coded with 1-3 being indicated by red and interpreted as poor, 4-6 being indicated by yellow and interpreted as fair, and 7-10 being indicated by green and interpreted as good. The rankings were added together for a total score to determine the most suitable option for sustainable water provision in Dania Beach.

- Technical feasibility
- Water quality: health
- Water quality: aesthetics
- Cost
- Space required

Chapter Three: Results

The goal of this project was to identify the impact of saltwater intrusion on water supply in Dania Beach and develop a long-term management plan for the city. This goal was achieved by researching background information on Dania Beach, forecasting population growth and water demand in Dania Beach, and researching Dania Beach's water quality and water treatment processes. Then, long-term management plan options for Dania Beach's drinking water were created. These management plan options were analyzed and ranked to determine their feasibility.

3.1 Background on Dania Beach

Dania Beach is a city located in Broward County in the southeast part of Florida, and is part of the Miami metropolitan area (DaniaBeachFL.gov, n.d.-a.). To the north lies Fort Lauderdale, and to the south lies Hollywood. Dania Beach is directly in contact with the Atlantic Ocean to the east (DaniaBeachFL.gov, n.d.-a). The local climate is hot and wet. Precipitation averages 62 inches (1575 mm) per year, compared to the national average of 38 inches (965 mm), and snow is rare. The temperature fluctuates between 59 and 90 degrees Fahrenheit depending on the season (BestPlaces.net n.d.). Average monthly temperatures and precipitation in Miami are displayed in Figures 5 and 6 (Weather-And-Climate.com, 2021).

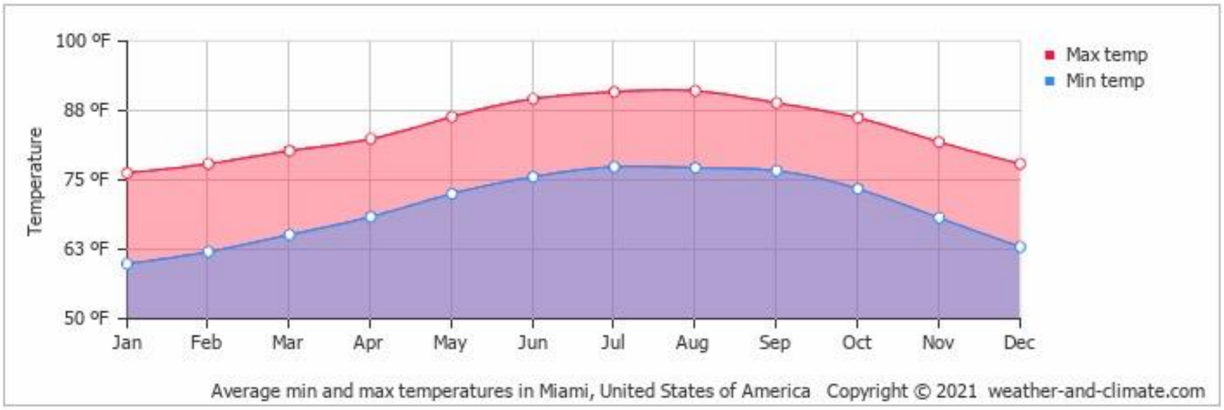


Figure 5**:** Average minimum and maximum temperatures in Miami, FL (Weather-And-Climate.com, n.d.).

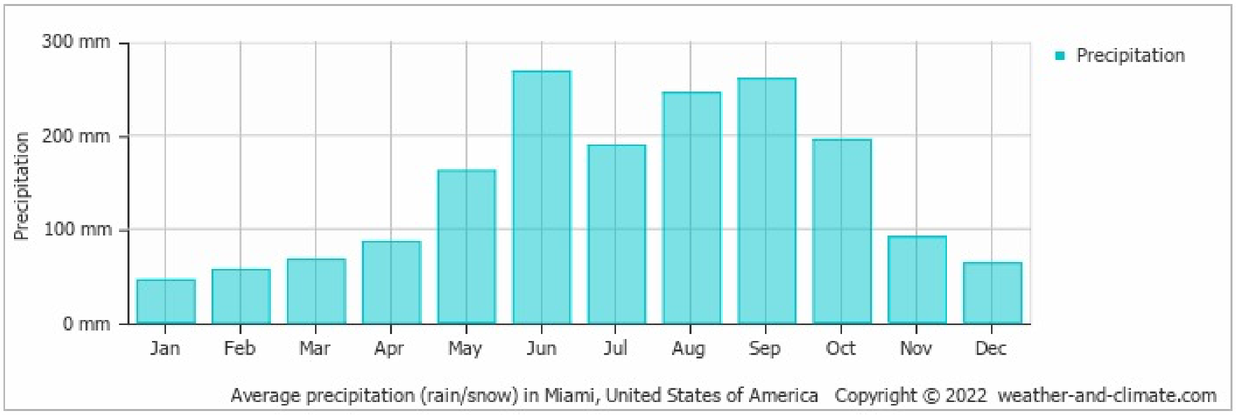


Figure 6: Average precipitation in Miami, FL (Weather-And-Climate.com, n.d.).

Dania Beach has an area of 8.1 square miles (DaniaBeachFL.gov, n.d.-a). Within the last 20 years, the population of Dania Beach has increased by 61%. In 2000, Dania Beach had a population of 20,061 people. In 2020, the city had an estimated population of 32,344. The city's population contains 12,237 households with an average of 2.6 people per home (United States Census Bureau, n.d.; World Population Review, n.d.-a; Personal communications, Fred Bloetscher, December 5, 2022). The city's population has 15,400 employed people and a 50.3% home ownership rate (Data USA, 2019). The average household income for the area was $47,135 in 2019, and the poverty rate was 17.7% (Data USA, 2019).

The Biscayne Aquifer is the main potable water source for the City of Dania Beach (DaniaBeachFL.gov, n.d.-b). As seen in Figure 7, the Biscayne Aquifer is located on the southern coast of Florida. The location of this aquifer in relation to the Atlantic Ocean puts it at a high risk for saltwater infiltration. Water obtained from the Biscayne Aquifer has high levels of hardness due to calcium and magnesium, and also high levels of natural organic matter and color. Further discussion of water quality in the Biscayne Aquifer is provided in Section 3.3.

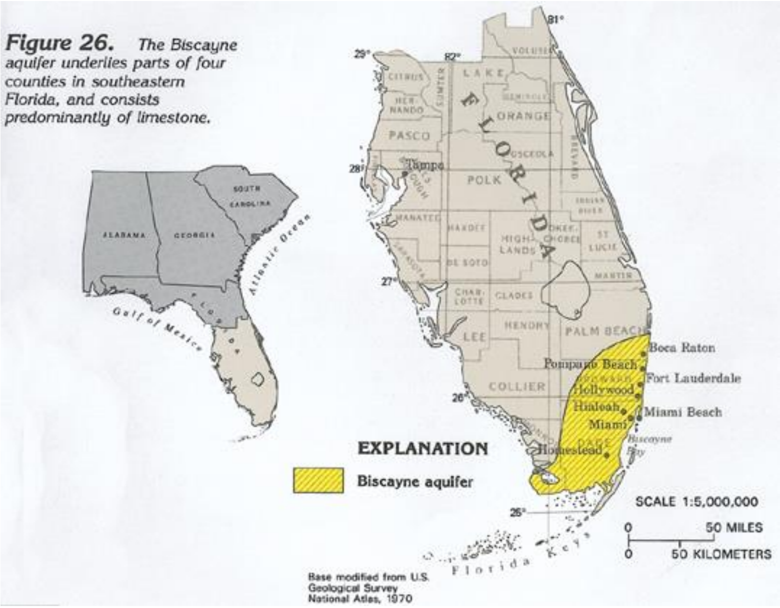


Figure 7: Map of Biscayne Aquifer (United States Geological Survey (USGS), n.d.-i).

The City of Dania Beach Water Utility serves a population of over 30,000 people, with 60% of the population receiving water directly from the Dania Beach water treatment system. The other area of the city (40% of the population) receives water that Dania Beach purchases from Broward County, which was decided upon in an agreement within the City of Hollywood, Florida (City of Dania Beach Water Utility, n.d.-b). This water is treated and distributed by the Broward County Water and Wastewater Service (WWS). The Dania Beach water treatment system typically receives water from its well system located in the city. However, the two active wells are currently offline, so the treatment system is receiving raw water from the Broward County regional wellfield (Personal communications, Fred Bloetscher, February 26, 2022). The City of Dania Beach Water Utility treatment plants are discussed in more detail in Section 3.3. The Broward County WWS and City of Dania Beach water distribution systems that supply water to Dania Beach are separate and have no pipe connection, with the exception of an emergency use pipe connection between Dania Beach and Hollywood at Dania Beach's water treatment plants. The two service areas that provide water to Dania Beach will continue to remain separate well into the future (Personal communications, Fred Bloetscher, February 25, 2022). The purchase agreements between Dania Beach and Broward County for raw water from the regional wellfield are described in more detail in Section 3.3. A map of the area of Dania Beach that receives service from the city's water treatment plants is shown in Figure 8.

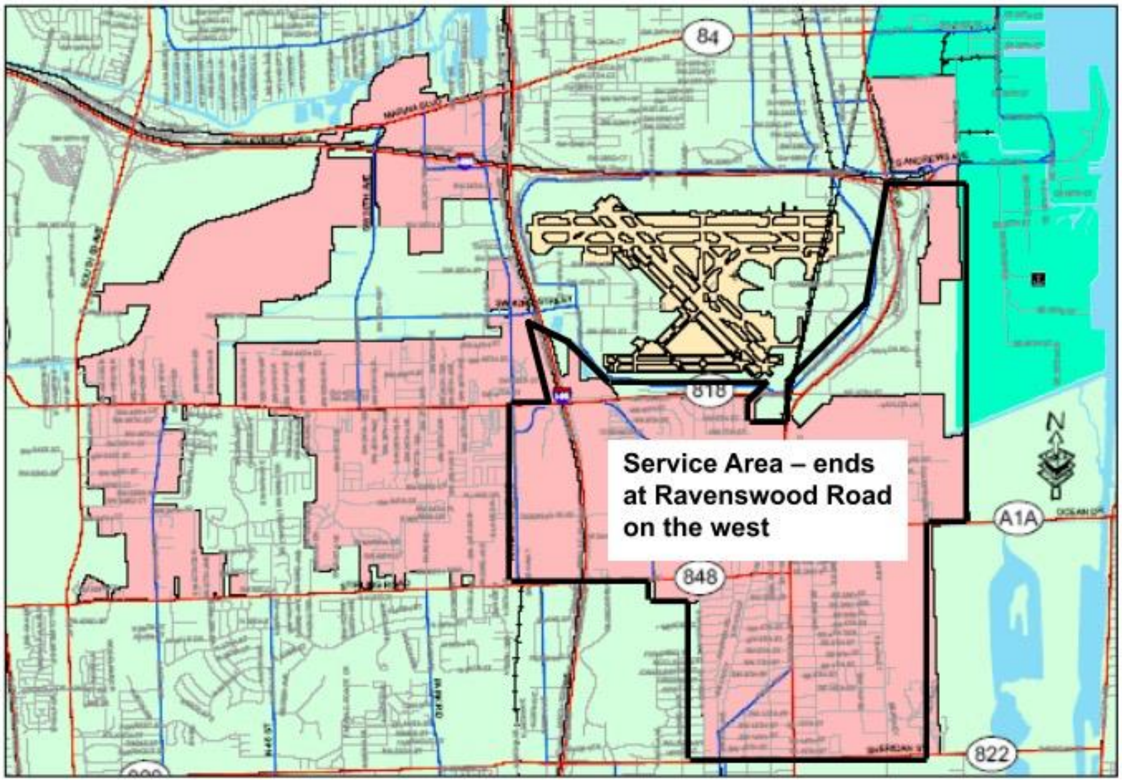


Figure 8: Map of Dania Beach (red) and area that receives service from The City of Dania Beach Water Utility's treatment plant (black outline) (City of Dania Beach Water Utility, n.d.-b).

3.2 Dania Beach Population Forecasting and Water Demand Forecasting

To determine Dania Beach's future water needs, the population and water demand were projected through the year 2050. Projections through this year were used in order to provide guidance for the design of a long-term management plan for Dania Beach. Projections were calculated using the Incremental Increase Method (see Section 3.2.1), which uses a mathematical model based on average population increase per decade. Populations from 1940 through 2020 were used to make predictions from 2020 to 2050 to support a 30-year management plan. This time frame was influenced by the estimated time that it takes for water treatment systems to fail. The average lifespan of water treatment plants is between 30 to 60 years (waterboards.ca.gov, n.d.). To consider the construction of new water treatment plants and use of current water treatment plants to address saltwater intrusion, the timeframe of 30 years was selected for population forecasting. This section provides information on forecasting methods, justifies selection of a method for Dania Beach, and provides calculated estimates for the future population and water demand.

3.2.1 Methods of Population Forecasting

There are three categories of population forecasting. The first category includes methods in which the population changes at a constant rate over time. This includes the Arithmetical Increase Method, the Geometrical Increase Method, and the Simple Graphical Method. The Arithmetical Increase Method assumes that the population changes at a constant rate over time (Sengupta, 2017). For a population that increases at a constant percentage each decade, the Geometrical Increase Method should be used (Sengupta, 2017). The average percent increase per decade can be calculated using census data, and used to project further population change (Gawatre *et al*., 2016). In the Simple Graphical Method, a plot is made of the available census data, and an appropriate curve drawn to connect the data. This curve can then be extended to project future population growth (Gawatre *et al.*, 2016).

The second group covers comparative methods. This includes the Comparative Graphical Method which compares the city whose future population is to be estimated to cities with conditions and characteristics similar to that city. Since these cities are similar, the assumption is that they will develop in the same way (Sengupta, 2017). It also includes the Master Plan Method. Most major cities create master plans that predict the development of the city for 25 to 30 years into the future. These plans include fixed population densities in different areas in the city. The Master Plan Method takes advantage of this fixed population prediction to design water supply systems to operate under the maximum future population (Sengupta, 2017).

