Master's Thesis

The Long Beach barrier island and a rising sea



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Abstract

Barrier coasts have a meagre elevation above the sea and their location in front of the mainland makes them very vulnerable for sea level rise and climate changes. Barrier coasts are very prone to floods and a first line of defence against the natural violence of hurricanes and North Easter storms (nor'easters). The Long Beach barrier island is located a few steps away from New York City. It is highly urbanized and has a high exposure to water related problems. Therefore, the Long Beach barrier island forms an interesting case study. This thesis aims to gain a broad and better understanding of the effects of sea level rise and climate changes on the groundwater level of the Long Beach barrier island. In addition, the study tries to find out how these changes might affect the island.

To evaluate the effect of climate change and sea level rise, numerical groundwater models have been developed. Scenarios are used as input for these models and are based on climate change projections of the New York Panel on Climate Change (NPCC). The model outcomes show that future climate changes and sea level rise might have a large impact on the groundwater level of the island. As climate change induces less recharge the shape of the groundwater level might become less convex in the future. On the other hand, sea level rise will result in a global rise of groundwater levels in two of the three scenarios. The model outcomes show that the shores of the island will experience the highest groundwater level rise. These changes are greatest in winter months where groundwater levels might increase with one meter at the shores. As evapotranspiration increases in summer months, groundwater levels in summers are expected to decline. The model outcomes show that seasonal differences in groundwater levels become greater.

This research also shows that the groundwater level quickly responds to storm surges alike the one induced by hurricane Sandy. A lag in groundwater level response at the start of a storm has been observed on the bay side of the island which is likely caused by funnel flow through the barrier inlets. As a result of strong North Eastern winds the surges on the bay side and the same funnel flow result in higher groundwater level on the bay side hours after a hurricane has passed.

These changes in groundwater level might have a great impact on the City of Long Beach, the biggest city on the barrier island. As the islands elevation is lower on the north side than on the south side, the groundwater changes are expected to have the largest impact on the north side of the city. In this area, groundwater levels might rise critically close to the surface. The model outcomes show that in a moderate scenario groundwater levels rise within 70 cm of the surface. This could lead to uplift of pools and subsurface infrastructure and frost heave under roads and pavements. It could also affect plants and trees in the city, limiting their growth and causing diseases related to water saturated soils.

To enhance to reliability, accuracy and usability of the model outcomes and to get a better understanding of the topsoil on the island the conduction of a large scale soil survey across the island is recommended. In addition, the installation of a groundwater monitoring system to record seasonal fluctuations in groundwater level is recommended. Applying a full water balance equation for the island would give more insights in the impact of changing groundwater levels.

In sum, the approach taken in this study can be applied to other barrier coasts and could help in better understanding the effects of climate change and sea level rise on such islands.

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1. Introduction & research questions

On the 29th of October 2012, hurricane Sandy made landfall at the North Eastern coast of the United States, beginning its ravaging path through the states of New Jersey and New York. Sandy killed 233 people in total. She ran up a total bill of an estimated \$68 billion (USD) of which \$19 billion ended up on the account of New York City. Sandy questioned the resilience of Greater New York and other parts of the North Eastern coast against a changing climate.

The anticipated changes in global temperatures and CO_2 concentrations in the atmosphere will lead to higher sea levels. The IPCC's latest climate change report shows that in the most cautious scenario current sea levels are likely to rise with 0.26 - 0.55 m, before 2100 (RCP 2.6) (Church et al., 2013). The 2015 Climate Change Report of the New York Panel on Climate Change (NPCC) shows even more extreme numbers for local sea level rise ranging from 0.38 – 1.90 m (Horton et al., 2015). Globally, 60% of this observed sea level rise is caused by thermal expansion of the ocean water, melting of icecaps and glaciers, land water storage losses (groundwater mining, urban runoff, impoundment in reservoirs) and local water mass densities (temperature, salinity, ocean currents). The other 40% is caused by land subsidence and glacial isostasy (Engelhart & Horton, 2012; Peltier, 2004).

In addition to sea level rise, both the IPCC and NPCC state that rainfall will intensify and will fall in changing patterns. According to the NPCC's latest Climate Change Report, since 1991, the average annual precipitation has increased with 5 – 15% in the North-East of the United States (U.S.) (Horton, Bader, et al., 2015; Melillo,Richmond, & Yohe, 2014). The same report states that the amount of rain fallen in the 1% heaviest events has increased with approximately 70% between 1985 and 2011. Moreover, hurricanes will become more intense with stronger winds, more precipitation and as sea level rises, their storm surges will attack higher upland (Colle et. al., 2013; Melillo et. al., 2014; Vecchi et. al., 2008; Yaukey, 2014).



Figure 1 Presence of barrier islands along the East coast of North America

With regards to these profound climatic changes, barrier coasts are among the most vulnerable areas along the East Coast of the United States. Their meagre elevation above the sea and their location in front of the mainland makes these coasts very prone to floods and a first line of defence against violent hurricanes and North Easter storms (also known as nor'easters). Figure 2 gives an impression of the presence of barrier coasts along the East coast of North America.

Additionally, coasts are among the most populous areas in the United States. According to the NOAA¹, 39% of the United States' population lives in coastal areas and this