The third group includes methods that change inconsistently over time. This includes the Incremental Increase Method, the Decreasing Rate Method, the Logistic Curve Method, and the Apportionment Method. The Incremental Increase Method uses aspects of both the Arithmetical Increase Method and the Geometrical Increase Method. In this method, the future population is determined by a combination of the average increase per decade and the average percentage increase per decade. This method uses the formula:

$$Pn = P + n(la + lc)$$

where Pn represents the future population after ‘n’ number of decades, P is the population of the previous decade, n is the number of decades, la is the average population increase per decade, and lc represents the average incremental increase per decade (Sengupta, 2017). The Decreasing

Rate Method assumes the population grows at an increasing rate first, followed by a decline in population growth. To determine the final population forecast, the average decrease in growth is subtracted from the latest percentage increase for each successive decade (Sengupta, 2017). The third forecasting method is the Logistic Curve Method. In this method, the population is plotted on a graph with respect to time. This logistical growth pattern can be seen in Figure 9 (Sengupta, 2017). This curved plot is characterized by its tendency to begin at a low rate of population rate, grow to a high rate, and then return to a lower rate when it nears the saturation limit (Gawatre *et al.*, 2016).

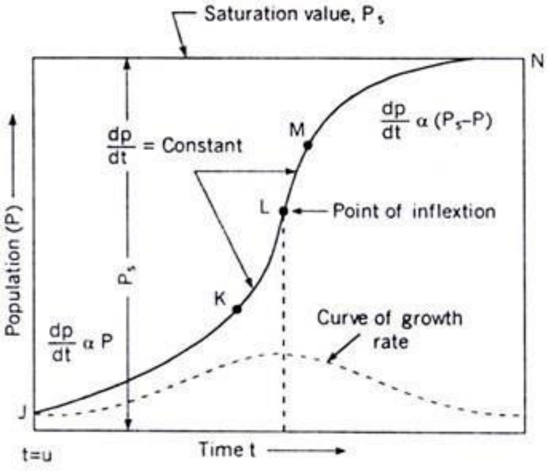


Figure 9: Logistic Curve Method (Sengupta, 2017).

A final method for projecting inconsistent population growth is the Apportionment Method. Also known as the ratio method, this method expresses the census population record as the percentage of the population of the whole country (Sengupta, 2017). The population of the city under consideration and the country's population for the last four to five decades are collected from the census department. The ratio of the town under consideration to the national population is calculated for these decades. Then, a graph is plotted between these ratios and the time. The extension of this graph will give the ratio corresponding to the future years for which the forecasting of population is to be done. The ratio obtained is multiplied by the expected national population at the end of the designed period for determining the expected national population of the town under reference (Sengupta, 2017).

A population forecast method from the third grouping is appropriate for Dania Beach because it has a population that changes inconsistently over time. The incremental method was selected because it is a modified arithmetic increase method that is best suited for average size towns that have an overall positive growth rate. The decreasing rate method is most suitable for towns with overall negative, or decreasing, growth rates, which does not apply to Dania Beach (Sengupta, 2017). The logistic curve method requires specific normal conditions in which the population is not exposed to sudden changes that can result from epidemics, war, natural disasters, and other population altering events (Post, 2020). This is unrealistic for most cities, especially in times of COVID. Broward County had the second highest 7-day COVID infection rate in Florida (after Miami-Dade County) and has had upwards of 3,000 COVID related deaths (USA Facts, 2022). Additionally, population growth rates often do not follow the smooth S curve, and rarely do they increase in growth and stay at an asymptote (Post, 2020). The apportionment method is applicable for large and old cities with considerable development and assumes that the city's growth rate percentage is comparable to the national growth rate percentage (see Figure 10) (Sengupta, 2017). The United States historical annual population growth rate for the past decade has been slowly declining. In 2010, the annual growth rate was 0.88%, and ten years later this rate decreased to 0.59%. Additionally, as shown in Figure 11, the population annual growth rate is projected to decline from 0.59% to 0.31% from 2020 to 2050 (MacroTrends.com, 2022). Considering that the US annual growth rates are declining in present day and are projected to decline in the future, the apportionment method is not an ideal method to project Dania Beach's increasing population growth. Therefore, the incremental increase method was best suited for Dania Beach.

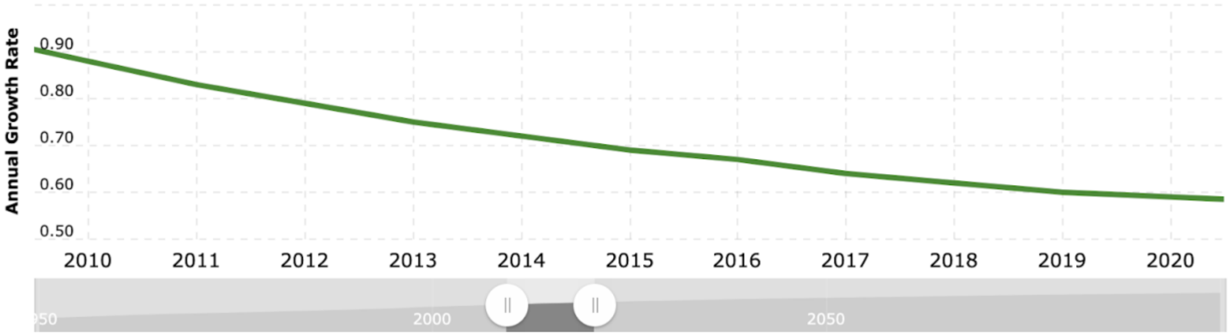


Figure 10: United States Population Annual Growth Rate from 2010 to 2020 (MacroTrends.com, 2022).

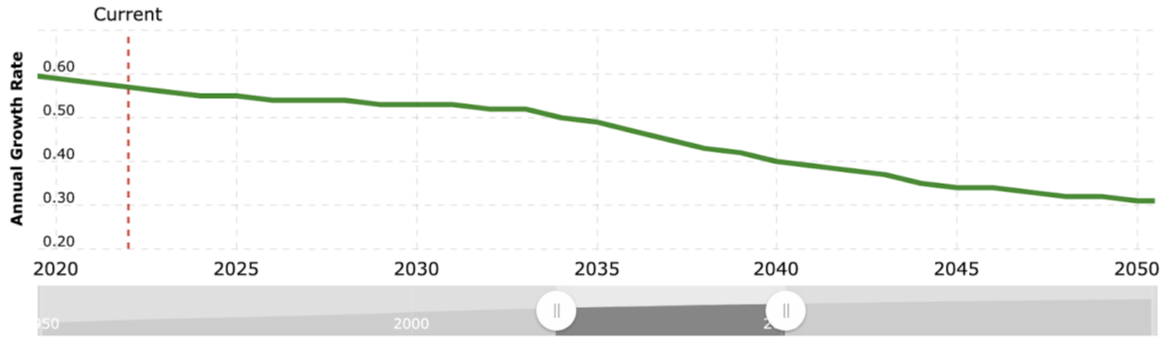


Figure 11: United States Population Annual Growth projected from 2020 to 2050 (MacroTrends.com, 2022)

3.2.2 Dania Beach Water Demand

The water demand by land use is shown in Appendix 2. These data were obtained through correspondence with Frederick Bloetscher, a consultant who has worked with the Dania Beach water utility. The data include daily water demand for dwellings, businesses, public services, and industries. Water demands range from 0.1 GPD per square foot of a retail store to 150 GPD per single family dwelling. The majority of land use water demand values (e.g., retail stores, theaters, schools) account for a small portion of daily water consumption in Dania Beach. The per capita consumption value takes into account water use both within and outside of one's residence (Personal communications, Fred Bloetscher, December 5, 2021).

To determine if a single per capita water use value can be used for Dania Beach, current data on population and water production were evaluated. The water produced by Dania Beach's water treatment plants was an average of 2.1 MGD in 2009, with an expected increase to 2.7 MGD by 2028 (City of Dania Beach, 2009). The population of Dania Beach was 32,344 people in 2020 (United States Census Bureau, n.d). Interpolating between the water demand of 2009 and estimated demand of 2028, the water demand of 2020 is estimated to be 2.45 MGD. As noted in Section 3.1, 60% of the population of Dania Beach receives water from the city of Dania Beach Water Utility, which is approximately 19,406 people. Using a water demand per capita of 120 GPD for 19,406 people, the water demand would be 2.33 MGD in 2020. There is a 5% difference between the interpolated water demand based on expected plant production (2.45 MGD) and the estimated demand based on population and a single per capita usage (2.33 MGD). Because these two estimates are similar, using the per capita demand of 120 GPD is reasonable for water demand projections.

3.2.3 Population and Water Demand Projections for Dania Beach

Population and water demand were projected over the next 30 years for Dania Beach. The water demand forecast through 2050 was conducted to provide guidance for the design of a long-term management plan for Dania Beach. The population was projected by using the Incremental Increase method equation, as described in Section 3.2.1. The population projection calculations are shown in the appendix, and the data are in Table 2. The table includes various columns, which were either used in the calculations or are the result of calculations. The columns are the year (in decades), the historical population data of Dania Beach, the increase in population between decades, the incremental increase of the population per decade, the population forecast of the entire city of Dania Beach, the population forecast of the residents served by the City of Dania Beach Water Utility, the water demand forecast of all of Dania Beach, and the water demand forecast of the City of Dania Beach Water Utility.

The results for the population forecast, Pn, are shown in the column titled "Population Forecast: Dania Beach". The Incremental Increase equation is:

$$Pn = P + n(la + lc)$$

The equation uses the population of the decade previous (P) to calculate the population in a future decade (Pn). The values used for the prior decade are shown in the column of historical data (using 2020 data to project to 2030) and the column of forecast data (e.g., using 2030 data to project to 2040). The Dania Beach historical population from 1940 to 2020 is shown in Figure 12. Because the previous decade's data was used for P, the term n in the equation was always 1. The term la, the average arithmetical increase, was determined by taking the difference in population between each decade (1940 through 2020) and taking the average of these differences. These values for la are shown in the column titled "Increase in population" in Table 2. The lerm lc is the average incremental increase, which was calculated by taking the difference between each decade's population increase from 1950 to 2020. For example, to determine the incremental increase of the population in 1960, the population increase of 1950 was subtracted from the population increase of 1960. These values for lc are shown in the column titled "Incremental Increase (per decade)" in Table 2. Because 60% of Dania Beach's population is served by the City of Dania Beach Water Utility, the projection for the population served by the utility was calculated by multiplying the population projection values for the entire city of Dania

Beach by 0.6. The population forecast for those served by the utility is shown in the column titled “Population forecast: residents served by Dania Beach water utility” in Table 2.

To calculate water demand projections, it was assumed that Dania Beach’s population will grow uniformly across the city, causing the population ratios served by Broward County and the City of Dania Beach Water Utility to remain the same over time. To calculate the water demand forecast of Dania Beach, the population forecast values were multiplied by 120 GPD, as this value is the water demand per capita. The values of Dania Beach’s water demand projections are shown in the column titled “Water demand forecast: Dania Beach (MGD)”. The water demand forecast for Dania Beach’s Water Utility was calculated by multiplying the population served by Dania Beach’s Utility by the water demand per capita (120 GPD). All results are shown in Table 2 and Figure 13, and all calculations are shown in Appendix 1. Overall, the results in Table 2 show a population forecast and water demand projection that increase every decade. The area served by the water utility is projected to grow from 19,406 in 2020 to 26,273 in 2050, and correspondingly the water demand from an estimated 2.33 MGD to 3.15 MGD over the same time period.

Table 2: Population and Water Demand Forecast of Dania Beach

Year	**Historical Population Data**	**Increase in population**	**Incremental increase (per decade)**	**Population forecast: Dania Beach**	**Population forecast: residents served by Dania Beach water utility**	**Water demand forecast: Dania Beach (MGD)**	**Water demand forecast Dania Beach Water Utility (MGD)**
1940	2,900	---	---	---	---	---	---
1950	4,500	1,600	---	---	---	---	---
1960	7,100	2,600	+1000	---	---	---	---
1970	9,000	1,900	-700	---	---	---	---
1980	11,796	2,796	+896	---	---	---	---
1990	13,024	1,228	-1568	---	---	---	---
2000	20,061	7,037	+5,809	---	---	---	---
2010	29,808	9,747	+2,710	---	---	---	---
2020	32,344	2,536	-7,211	---	19,406	3.88	2.33
2030	---	---	---	36,159	21,695	4.34	2.60
2040	---	---	---	39,974	23,984	4.78	2.88
2050	---	---	---	43,789	26,273	5.26	3.15
Average	---	3,681	+134	---	---	---	---

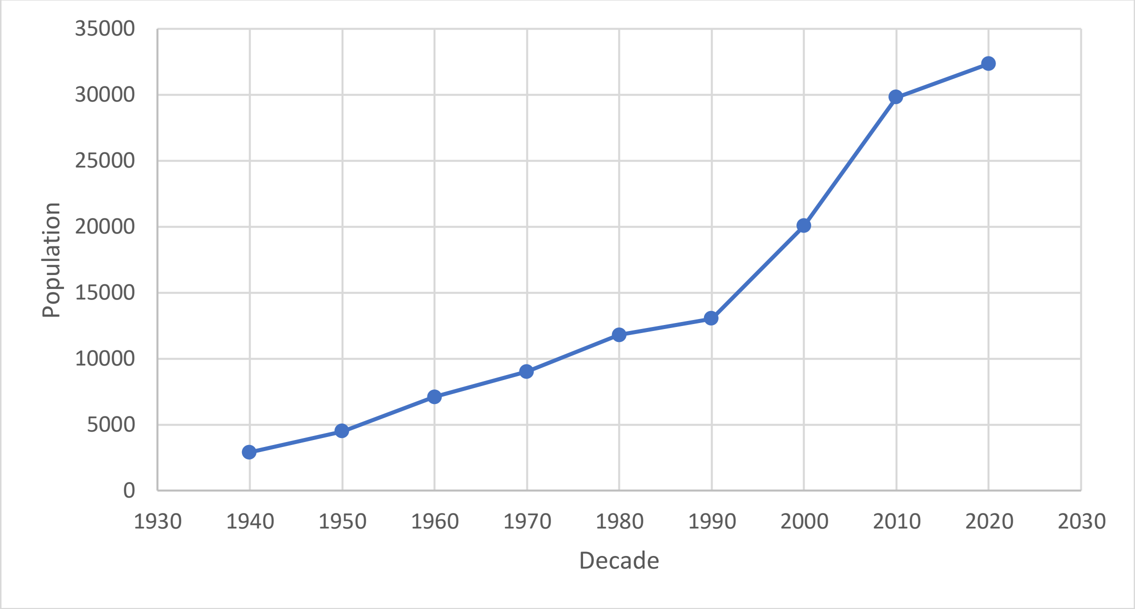


Figure 12: Dania Beach's historical population data between 1940-2020

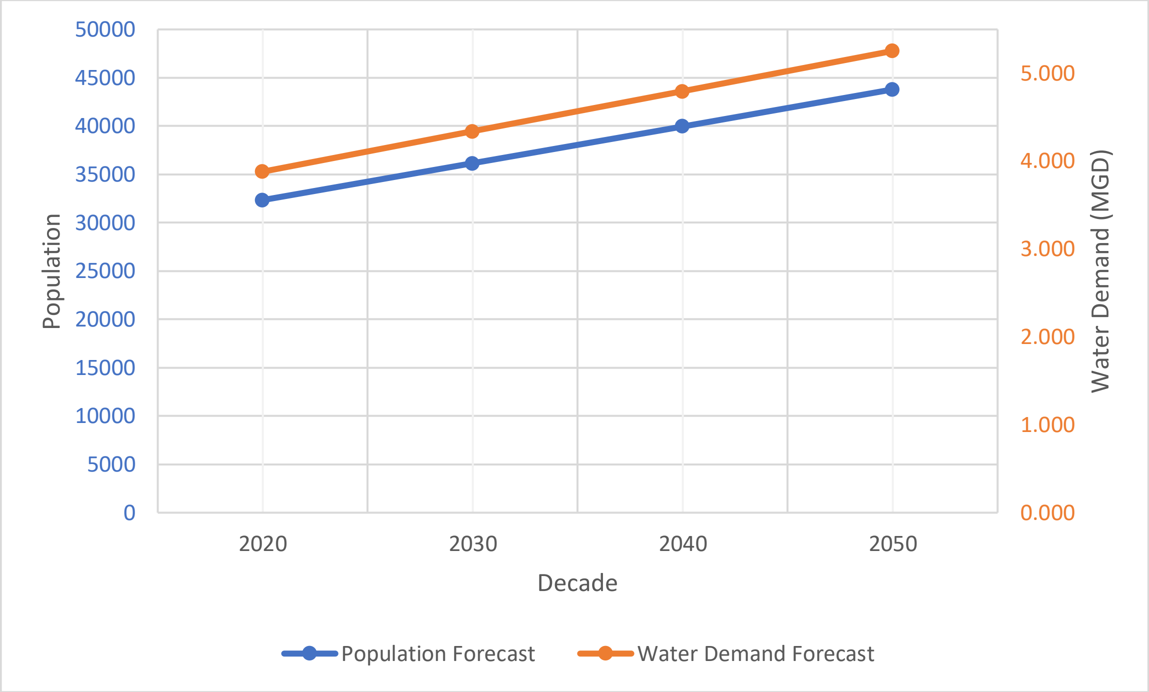


Figure 13: Dania Beach Population and Water Demand Forecast from 1940 to 2050

3.3 Impacts of Saltwater Intrusion on Water quality in Dania Beach

The City of Dania Beach water utility has used water from numerous wells over the city's history. The first wells (wells A, B, and C) were constructed in the downtown area of Dania Beach in the 1920's. These wells had depths of 40 ft, but the capacities of these wells are unknown. In 1951, wells D, E, and F were constructed along the Florida East Coast Railroad due to both the deterioration of wells A, B, and C and a need for higher water capacity. The exact cause of the deterioration of wells A, B, and C is unknown due to a lack of data on those wells (Personal communications, Fred Bloetscher, December 3, 2021). Wells A, B, and C were abandoned after wells D, E, and F were constructed. Wells D, E, and F had depths of 40 ft and each had a capacity of 2100 gpm. In 1986, wells D, E, and F were no longer used due to the water having high levels of chlorides, indicating saltwater intrusion. Wells D, E, and F were officially abandoned in 2008. In 1985, wells G and H were constructed on the west side of Dania Beach to replace wells D, E, and F (City of Dania Beach Water Utility, n.d.-b; Personal communications, Fred Bloetscher, December 3, 2021). Wells G and H each had a depth of 64 ft and an original capacity of 2100 gpm. In 2012, well G's capacity was reduced to 250 gpm due to saltwater intrusion. Well H's capacity was reduced to 1400 gpm, and then reduced again to 700 gpm before it was deemed unusable in 2010. These restrictions in capacity in wells G and H were all due to water use permits, which were issued to restrict overpumping and prevent saltwater intrusion (City of Dania Beach Water Utility, n.d.-b, Personal communications, Fred Bloetscher, December 3, 2021). To replace well H, well I was constructed in 2010. Because saltwater underlies Dania Beach's wells, well I was constructed with a depth of 40 ft. As of 2022, wells G and I are temporarily out of service for maintenance and saltwater intrusion concerns (Personal communications, Fred Bloetscher, December 3, 2021). A water use permit for 2021 is proposed to bring the wells back into service and to limit the combination discharge rate from both wells to 250 gpm, addressing saltwater intrusion concerns (City of Dania Beach Water Utility, n.d.-b; Personal communications, Fred Bloetscher, December 3, 2021). A map of the wells is shown in Figure 15, with an exception of wells A, B, and C. The location of wells A, B, and C is unknown, as data about these wells was lost between 1951 and present day (Personal communications, Fred Bloetscher, December 3, 2021).

Overall, most of the groundwater wells in Dania Beach have been taken out of service due to saltwater intrusion. In total, seven of the nine wells constructed in Dania Beach have been permanently taken out of service for a variety of reasons, including deterioration of wells, capacity issues, and saltwater intrusion. Four wells have been permanently taken out of service due to saltwater intrusion. Dania Beach typically relies on well G, well I, and the Broward County County regional wellfield. However, wells G and I have been temporarily removed from service for maintenance and saltwater intrusion concerns (Personal communications, Fred Bloetscher, December 3, 2021). Therefore, Dania Beach solely relies on the Broward County regional wellfield as of 2022 (Personal communications, Fred Bloetscher, February 26, 2022).

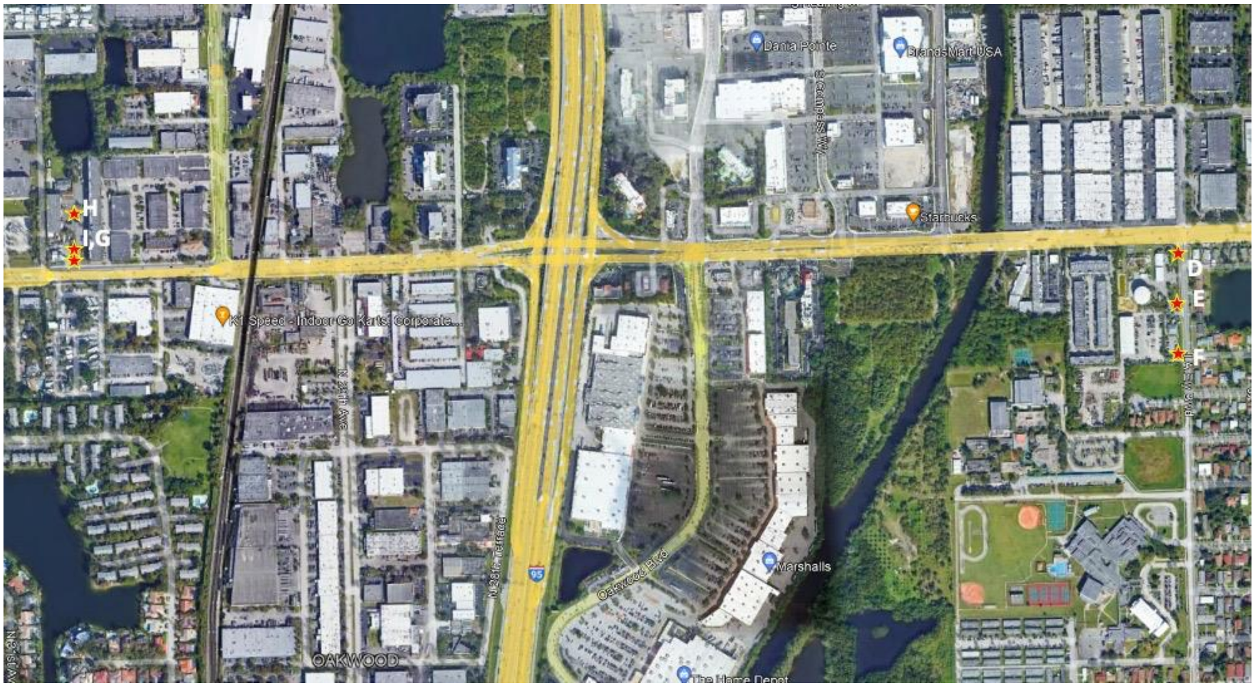


Figure 14: Map of Wells D, E, F, G, H, and I in Dania Beach shown by red stars with the corresponding letter name next to the star.

Information on the wells is summarized in Table 3. Table 3 shows the name of the well, the year the well was constructed, the well type, the depth of the well, and the capacity of the well. This table also shows the date range of usage, changes or restrictions, the year taken out of service, and the reason the wells were taken out of service. As shown, four out of nine wells in Dania Beach have been completely taken out of service due to saltwater intrusion.

Table 3: Data on Wells A through I

Well	Year constructed	Well Type	Depth (ft)	Capacity (gpm)	Date range of usage	Changes/ restrictions	Year taken out of service	Reason taken out of service
A	1920's	Production Well	40	Unknown	1920's-1952	No longer in service	1952	Deterioration of well and capacity issues
B	1920's	Production Well	40	Unknown	1920's-1952	No longer in service	1952	Deterioration of well and capacity issues
C	1920's	Production Well	40	Unknown	1920's-1952	No longer in service	1952	Deterioration of well and capacity issues
D	1951	Production Well	40	2100	1951-1986	No longer in service	1986	High chloride levels (saltwater intrusion)
E	1951	Production Well	40	2100	1951-1986	No longer in service	1986	High chloride levels (saltwater intrusion)
F	1951	Production Well	40	2100	1951-1986	No longer in service	1986	High chloride levels (saltwater intrusion)
G	1986	Production Well	64	2100, reduced to 250	1985-present	Temporarily out of service	N/A	Maintenance and saltwater intrusion concerns
H	1986	Abandoned as production well, currently used as a monitoring well	64	2100, reduced to 1400, reduced to 700	1985-2010	No longer in service	2010	Saltwater intrusion
I	2010	Production Well	40	700, reduced to 250	2010-present	Temporarily out of service	N/A	Maintenance and saltwater intrusion concerns

In the 1920's, Dania Beach relied on untreated water from wells A, B, and C. This well system was not able to handle an increasing population due to increased water demand. This increase in water demand resulted in the deterioration of wells due to excessive pumping (Bloetscher *et al*., 2013). Because the wells deteriorated early in the city's history, it is unknown what exactly occurred within the wells that contributed to their deterioration. In 1952, the city finished construction of a 3 MGD capacity lime softening water treatment plant and began operation (Bloetscher *et al*., 2013; Day, 2017). In the softening process, calcium and magnesium are precipitated out to reduce the hardness of the source water, and sodium hypochlorite is added for disinfection (Day, 2017). However, this system had its shortcomings. The wells at Dania Beach had reached their maximum discharge capacity, causing supply concerns. This issue led the city to purchase a portion of its raw water from the Broward County regional wellfield starting in 1992. As of 2022, the regional wellfield supplies the City of Dania Beach's water treatment plants. Dania Beach is also in another agreement from 2008 to receive emergency or bulk water from the City of Hollywood, FL (City of Dania Beach Water Utility, n.d.-a). Both the Broward County and Hollywood agreements were in effect at the time of writing this report (2022). Water from the Broward County regional wellfield is higher in color and iron than the water from Dania Beach, and after treatment, it is higher in disinfection byproducts. This issue in water quality negatively interacted with the lime softening process operation that the city already had in place. As a result, this issue caused the city difficulties in meeting regulatory requirements for color, trihalomethanes, and organics. These difficulties spurred the city to reimagine its water supply system, and in 2003, Dania Beach developed a water, sewer, and stormwater strategic plan. The city analyzed options to solve their water quality issues, and years later, the city decided to construct a nanofiltration plant.

In 2012, the first LEED Gold-certified nanofiltration water plant in the world began operation in Dania Beach. The nanofiltration plant and lime softening plant have a combined maximum processing capacity of 8 MGD. The plants are typically fed by a mixture of water from well G, well I, and the Broward County regional wellfield. However, wells G and I have been temporarily removed from service for maintenance and saltwater intrusion concerns. Currently, the Broward County regional wellfield supplies the water treatment plants (Personal communications, Fred Bloetscher, February 26, 2022).

The nanofiltration system includes a two-stage nanofiltration membrane system and a third and fourth stage of reverse osmosis membranes to achieve up to 96% recovery, compared to most nanofiltration processes which achieve about 85%. The lime softened water (which has sufficient alkalinity) is then combined with the nanofiltered water (which is deficient in alkalinity) to create a blended water. In addition, the acidity of the water put through nanofiltration (pH of approximately 6) can become more basic if it is blended with the lime treated water. Otherwise, the acidic water would have to be treated with sodium hydroxide. At distribution, the water has a pH of between 8.5 and 8.8. Combined use of these two treatment systems reduces chemical use and the costs that come with post treatment processes (Day, 2017)**.**

3.4. Long Term Management Plan for Dania Beach's Water Supply

Because Dania Beach's wells are facing water quality issues caused by saltwater intrusion, a long-term management plan for water supply is needed for the portion of the city served by the City of Dania Beach Water Utility. As discussed in Section 3.2.3, the 2020 water demand for the area of Dania Beach supplied by the City of Dania Beach Water is estimated at 2.33 MGD based on population and a 120 GPD per capita usage. There is additional demand in the area supplied by Broward County WWS. These two supply systems are not connected. Broward County WWS has no intentions of selling its entire water system to Dania Beach. The separation of these systems is planned to continue well into the future, as the two systems are run by separate entities (Personal communications, Fred Bloetscher, February 25, 2022). Therefore, only the City of Dania Beach Water Utility system is taken into consideration in the majority of this section.

The City of Dania Beach Water Utility is supplied with water from a lime softening treatment plant and a nanofiltration treatment plant. The capacity of the lime softening water treatment plant is 3 MGD, and the capacity of the nanofiltration treatment plant is 5 MGD, producing a combined capacity of 8 MGD. In 2050, the total water demand will be 3.15 MGD for the portion of Dania Beach that receives service from the water utility. Currently, both water treatment plants work together and are not capable of treating water with high salinity levels. The lime softening plant is not able to handle saltwater intrusion because it does not have the proper equipment included in the plant. The nanofiltration plant is not able to handle saltwater intrusion either. While the nanofiltration plant contains reverse osmosis membranes, it cannot effectively treat saltwater because it does not operate at a high enough pressure. The pressure in the nanofiltration plant does not exceed 225 psi, and a minimum pressure of 800 psi would be needed to treat saltwater in Dania Beach (Personal communications, Fred Bloetscher, February 8

2022). Therefore, modifications would need to be made to the city's water supply plan to provide residents with usable water if the salinity of the raw water supply increased.

To provide solutions to the City of Dania Beach Water Utility's future water supply needs, the following options for the management plan were researched and analyzed. This analysis is shown in the sections below. These options include the following:

- Use surface water instead of groundwater
- Construct wells further from the ocean
- Purchase additional water from a nearby system
- Construct and operate a desalination plant in Dania Beach
- Utilize existing wetlands in Dania Beach

Each of these options are discussed in detail in Sections 3.4.1 through 3.4.5. Table 4 shows a summary of the analysis, with five criteria ranked from 1 to 10 as applicable. The options to use surface water instead of ground water, construct wells further from the ocean, construct and operate a desalination plant, and utilize existing wetlands were not ranked in every category because they were deemed infeasible, as described in Section 3.4.1, Section 3.4.2, Section 3.4.4, and Section 3.4.5.

Table 4: Summary of Management Plan Scores

Management Plan Option	**Cost Score**	**Technical Feasibility Score**	**Water Quality: Heath Score**	**Water Quality: Aesthetics**	**Space Score**	**Total Score**
Use surface water instead of groundwater	1	N/A	N/A	N/A	N/A	N/A
Construct wells further from ocean	N/A	1	N/A	N/A	1	N/A
Purchase additional raw water from a nearby wellfield	9	8	10	10	10	47
Purchase additional treated water from a nearby utility	8	8	10	10	10	46
Construct and operate a desalination plant in Dania Beach	2	N/A	N/A	N/A	N/A	N/A
Utilize existing wetlands in Dania Beach	N/A	1	N/A	N/A	1	N/A

3.4.1 Management Plan Option 1: Use Surface Water Instead of Groundwater

Typically, the City of Dania Beach Water Utility receives water from well G, well I, and the Broward County regional wellfield. However, these are currently restricted in capacity, so the city is receiving water from the Broward County regional wellfield, as stated Section 3.1 and Section 3.2. Alternative sources to Dania Beach's well water could provide solutions to the water quality issues that the city faces. One alternative is using surface water sources within 100 miles of Dania Beach instead of groundwater, as groundwater in Dania Beach has been impacted by saltwater intrusion. Cities such as Boston and New York City use surface water sources within about 50 to 100 miles from the cities to provide them with water, and these cities have seen success from this method.

One large fresh surface water source within 100 miles of Dania Beach is Lake Okeechobee. Dania Beach is located 62 miles away from the southeast side of Lake Okeechobee. Lake Okeechobee is 35 miles long, covers 730 square miles of land, and has an average depth between 10 to 12 meters (Britannica, T. Editors of Encyclopaedia, n.d.). Lake Okeechobee's watershed is located in an agricultural area, so phosphorus inflows into the lake are high due to overfertilization of farmlands. This high phosphorus inflow from the watershed causes toxic blue-green algae blooms in a process known as eutrophication (Audubon Florida, 2018).

Because of regulations set by the EPA, the surface water from Lake Okeechobee must be treated to be used for public supply. The EPA requires that all surface waters be treated by filtration and disinfection processes; meet treatment technique requirements; and meet limits on the amount of contaminants allowed in drinking water. The treatment technique requirements for pathogens are 99.99% removal/inactivation of viruses, 99.9% removal/inactivation of *Giardia lamblia*, and 99% or more removal of *Cryptosporidium*. In addition, unfiltered systems are required to include *Cryptosporidium* in their existing watershed control provisions (USEPA, n.d.-j).

Dania Beach would have to construct a new water treatment plant or adapt their current water treatment plant to meet EPA requirements while treating surface water. To analyze the most cost effective treatment processes, three water treatment plants that use surface water sources in Florida were reviewed. Table 5 shows a review of the West Palm Beach Surface Water Treatment Plant, the Claude H. Dyal Water Treatment Plant, and the Miramar East Water Treatment Plant. The West Palm Beach Surface Water Treatment Plant uses softening, filtration, and disinfection; the Claude H. Dyal Water Treatment Plant uses softening, coagulation, filtration, and disinfection; and the Miramar East Surface Water Treatment Plant uses filtration through nanofiltration and reverse osmosis membranes (West Palm Beach, FL, n.d.; City of Cocoa Florida, 2009; City of Miramar, n.d.). Treated water has a customer cost per 1000 gallons of $3.98 in West Palm Beach, $3.56 in Cocoa (the location of Claude H. Dyal treatment plant), and $2.81 in Miramar (South Florida Water Management District, 2008; City of Cocoa Florida, 2009). The West Palm Beach Surface Water Treatment Plant supplies 50 MGD and serves a population of 120,000 persons, the Claude H. Dyal Water Treatment Plant supplies 48 MGD and serves a population of 250,000 persons, and the Miramar East Surface Water Treatment Plant supplies 6 MGD and serves a population of 70,000 people (West Palm Beach, FL, n.d.; City of Cocoa Florida, 2009; City of Miramar, 2020). Dania Beach's lime softening plant uses coagulation and has an aeration process, a filtration process, and a disinfection process. The nanofiltration plant has nanofiltration membranes and reverse osmosis membranes. The current customer cost of water from the City of Dania Beach Water Utility has a base price of $14.55 with a cost of $2.98 per thousand gallons (Bloetscher, personal communication, December 29, 2021). The City of Dania Beach served an estimated population of 19,406 in 2020 and supplied an estimated 2.33 MGD.

Table 5: Comparison of Surface Water Treatment Systems

Water Treatment Plant	Location	Water Sources	Customer Cost ($/1000gal)	Capacity (MGD)	Primary Treatment Type	Population Served
West Palm Beach Water Treatment Plant	West Palm Beach, FL[1]	Surface water [1]	$3.98[2]	50[1]	Softening, filtration, disinfection [1]	120,000 persons [1]
Claude H. Dyal Water Treatment Plant	Cocoa, FL[4]	Surface water and groundwater [3]	$3.56[4]	48[4]	Softening, coagulation, filtration, disinfection[4]	250,000 persons[4]
Miramar East Water Treatment Plant	Miramar, FL[5]	Surface water and groundwater [5]	$2.81[2]	6[6]	Filtration (nanofiltration/reverse osmosis)[5]	Estimated 70,000 people[6]

1. (West Palm Beach, FL, n.d.); 2. (South Florida Water Management District, 2008); 3. (City of Cocoa Florida, n.d.); 4. (City of Cocoa Florida, 2009); 5. (City of Miramar, n.d.); 6. (City of Miramar, 2020)

The most suitable surface water treatment plant option for Dania Beach would be the continuation of using the lime softening plant and nanofiltration plant. Because Dania Beach's lime softening plant has a coagulation process, a filtration process, and a disinfection process, it has the capability of treating surface water when used together with the nanofiltration plant. The nanofiltration plant has nanofiltration membranes and reverse osmosis membranes, which are also capable of treating surface water, as this process is used by Miramar, FL in surface water treatment. Using these two plants to treat surface water would produce a combined capacity up to 8 MGD combined capacity of treated water, which is greater than the forecasted 3.15 MGD demand in 2050. Within this option, Dania Beach's Water Treatment plants would have to undergo renovations to treat surface water, as the plants are currently designed to treat groundwater. Renovations would likely be less expensive than constructing a new treatment plant. Because the renovations needed are site-specific, the cost of renovating the lime-softening treatment plant and the nanofiltration plant are beyond the scope of this project.

To transport surface water from Lake Okeechobee to Dania Beach, a pipeline would have to be constructed from the lake to the city (American Geosciences Institute, 2016). A cost of $1.1 million per mile was used by the Sacramento Suburban Water District for planning the placement of a ductile iron pipeline in Sacramento (Sacramento Suburban Water District, 2011). Using the value of $1.1 million per mile provides an estimated figure of $68,200,000 million for a pipeline from Lake Okeechobee to Dania Beach, as shown in appendix 1. This figure was determined by multiplying the cost per mile of constructing a pipeline ($1.1 million) by the length of the pipeline needed (62 miles). With an assumed municipal bond interest of 5% (the average municipal bond interest rate) the cost would rise to $300 million, as shown in Appendix 1 (Kennon, 2021). Accounting for inflation between the time the Sacramento Suburban Water District published their estimate and now (2011 to 2022), this cost would rise by 26% to $378 million (CPI Inflation Calculator, n.d.). This cost is reasonable for the cost of a pipeline, which typically cost anywhere from millions to billions of dollars depending on pipe materials and length of the pipe (Hollingsworth & Associated Press, 2015; Carr & Taylor, 2014). This cost would be distributed across a 30-year timespan within the monthly water bill that each Dania Beach citizen receives. The 30-year period was chosen because this management plan option is proposed for a 30-year timeframe. To determine if dividing this cost among Dania Beach's population is feasible, $378 million was divided among the population served by the City of

Dania Beach Water Utility. As shown in Appendix 1, the average population of Dania Beach served by the city's water treatment plants from 2020 to 2050 is 22,839 people. The cost per person would be the total construction cost divided by the population over a 30-year time period, or $551.68 per person each year. This cost breaks down to $45.97 per person per month over the 30-year time period. Considering an average household size of 2.6, this equates to $119.52 per household per month. Currently, Dania Beach charges a base cost of $14.55 and an additional $2.98/1000 gallons per month for water and debt service (City of Dania Beach, n.d.-b; Bloetscher, personal communication, December 29, 2021). If the average person uses 120 GPD and the average household is 2.6 people, the average monthly water bill is estimated to be $42.44. Adding $119.52 to each household bill would increase this bill to $161.96. Constructing a pipeline would create an average water bill increase of 282%. This cost increase is not feasible for the average Dania Beach resident due to the average income and poverty rate in Dania Beach, as described in Section 3.1. Because this cost is infeasible, this option was not considered further.

3.4.2 Management Plan Option 2: Construct Wells Further From the Ocean

The wells that Dania Beach typically relies on, wells G and I, have been impacted by saltwater intrusion and are temporarily out of service. A potential long term management plan is constructing new wells further from the ocean than the city's former and current wells. The distance of each well from the ocean was determined using a measuring tool in Google Earth Pro. As shown in Table 6, wells D, E, and F are 2.47 miles from the ocean and wells G, H, and I are 3.65 miles from the ocean. The distance of wells A, B, and C from the ocean are unknown, as the location of these wells is not known.

Table 6: Distance of Dania Beach's Wells from the Ocean

Well	**Distance from the ocean (mi)**
A	Unknown
B	Unknown
C	Unknown
D	2.47
E	2.47
F	2.47
G	3.65
H	3.65
I	3.65

The furthest location in Dania Beach from the ocean is 5.8 miles. If a well was constructed 5.8 miles away from the coastline, the new well would potentially be less likely to be impacted by saltwater intrusion than the current wells in Dania Beach. This was evaluated by using a map of the saltwater intrusion line in Broward County that was created by South Florida Water Management District and the U.S. Geographical Survey (Figure 15) and a map of Dania Beach (Figure 16). These two maps were sized until the details of the maps were the exact same size, and then layered (Figure 17). From this analysis, it was determined that Dania Beach lies within the area of Broward County that is impacted by saltwater intrusion. Constructing a well in Dania Beach as far as possible from the ocean would not solve the city's water quality problem, as this new well would be likely to have saltwater intrusion over time. This option was therefore not a viable option for a long-term management plan and was not considered in the final management plan decision.

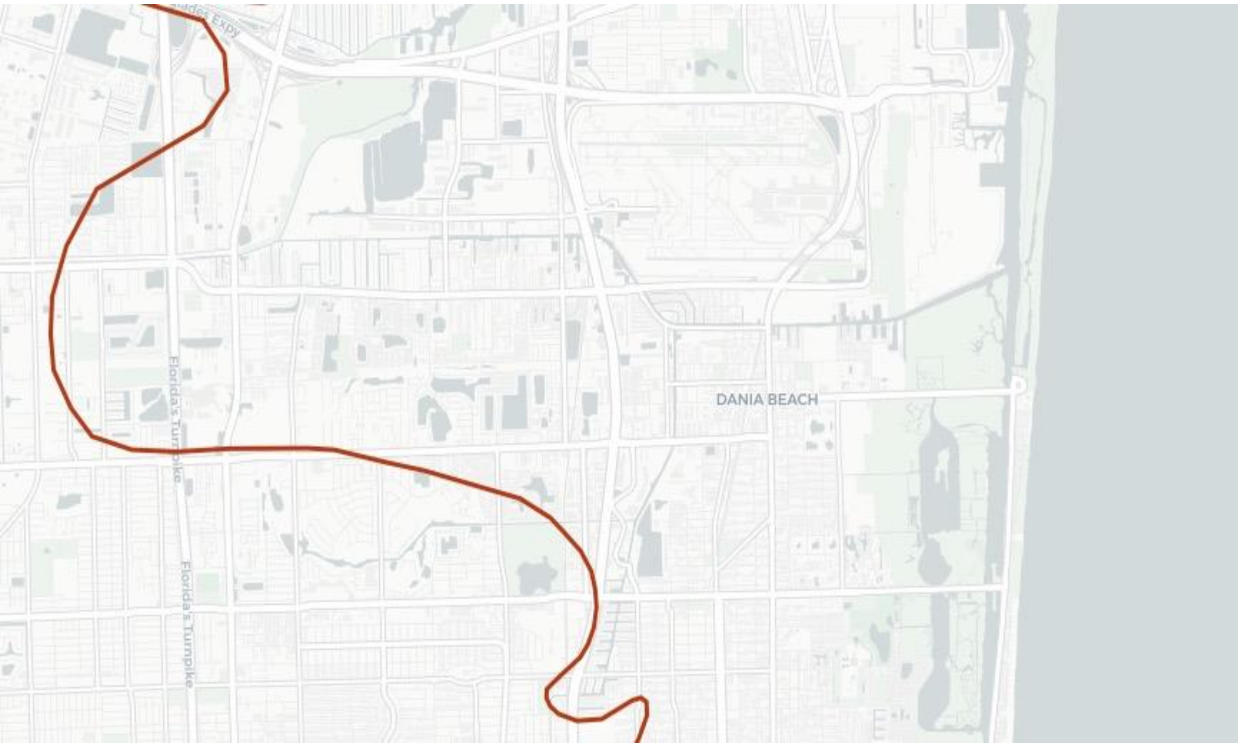


Figure 15: Saltwater intrusion line in Broward County (shown in red) (Sentinel, 2018)

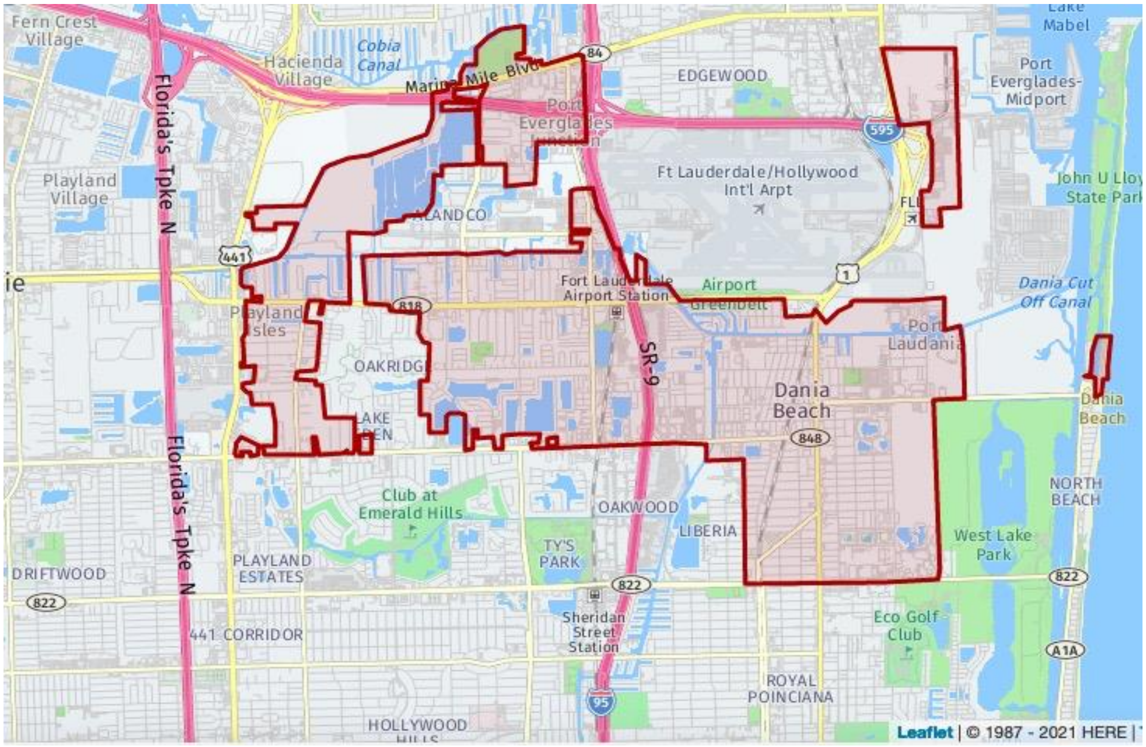


Figure 16: Borders of Dania Beach (shown by red outline)

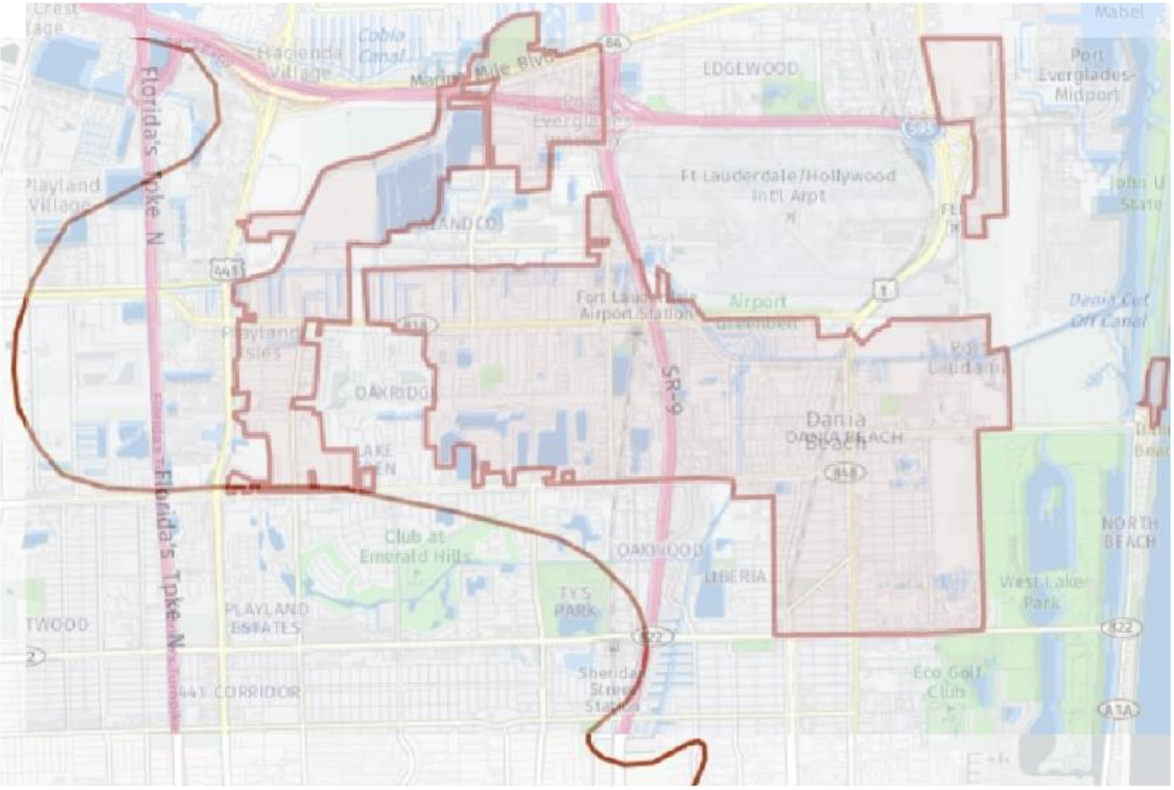


Figure 17: Borders of Dania Beach (shown by red outline) compared to saltwater intrusion line (shown by dark red line)

3.4.3 Management Plan Option 3: Purchase Additional Water From a Nearby System

An alternative to using wells in Dania Beach as a source of water is to purchase additional water from a nearby system. Dania Beach's water treatment plants currently receive water from Broward County regional wellfields due to wells G and I being temporarily removed from service, as discussed in Section 3.3. Dania Beach is also in an arrangement with Hollywood, FL to receive emergency and/or bulk water. Because these agreements have been successful up to the time of writing (2022), purchasing additional raw water or treated water from a nearby system is an option to address the city's water quality and supply issues.

There are several nearby counties/municipalities that could potentially provide water to Dania Beach through a purchase agreement: raw water from Broward County through the regional wellfield, treated water from Broward County through the water and wastewater service, treated water from Miami-Dade County, and raw water from Fort Lauderdale. Table 7 summarizes capacity and cost information for each of these systems. Given potential future problems with saltwater intrusion in Dania Beach's wells, the ability of each system to supply the total demand in Dania Beach (3.15 MGD by 2050) was determined.

Table 7: Information on Broward County, Miami-Dade County, and Fort Lauderdale water supply systems

Name	Source	Treatment Methods	Demand in 2020 (MGD)	Demand in 2050 (MGD)	Capacity (MGD)	Wholesale Cost
Broward County Regional Wellfield	Biscayne Aquifer	N/A	28.85 [1]	33.59 [1]	63.76 [1]	\$0.50/1000 gallons[2]
Broward County WWS	Biscayne Aquifer[1]	Lime Softening[1]	20.32 [1]	24.22 [1]	46 [1]	\$1.06/1000 gallons[2]
Miami-Dade County WWS	Biscayne Aquifer[3]	Filtration, flocculation, sedimentation, softening, disinfection[4]	300 – 320 [4,5]	406 [6]	470 [4,5]	\$1.83/1000 gallons[7]
Fort Lauderdale Well System	Biscayne Aquifer[8]	N/A	52.9 [8]	63.65 [9]	90 [8]	\$0.23/1000 gallons[10]

1. (Broward County, 2020-a); 2. (City of Dania Beach, 2009); 3. (Flavelle, 2018); 4. (Miamidade.gov, n.d.); 5. (Miami-Dade County, n.d.); 6. (Miami-Dade County, 2014); 7. (Bal Harbour Village, 2018); 8. (City of Fort Lauderdale, n.d.-a); 9. (City of Fort Lauderdale, 2015); 10. (Broward County, 2020-b).

The first system considered was Broward County’s regional wellfield. Dania Beach’s water utility currently receives water from the regional wellfield, supplying 60% of the city. The wellfield currently produces 28.85 MGD of water, and has a capacity of 63.76 MGD (Broward County, 2020-a). Broward County regional wellfield’s projected water demand in 2040 is 32.95 MGD, which is the furthest water demand projection the county has performed for the future (Broward County, 2020-a). Broward County regional wellfield’s water demand has an average increase of 0.32 MGD every 5 years. If this trend continues into 2050, the water demand is estimated to be about 33.59 MGD. Therefore, Broward County’s regional wellfield is projected to have an estimated excess capacity of 30.17 MGD in 2050 and could supply the needed 3.15 MGD to Dania Beach.

The next system considered was Broward County WWS. The Broward County WWS currently supplies 40% of Dania Beach (City of Dania Beach Water Utility, n.d.-b). Broward County WWS’s water system has two treatment plants, with one plant in the City of Lauderdale Lakes and the other plant in the City of Pompano Beach. The systems currently produce a combined total of 20.32 MGD of water with a capacity of 46 MGD (Broward County, 2020-a). Broward County WWS’s projected water demand in 2040 is 22.9 MGD, which is the furthest water demand projection the county has performed for the future as stated above (Broward County, 2020-a). Broward County WWS’s water demand has an average increase of 0.66 MGD every 5 years. If this trend continues into 2050, the water demand is estimated to be about 24.22 MGD. Therefore, Broward County WWS is projected to have an estimated excess capacity of 21.78 MGD in 2050 and could supply the needed 3.15 MGD to Dania Beach.

Miami-Dade County uses 15 wells that remove water from the Biscayne aquifer, serving a population of 2.3 million (Flavelle, 2018). This system produces between 300 to 320 MGD of treated water, depending on the season, and has a capacity of 470 MGD (Miamidade.gov, n.d.; Miami-Dade County, n.d). The projected water demand in Miami-Dade County is 355 MGD in 2033, which is the furthest year in the future that they have projected water use to in a 20 year management plan from 2014 to 2033 (Miami-Dade County, 2014). Miami-Dade County sees an average increase in water demand by 3 MGD each year according to historical water demands and water demand forecasts (Miami-Dade County, 2014). Using this value to continue Miami-Dade County’s water demand projections, it can be estimated that Miami-Dade County’s water demand in 2050 will be 406 MGD. Therefore, the system will have 64 MGD of excess capacity in 2050, which far exceeds the 2050 demand of 3.15 MGD in Dania Beach.

The last system evaluated was the city of Fort Lauderdale. Fort Lauderdale receives water from 36 wells that withdraw from the Biscayne aquifer and serves a population of 183,109. The system provided an estimated 52.9 MGD of water to its residents in 2020 and has a capacity of 90 MGD (City of Fort Lauderdale, n.d.-a; World Population Review, n.d.-b). Fort Lauderdale is projected to use 57.65 MGD of water in 2035, with an estimated increase of 2 MGD every 5 years (City of Fort Lauderdale, 2015). If this trend continues until 2050, Fort Lauderdale's water demand would be an estimated 63.65 MGD and the excess capacity would be 26.35 MGD. This far exceeds the 2050 demand of 3.15 MGD in Dania Beach. Therefore, Fort Lauderdale is capable of providing water to Dania Beach.

The system connection to Broward County regional wellfield is currently in use by the City of Dania Beach Water Utility, so pipe connections are already in place between the wellfield and Dania Beach. As a result, purchasing additional water from this source would not incur capital cost. However, to allow the area of Dania Beach served by the city's water utility to receive water from Broward County WWS, Miami-Dade County WWS, or Fort Lauderdale's well system, pipe connections from each area and Dania Beach would have to be installed. As discussed in Section 3.4.1, the cost increase to consumers can be estimated using the pipeline cost of $1.1 million per mile adjusted for interest, inflation, and distributing that cost to Dania Beach's population over a 30-year time frame. Table 8 shows a summary of these calculations. These calculations used the process of Calculation 4 and 5 in Appendix 1.

Table 8: Summary of Pipeline Costs

Option	Distance (miles)	Original Cost	Cost with compounding interest	Cost with inflation	Monthly Cost Added to Bill	Total Monthly Cost	Increase in Cost
Pipeline: Broward County WWS	1	$1,100,000	$4,839,768	$6,098,107	$1.93	$44.37	4.5%
Pipeline: Miami-Dade County	20	$22,000,000	$96,795,374	$121,962,171	$38.56	$81.00	90.9%
Pipeline: Fort Lauderdale	5.1	$5,610,000	$24,682,820	$31,100,353	$9.83	$52.27	23.2%

As discussed previously, installing a pipeline costs an estimated $1.1 million per mile, but the cost of a pipeline from each service location to Dania Beach is site specific (Sacramento Suburban Water District, 2011). To provide the City of Dania Beach Water Utility water from Broward County WWS, pipe connections would have to be made. To achieve this connection, a pipe approximately one mile long would need to be constructed. Overall, construction of this pipe results in a cost increase of 4.5% to the City of Dania Beach Water Utility's monthly bill. This increase of 4.5% would be feasible for the residents of Dania Beach, while still considering the average income and poverty rate of the city discussed in Section 3.1. Pipe connections between Dania Beach and Miami-Dade County require more labor and construction because the distance between Dania Beach and Miami is 20 miles. Construction of a 20-mile pipe results in a cost increase of 90.9% to the City of Dania Beach Water Utility's monthly bill. This increase would not be feasible for the residents of Dania Beach due to the city's poverty rate and average income. Therefore, it is not suitable for Dania Beach to purchase water from Miami-Dade County. Pipe connections between Dania Beach and Fort Lauderdale would require less labor and construction than what is required between Dania Beach and Miami-Dade County, as Dania Beach and Fort Lauderdale are 5.1 miles apart. The construction of this pipe would result in a 23.2% water bill increase. This increase of 23.2% would be feasible for the residents of Dania Beach who are above the poverty line. However, considering the city's poverty rate and average income discussed in Section 3.1, this cost may be difficult to some residents of the city. Therefore, it is not the best option for Dania Beach to purchase raw water from Fort Lauderdale. To minimize increases in customer's water bills, it is suggested for Dania Beach to purchase raw water from Broward County's regional wellfield before considering Fort Lauderdale's raw water because no money needs to be spent on pipe connections between Dania Beach's water utility and Broward County's regional wellfield.

Overall, the option of Dania Beach purchasing water from a nearby wellfield ranks 47/50. This ranking only considered purchasing water from Broward County's regional wellfield, as this is the most cost-effective option. As shown in Table 4, the criteria Cost received a ranking of 9 (green) because the overall cost of purchasing water is relatively low and would be compensated for by charging the residents of Dania Beach for their water use. Technical feasibility received a ranking of 8 (green) because if Dania Beach purchases raw water, the additional steps needed to prepare the town to receive it are current water treatment processes used in Dania Beach. The criteria of Water Quality: Health ranked 10 (green) because the water purchased from the wellfield will be treated in Dania Beach and will be safe for use and consumption. The criteria of Water Quality: Aesthetics ranked 10 (green) because the water purchased from Broward County's regional wellfield would be treated in Dania Beach for aesthetic purposes prior to use and consumption as well. The criteria of Space received a ranking of 10 (green) because no additional space would need to be required for this option.

The option of Dania Beach purchasing water from a nearby utility ranks 46/50. This ranking only considered purchasing water from Broward County WWS, as this is the most cost-effective option for purchasing water from a utility. As shown in Table 4, the criteria Cost received a ranking of 8 (green) because the overall cost of purchasing water is relatively low. While a pipe connection would need to be made to supply Dania Beach's water utility with water from Broward County WWS, this pipe connection cost would only cause a water bill increase of 4.5%. Technical feasibility received a ranking of 8 (green) because if Dania Beach purchases treated water, the additional steps needed to prepare the system is installing a pipe connection. The criteria of Water Quality: Health ranked 10 (green) because the water purchased from Broward County WWS will be treated before use, and therefore will be safe for use and consumption. The criteria of Water Quality: Aesthetics ranked 10 (green) because the water purchased from Broward County WWS will be treated for aesthetic purposes prior to use and consumption as well. The criteria of Space received a ranking of 10 (green) because no additional space would be necessary for this option.

3.4.4 Management Plan Option 4: Construction and Operation of a Desalination Plant in Dania Beach

Due to saltwater intrusion in the area, drinking water is being contaminated by nearby water from the Atlantic Ocean. As seen in Figure 18, the boundary line between brackish water and freshwater has been moved inland. This shift was determined by analyzing samples collected from monitoring wells (Lambrecht, 2020). Saltwater contamination is not rare for the state of Florida, and therefore many water utilities are designed to treat waters with high salt content. There are currently more than 120 desalination plants in the state, of which 26 facilities are located in the South Florida Water Management District (SFWMD) that specifically treat brackish water using reverse osmosis treatment (Akpoji, n.d.). The SFWMD is one of five of

Florida’s water management districts and includes 10 full counties and portions of 6 other counties spanning from Orange County to Miami-Dade (South Florida Water Management District, n.d.). Across these 26 plants, there is a total capacity of over 140 MGD. For comparison, other states that struggle with saltwater intrusion issues have far fewer desalination plants: Texas has 38 and California has 33 (Akpoji, n.d.). In addition to providing drinking water, treating seawater has environmental benefits in Florida as it “reduces competition with the Everglades initiatives and relieves dependence on existing conventional surface water and groundwater supply sources,” (Akpoji, n.d.).

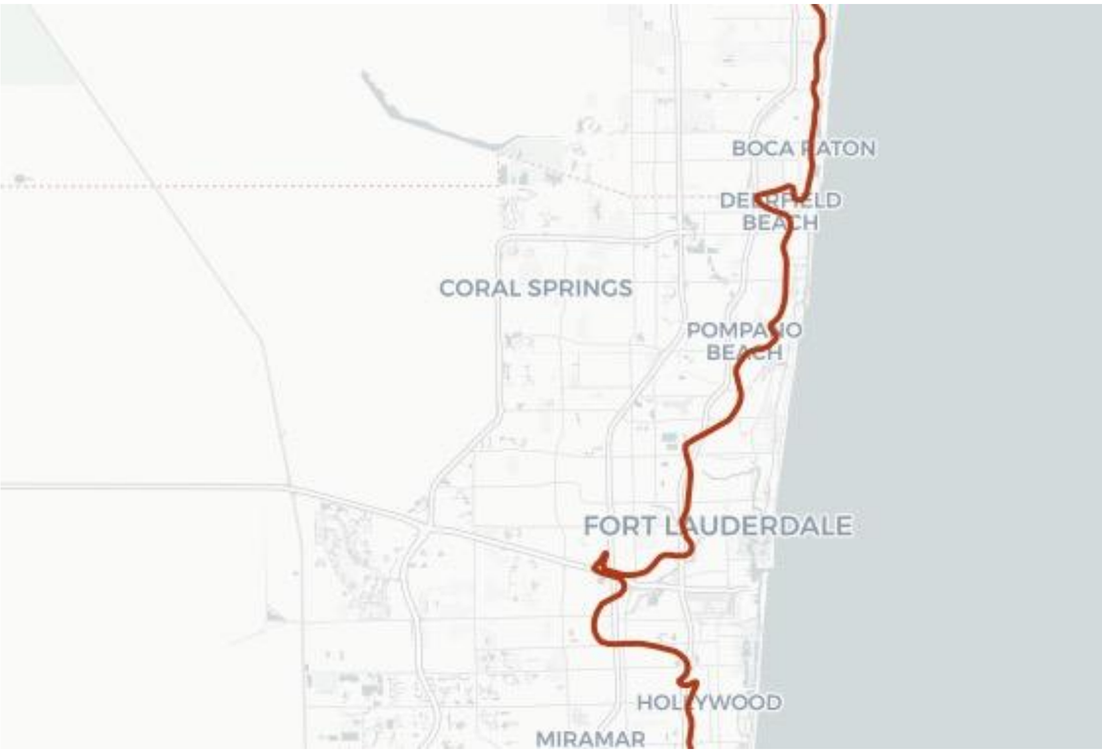


Figure 18: Approximate inland extent of saltwater intrusion in the Biscayne Aquifer in Southern Florida shown by the red line (Sentinel, 2018)

Currently the Biscayne Aquifer is the main source of water for Dania Beach (City of Dania Beach, n.d.). However, in recent years the saltwater wedge in the bottom of the aquifer has expanded. In 1999, a monitoring well was installed by the U.S. Geological Survey underneath the Homestead-Miami Speedway in South Florida to measure the extent by which saltwater was moving inland. By 2018, the measured chloride concentration at this well had increased tenfold, to about 12,000 milligrams per liter (for reference, the chloride concentration of seawater is about 35,000 milligrams per liter). This is one example that the interface between saltwater and freshwater is being drawn inland (Lambrecht, 2020). The goal of a desalination plant would be to reduce the salinity to less than 200 mg/L.

The cost of using desalination to treat water for Dania Beach was estimated by comparison to existing desalination plants in Florida and California. As discussed in Section 3.3, the water treatment system in Dania Beach consists of two facilities: one that uses nanofiltration and reverse osmosis, and one that uses softening. The first system has a capacity of 5 MGD and a production of 2.2 MGD as of 2017 and includes a two stage nanofiltration membrane system and a third and fourth stage of reverse osmosis. That system operates in conjunction with a 3 MGD capacity lime softening system (Day, 2017). The treated water from both is then blended to create the final distributed product. Three treatment plants with similar characteristics to the current nanofiltration system in Dania Beach were evaluated: The Tampa Bay Plant, the Robert W. Goldsworthy Desalter, and the City of Cape Coral RO Water Treatment Facility. All three of these treatment plants are desalination plants that use reverse osmosis (RO) as the primary treatment method.

A summary of the Dania Beach treatment plant and the three comparison RO plants is provided in Table 8. The seawater treatment plant in Tampa Bay, FL is the largest desalination plant in the U.S. and therefore demonstrates the cost of a plant which processes a higher volume than the current plant in Dania Beach (Verdict Media Limited, 2022). This plant produces 25 MGD (Verdict Media Limited, 2022 & Tampa Bay Water, n.d.). The Robert W. Goldsworthy Desalter in Torrance, CA, while not located in Florida, has similar characteristics to the Dania Beach water treatment plant. This plant was expanded to increase its capacity of 2.5 MGD to 5 MGD (Scauzillo, 2018). This allowed the facility to serve 50,000 people rather than the previous 15,000 (Scauzillo, 2018 & Southern California Public Radio, 2016). The Robert W. Goldsworthy Desalter treats brackish water (Southern California Public Radio, 2016). Some areas in Dania

Beach, including the area depicted in the map of the base of the Biscayne Aquifer in Figure 18, are considered brackish based on their level of Total Dissolved Solids (TDS). Brackish water has a TDS content of 1,000 mg/L to 15,000 mg/L (Consolidated Water, 2022). In Figure 18, the nanofiltration plant in the base of the aquifer reached a TDS level of 12,000 mg/L which is within the brackish range (Lambrecht, 2020). The Goldsworthy plant also has the same processing capacity as Dania Beach and thus costs would likely be comparable. Finally, the City of Cape Coral RO Water Treatment Facility was constructed due to similar water quality issues as experienced in Dania Beach. The Southwest Cape Coral facility started with a combined water stream from a RO plant and a lime softening plant. Over time however, due to population growth and saltwater intrusion, renovations were needed to the plant. What started in 1977 as a 3 MGD plant in Cape Coral became an 18 MGD treatment center in 2008 (Fenske, 2019). This is a significantly larger volume of water than required in Dania Beach, as the Cape Coral predicted population exceeds 400,000 residents (Fenske, 2019).

Table 9: Cost Estimation via Comparison of Desalination Plants

Plant	**Location**	**Approximated Population Served**	**Capacity (MGD)**	**Primary Treatment Type**	**Approximate Capital Cost (Millions)**	**Adjusted Capital Cost for 1 MGD Capacity (Millions)**	**Cost to Consumer per 1000 gallons (up to approximately 5,000 gallons)**
The Tampa Bay Plant	Southern Hillsborough County, FL	2.5 million [1]	28.8 [1]	Salt Water Reverse Osmosis[2]	$158 [3]	$5.49	$3.82 [4]
Robert W. Goldsworthy Desalter	Torrance, CA	50,000 [5]	5 [6]	Salt Water Reverse Osmosis	$22.5 [5]	$4.50	$4.33 [7]
City of Cape Coral RO Water Treatment Facility (Southwest)	Cape Coral, FL	226,900 [8]	18 [9]	Brackish Water Reverse Osmosis[10]	$15.6 [11]	$0.87	$3.90 [12]
Current Dania Beach Nanofiltration Water Treatment Plant	Dania Beach, FL	19,406	5 [15]	Nanofiltration[15]	$8.8 [15]	$1.76	$2.98 [14] (plus 14.55 base cost)
Proposed Expansion of Dania Beach Plant (2050 Projections)	Dania Beach, FL	26,273	3.15 projected; 4.40 with safety factor	Brackish Water Reverse Osmosis	$15.9	$3.62	$4.02

References

1. (Acconia, n.d.); 2. (Verdict media limited, 2022); 3. (Tampa Bay Water, n.d.); 4. (Hillsborough County, FL., 2020); 5. (Southern California Public Radio, 2016); 6.(Scauzillo, 2018); 7. (City of Torrance, 2021); 8. (South Florida Water Management District. 2005-2006); 9. (Fenske, 2019); 10. (Harvey & Missimer, 2020); 11. (Babb, 2021); 12. (Financial Services Department/Customer Service Division, 2013); 13. (Moore, 2019); 14.(Bloetscher, personal communication, December 29, 2021); 15. (Day, 2017).

Capital costs and operation and maintenance costs for each treatment plant were compiled to determine an approximate cost of desalination in Dania Beach. Capital costs cover the one-time costs to build, expand, or renovate systems and therefore represent the total cost to create a commercially operable water treatment plant. The capital cost of each of the three comparable projects can be seen in Table 8. These costs were scaled to 1 MGD in order to more accurately compare the capital costs of treatment plants with different capacities. The cost per MGD of water was then scaled again to meet the forecasted capacity needs of the population served by the Dania Beach water utility in 2050 (3.15 MGD) plus a factor of safety. This was calculated by averaging the costs for the three comparable treatment plants at 1 MGD and multiplying this result ($3.62 million) by the design capacity. The design capacity of the proposed plant was calculated by adding a safety factor of 1.25 MGD to the forecasted water demand of Dania Water Beach Utility in 2050 (3.15 MGD). The factor of safety was determined to be 1.25 considering the estimated maximum peak daily flow (Bloetscher, personal communication, March 14, 2022). This results in a total capacity of 4.40 MGD. The estimated cost was therefore $15.9 million. This scaling may underestimate costs for small plants or overestimate costs for large plants, as cost savings per unit capacity are realized for larger capacities. There is also a capital cost difference between constructing a new plant versus upgrading an existing facility. The Tampa Bay plant was newly constructed while the Goldsworthy Desalter and the Cape Coral treatment plant were upgraded to treat brackish water at a greater capacity.

Operation and Maintenance (O&M) costs are the costs associated with normal functioning of a treatment system, including energy for the facility, chemical usage, critical component replacement, water supply, disposal of waste concentrate, and labor and servicing (Pearson *et al.*, 2021). The cost to consumers is therefore based on a combination of capital costs (recovered over a long time period) and O&M costs and distributed among the population served.

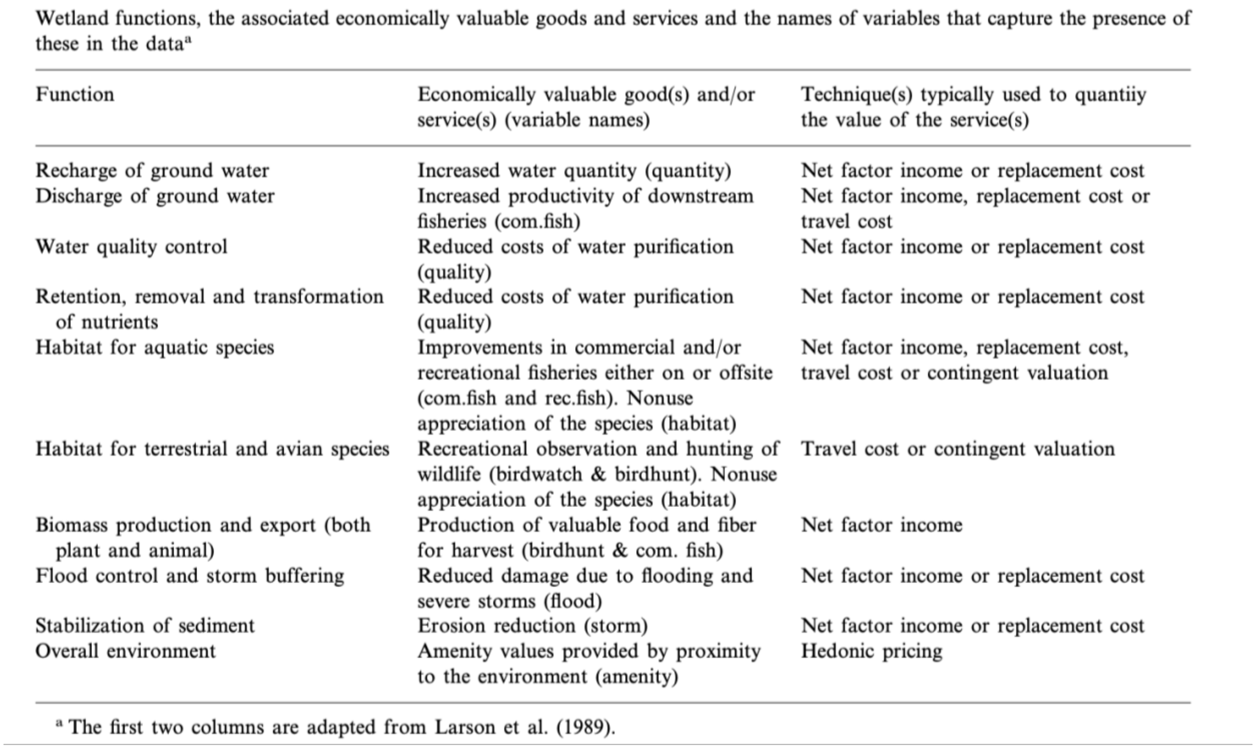
The current cost of water to consumers served by the Dania Beach water utility is $2.98 per thousand gallons including debt service (Bloetscher, personal communication, December 29, 2021). There is also a base cost of $14.55 per month. A renovated desalination plant would raise the price of water to approximately $4.02 per thousand gallons (seen in Table 8). This was calculated by averaging the costs to consumers of the three comparable water treatment plants. This would represent a 35% increase in the unit water cost. The average U.S. inflation rate has been steadily decreasing from 5.4 % in 1990 to 1.23 % in 2020. In fact, within the last year the average rate of inflation in the U.S. declined by 0.58 % (MacroTrends, n.d.). Additionally, the average household income in Dania Beach is 28% less than the U.S. average (Sperling's Best Places, n.d.). Based on the current average U.S. rate of inflation and residents' average annual income, current residents would not be able to afford a 35 % increase in unit costs.

The current system in Dania Beach already includes the use of RO membranes in the third and fourth steps of treatment, which is evidence that they already have some systems in place that could benefit from nanofiltration to reverse osmosis conversion. However, the proposed desalination plant for Dania Beach would require significant renovation of the current system. The category of Cost received a ranking of 2 (red) because the proposed plan would cause an estimated 35% increase in consumer costs of water per thousand gallons which would strain residents. Further categories did not receive a ranking because no further cost estimations needed to be made after it was concluded that the expense of this new water utility system is not feasible within residents' current financial limitations.

3.4.5 Management Plan Option 5: Utilize Wetlands in Dania Beach

The fifth option is for the City of Dania Beach Water Utility to utilize wetlands in Dania Beach and surrounding wetlands in Broward County for water storage and as a drinking water source. Wetlands are essential to maintain a healthy coastal ecosystem. According to the EPA, "Wetlands are among the most productive ecosystems in the world, comparable to rain forests and coral reefs" (USEPA, 2015 -b). They are formed naturally when runoff from watersheds and rainwater accumulate and are absorbed into the ground or continue to flow as groundwater into a surface water source (Wayne County Soil & Water Conservation District, n.d.). A watershed is an area where water and its contents, including contaminants and sediments, flow from a high elevation to an outlet at a lower elevation (USEPA, 2015 -b). Wetlands are able to flourish due to nutrients provided from contaminated water introduced by watersheds, and due to shallow water levels in the wetlands themselves. The influent water contains high levels of nutrients such as nitrates and phosphates as well as other organic materials that can help foster the development and growth of native species (USEPA, 2015 -b). These species then contribute to the overall ecological health of the landscape. The aquifer and wetlands throughout southern Florida are fed by Lake Okeechobee through the network of canals.

Table 10: Wetland Economic Values and Their Benefits (Woodard & Wui, 2000).



Wetland functions, the associated economically valuable goods and services and the names of variables that capture the presence of these in the data[a]

Function	Economically valuable good(s) and/or service(s) (variable names)	Technique(s) typically used to quantiiy the value of the service(s)
Recharge of ground water	Increased water quantity (quantity)	Net factor income or replacement cost
Discharge of ground water	Increased productivity of downstream fisheries (com.fish)	Net factor income, replacement cost or travel cost
Water quality control	Reduced costs of water purification (quality)	Net factor income or replacement cost
Retention, removal and transformation of nutrients	Reduced costs of water purification (quality)	Net factor income or replacement cost
Habitat for aquatic species	Improvements in commercial and/or recreational fisheries either on or offsite (com.fish and rec.fish). Nonuse appreciation of the species (habitat)	Net factor income, replacement cost, travel cost or contingent valuation
Habitat for terrestrial and avian species	Recreational observation and hunting of wildlife (birdwatch & birdhunt). Nonuse appreciation of the species (habitat)	Travel cost or contingent valuation
Biomass production and export (both plant and animal)	Production of valuable food and fiber for harvest (birdhunt & com. fish)	Net factor income
Flood control and storm buffering	Reduced damage due to flooding and severe storms (flood)	Net factor income or replacement cost
Stabilization of sediment	Erosion reduction (storm)	Net factor income or replacement cost
Overall environment	Amenity values provided by proximity to the environment (amenity)	Hedonic pricing

[a] The first two columns are adapted from Larson et al. (1989).

Wetlands are also able to provide a variety of ecosystem services. The one most pertinent to Dania Beach's needs is water storage (Woodward & Wui, 2000). Networks of wetlands are able to hold massive amounts of water. "A one acre wetland, one foot deep, can hold approximately 330,000 gallons of water." (Miller, n.d.). There are a total of 382,901 acres of varying subtypes of wetlands in Broward County (U.S. Fish & Wildlife Service National Wetlands Inventory, 1984). Assuming all 382,901 acres are at least 1 foot deep, wetlands could hold, at a minimum 1.26 x 10^{11} (126,000,000,000) gallons of water. In addition to water storage, wetlands provide ecosystem services such as habitat for aquatic species and biomass production, detailed in Table 9. Benefits related to water treatment include reduced damage due to flooding and storm surges, water filtration, increased storage of water, reduced water purification costs, and erosion control (Woodward & Wui, 2000).

Water filtration processes performed in wetlands demonstrate an effective and sustainable model of filtration that has the potential to lower overall costs of treatment. Water filtration via wetlands often progresses as follows:

1. The velocity of the influent water reduces
2. Suspended sediments settle to wetland floor
3. Nutrients from sources such as fertilizer, septic tanks, municipal sewage are absorbed by plants and microorganisms
4. Soil particles stick to remaining pollutants
5. Effluent water leaves the wetland

Some wetlands are so efficient at filtration that industry experts have constructed artificial wetlands in order to treat stormwater and wastewater (USEPA, 2002 -a).

Figure 19 displays both the current contemporary wetlands as well as the historic wetlands in Dania Beach. The largest system of wetlands shown in Figure 19 in West Lake Park and surrounding that area. West Lake Park is a public urban park in Broward County that features recreational activities such as boating, basketball, walking paths, volleyball, tennis, and fishing for residents. The park is made up of mangrove estuaries and uplands, a waterfront, and mangrove-fringed shoreline (Broward.org, n.d. -a). Despite this being the largest connecting system of wetlands, as seen in Figure 19, this is not a viable source to harvest stored drinking water because it is a protected park, but also because residents participate in recreational activities on the land and water. The second largest system of wetlands are in Secret Woods Nature Center, another park in Broward County and the surrounding area (Broward.org, n.d. -b). Because Secret Woods Nature Center is a park, it is not viable to use the wetlands there as water storage or a drinking water source. The wetlands surrounding the park are underneath a highway overpass. Highway runoff such as sediments, metals, and other pollutants contaminants surface water and groundwater sources (USEPA, n.d.-h). Additionally, with road and highway maintenance as well as emissions from cars, the wetlands in this area are exposed to more pollution sources than the wetlands at West Lake Park.

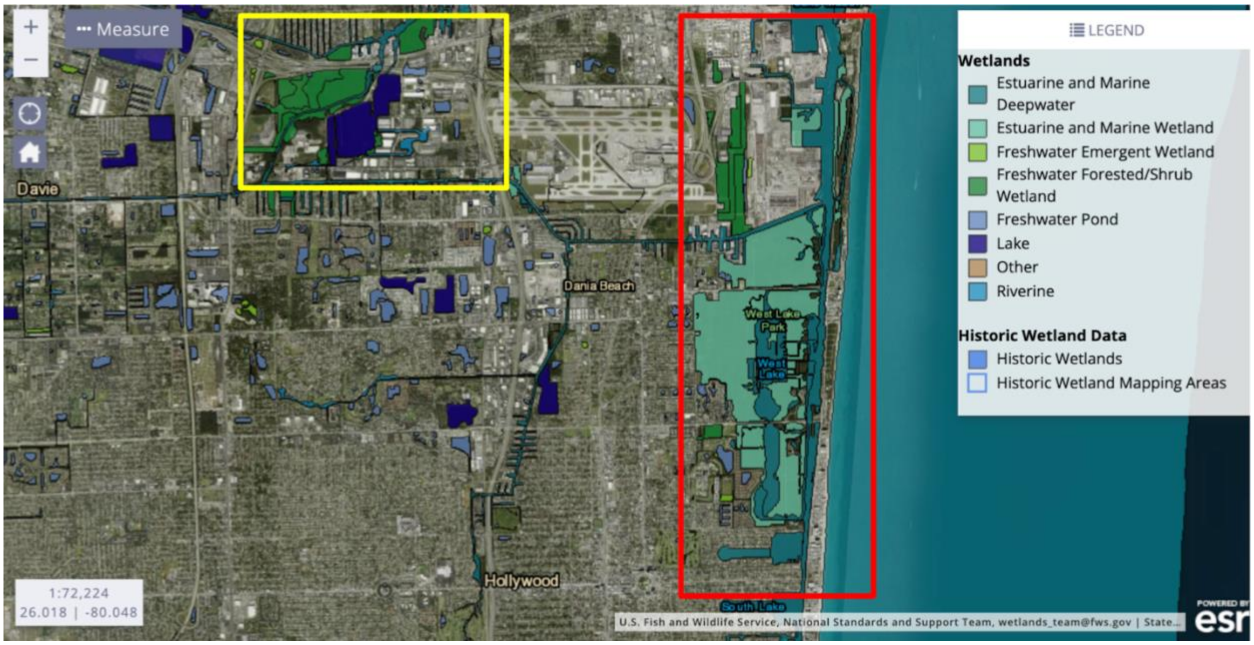


Figure 19: Wetlands in Dania Beach and surrounding areas: West Lake Park (red box) and at Secret Woods Nature Center (yellow box) (U.S. FWS, 2021).

All wetland areas are protected through the permitting process of the Florida Department of Environmental Protection and the United States Army Corps of Engineers. According to the South Florida Water Management District of the City of Dania Beach, “Through proper site planning controls and mitigation of any impacts to wetlands areas, these habitats can be enhanced and provide for a more suitable habitat for the propagation of a greater variety of flora and fauna” (DaniaBeachFL.gov, 2009). However, the ability to use these wetlands as a potable drinking water source is simply not viable. Additionally, the current layout of Dania Beach does not suggest the possibility of the creation of new wetlands because of how many streets, buildings, highways, parking lots and other constructed surfaces are present. Because wetlands are not a viable option for providing drinking water to Dania Beach, no further analysis was completed for this alternative.

Chapter 4: Conclusion and Recommendations

To address water supply concerns about saltwater intrusion in Dania Beach, this project evaluated long-term management plan options for the city. This chapter concludes the project and provides recommendations when implementing the long-term management plan.

4.1 Conclusion

Climate change has impacted coastal regions and contributed to saltwater intrusion in these regions. Dania Beach is a coastal community in Florida that has faced issues caused by saltwater intrusion. The city's wells have been impacted by saltwater intrusion, causing concern for the city's water supply. The goal of this Major Qualifying Project was to identify problems in water quality and supply in Dania Beach, Florida caused by saltwater intrusion and create a long-term management plan to address these problems. Long-term management plan options that were evaluated included the following: (1) use surface water instead of groundwater, (2) construct wells further from the ocean, (3) purchase additional water from a nearby system, (4) construct and operate a desalination plant in Dania Beach, and (5) utilize wetlands in Dania Beach. These long-term management plan options were ranked according to the following categories: (1) technical feasibility, (2) water quality: health, (3) water quality: aesthetics, (4) cost, and (5) space required. The most feasible long-term management plan option is to purchase water from a nearby system outside of Dania Beach, specifically purchasing additional raw water from the Broward County regional wellfield. An alternative option is to purchase treated water from Broward County WWS. All other long-term management plan options were determined to not be feasible due to cost limitations, space limitations, and difficulties meeting technical feasibility.

The Broward County regional wellfield produces raw water, and pipe connections between this system and Dania Beach's water treatment plants are already in use. Overall, this option would incur no capital cost, is technically feasible because water system connections are in place, and requires no additional space once implemented. In addition, the water would be treated by Dania Beach, as is currently done, so it would meet all water quality standards. Lastly, Dania Beach water treatment plants have the capacity to meet demand through 2050.

It is also feasible for Dania Beach to purchase treated water from Broward County WWS. The system already provides treated water to 40% of Dania Beach. A pipe connection would need to be made to provide the City of Dania Beach Water Utility with water from Broward

County WWS, which would increase water bills by 4.5%. Water from this system would be treated by Broward County WWS before supplying it to Dania Beach, so it would meet all water quality standards and is technically feasible. However, supplemental disinfection and/or corrosion control may be needed.

4.2 Recommendations

It is recommended that Dania Beach purchase additional water from Broward County regional wellfield if the city's wells are shut off due to saltwater intrusion or cannot meet demand. Dania Beach's water utility currently receives water from Broward County's regional wellfield, so purchasing additional water from this source would not incur additional capital cost. Additionally, Broward County's well field water supply would not reach capacity by providing water to Dania Beach. The water demand from Broward County's regional wellfield was 28.85 MGD in 2020 and is projected to be 33.59 MGD in 2050. The water demand from Dania Beach's utility was 2.33 MGD in 2020 and is projected to be 3.15 MGD in 2050. Overall, the combined demand between Broward County's regional wellfield and Dania Beach was 31.18 MGD in 2020 and is projected to be an estimated 36.74 MGD in 2050. Broward County's regional well water supply capacity is 63.76 MGD, so the wellfield is capable of supplying water to Dania Beach well into the future. In addition, the Dania Beach treatment plants have sufficient capacity to meet future water demands.

If an agreement cannot be reached to purchase water from Broward County regional wellfield, an alternative is for Dania Beach to purchase treated water from Broward County WWS. Purchasing water from Broward County WWS only causes the Dania Beach water utility bill to increase by 4.5%, resulting in it being cost effective. Additionally, Broward County's WWS water supply would not reach capacity by providing water to Dania Beach. The water demand from Broward County WWS was 20.32 MGD in 2020 and is projected to be 24.22 MGD in 2050. The water demand from Dania Beach's utility was 2.33 MGD in 2020 and is projected to be 3.15 MGD in 2050. Overall, the combined demand between Broward County WWS and Dania Beach was 22.65 MGD in 2020 and is projected to be an estimated 27.37 MGD in 2050. Broward County's WWS water supply capacity is 46 MGD, so this system is capable of supplying water to Dania Beach well into the future.

Before implementing the long-term management plan option of purchasing water from Broward County's regional wellfield or Broward County WWS, communication between Broward County and Dania Beach would have to take place. Additionally, further evaluation on the feasibility of both long-term management plan options would have to take place. Dania Beach would have to conduct a detailed analysis on the cost of purchasing water and the impact on household water bills. Because Dania Beach is currently treating water from Broward County's regional wellfield, little adaptations would need to be made to the current water treatment plant and water distribution system. If Dania Beach chooses to purchase water from Broward County WWS, evaluation would have to take place on whether corrosion control or disinfection processes would be required to address water quality concerns. Dania Beach's water treatment plants could provide corrosion control and disinfection to the water if necessary, so the treatment plants would have to adapt to this change in processes.

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Appendices

Appendix 1: Calculations

Calculation 1: 2020 Dania Beach Water Demand Estimation

2009 water demand = 2.1 MGD
2020 water demand = x
2028 expected water demand = 2.7 MGD

Interpolation between 2009 and 2028 demand:
(2.7 - 2.1) / (2028 - 2009) = (x – 2.1) / (2020 – 2009)
x = 2.45 MGD

Comparing expected and actual 2020 demand:
Expected = 2.45 MGD
Actual = 2.3 MGD

100 * [(2.45 – 2.33)/2.45] = 5.2%

Calculation 2: Population forecasting using incremental increase method

Formula: Pn = P+n(la+lc)

Where,
Pn = population at "n" decade
P = population of previous decade
n = number of decades
la = average arithmetical increase
lc = average incremental increase

Calculating la :

Increase in population each decade (Growth beginning between 1940-1950):
1940: unknown increase (population at 1940 = 2900)
1950: 4500 - 2900 = 1600
1960: 7100 - 4500 = 2600
1970: 9000 - 7100 =1900
1980: 11796 - 9000 = 2796
1990: 13024 - 11796 = 1228
2000: 20061 - 13024 = 7037
2010: 29808 - 20061 = 9747
2020: 32344 - 29808 = 2536
Total increase (between 1940 – 2020) = 29444

Calculation of la: Average increase in population from 1940 to 2020

Average = 29444/8 = 3681

Calculating lc:

Incremental increase
1940: Incremental increase cannot be calculated
1950: Incremental increase cannot be calculated
1960: 2600 - 1600 = 1000
1970: 1900 - 2600 = -700
1980: 2796 - 1900 = 896
1990: 1228 - 2796 = -1568
2000: 7037 - 1228 = 5809
2010: 9747 - 7037 = 2710
2020: 2536 - 9747 = -7211

Calculation of lc: Average incremental increase each decade
Average =936/7=134

Population forecast:
Pn = P+n(la+lc)
2030: P_{2030} =32344+1(3681+134)= 36,159
2040: P_{2040} = 36159+1(3681+134)= 39,974
2050: P_{2050} = 39974+1(3681+134)= 43,789

Calculation 3: Water Demand Forecasting

Formula:
Water Demand (gpd) = Per Capita Water Consumption (gpcd) x Population served by Dania Beach (persons)

Per capita water demand: 120 gpcd (gallons per capita*day)
2020: Water demand per capita = 120gpcd * 32,344 persons = 3.881 MGD
2030: Water demand per capita = 120gpcd * 36,159 persons = 4.339 MGD
2040: Water demand per capita = 120gpcd * 39,974 persons = 4.797 MGD
2050: Water demand per capita = 120gpcd * 43,789 persons = 5.255 MGD

Population served by Dania beach (persons) = Total population of Dania Beach *0.6

2020: Water demand per capita = 120gpcd * 32,344 persons * 0.6 = 2.328 MGD
2030: Water demand per capita = 120gpcd * 36,159 persons * 0.6 = 2.603 MGD
2040: Water demand per capita = 120gpcd * 39,974 persons * 0.6= 2.878 MGD
2050: Water demand per capita = 120gpcd * 43,789 persons * 0.6 = 3.153 MGD

Calculation 4: Pipeline Construction Cost from Lake Okeechobee to Dania Beach

Cost = cost per mile *miles constructed
Cost = $1,100,000 per mile * 62 miles = $68,200,000

Cost with compounding interest: $A = P(1 + r/n)^{nt}$

Where A = final amount

P = intitial principal balance

r= interest rate

n = number of times interst applies per time period

t = number of time periods elapsed

$A = P(1 + r/n)^{nt} = \$68{,}200{,}000\ (1 + 0.05/2)^{2*30} = \$300{,}065{,}661$ = estimated \$300,000,000

Cost with inflation: \$300,000,000 + \$300,000,000 * 0.26 = \$378,000,000

Calculation 5: Pipeline Construction Cost Distributed Across 30 Years from Dania Beach to Lake Okeechobee

Distributed cost = Overall cost/(average population between 2020-2050 * 30 years)

Average population between 2020-2050:
(19,406 + 21,695 + 23,984 + 26,273)/4 = 22,839 people

Distributed cost = \$378,000,000/(22,839 people * 30 years) = \$551.68 per person per year
Cost per month: \$551.68 per person/year * (year/12 months) = \$45.97 per person per month

Cost added to each water bill per household = Cost per person * people per household

Average household size in Dania Beach = 2.6 people

Cost added to each water bill per household monthly = \$45.97 * 2.6 = \$119.52 per household per month

Average water bill in Dania Beach: \$14.55 and an additional \$2.98/1000 gallons of water

Average bill = \$14.55 + 120GPD per person*(30days/month)*(2.6 people/household) *(\$2.98/1000 gallons) = \$42.44 per month per household

Average bill with increase from pipeline cost: \$119.52 per household per month + \$42.44 per household per month = \$161.96

Percent increase of bill:
Percent increase = 100*[(final bill - initial bill)/initial bill]
Percent increase = 100*[(\$161.96- \$42.44)/\$42.44] = 281.62%

Calculation 6: Adjusted Capital Cost for 1 MGD of each Desalination Plant

Formula: $\frac{Approximate\ Capital\ Cost\ (Millions\ of\ Dollars)}{Capacity\ (MGD)}$

The Tampa Bay Plant: $\frac{158\ M}{28.8\ MGD}$= \$6.32 M

Robert W. Goldsworthy Desalter: $\frac{22.5\ M}{5\ MGD}$= \$4.5 M

City of Cape Coral RO Water Treatment Facility (Southwest): $\frac{15.6\ M}{18\ MGD}$= \$7.22 M

Current Dania Beach Nanofiltration Water Treatment Plant: $\frac{8.8\ M}{5\ MGD}$= \$1.76 M

Proposed Expansion of Dania Beach Plant: $\frac{26.46\ M}{4.403\ MGD}$= \$6.01 M

Calculation 7: Adjusted Capital Cost for 1 MGD for the Proposed Desalination Plant for Dania Beach

The approximate capital cost of the proposed desalination plant is the average of the capital cost adjusted for 1 MGD three desalination plants being used for comparison

$$\frac{6.32M+4.5M+7.22M}{3} = \$6.01\ \text{M}$$

Calculation 8: Capacity for Proposed Desalination Plant for Dania Beach

Formula: Forecasted Capacity Need + Factor of Safety

$$3.153\ MGD\ +\ 1.25\ MGD =\ 4.403\ MGD$$

$$3.153\ +\ 1.25\ =\ 4.403$$

Calculation 9: Approximate Cost to Consumer in Dania Beach of Proposed Desalination Plant

Formula: Adjusted Capital Cost for 1 MGD * Capacity (MGD)

\$6.01 M * 4.403 MGD = \$26.46 M

Appendix 2: Dania Beach Reference Materials

The average person uses 120 gpcd.

As a result, the City adopts the following:

1. <u>Dwellings:</u>
   Each Single Family Unit = 1 ERC = 150 gpd

2. <u>Condominium:</u>
   3 bedroom 150 gpd 1 ERC
   1&2 bedroom 120 gpd 0.8 ERC
   CRA Condo 100 gpd 0.7 ERC

3. <u>Motel/Hotel:</u>
   50 gpd CRA hotel room
   50 gpd per room
   150 gpd per mgr. apt.

4. <u>Mobile Home:</u>
   100 gpd per space

5. <u>Office</u>
   0.2 gpd per square feet

6. <u>Retail:</u>
   0.1 gpd per square foot

7. <u>Laundries:</u>
   400 gpd per machine

8. <u>Bar (no food service):</u>
   20 gpd per seat

9. <u>Restaurants:</u>
   24 hour - 50 gpd per seat (Including bar)
   Less than 24 hours -30 gpd per seat (Including bar)

10. <u>Theaters:</u>
    5 gpd per scat

11. <u>Assembly Hall:</u>
    2 gpd per seat

12. <u>Park</u>

10 gpd per person

13. Factories:
15 gpd per person per shift

14. Institutions:
100 gpd per person

15. Church:
7 gpd per seat

16. Service Station:
Full Service Station
First Two Bays - 750 gpd
Each Additional Bay - 300 gpd
Per Fuel Pump - 100 gpd

Self Service Station
Per Fuel Pump 50 gpd

17. Elementary School:
10 gpd per pupil
5 gpd per shower per pupil
5 gpd per cafeteria per pupil

18. High School:
15 gpd per pupil
5 gpd per shower per pupil
5 gpd per cafeteria per pupil

19. Hospital and Nursing Home:
200 gpd per bed
100 gpd per staff

20. Warehouse:
0.1 gpd per square foot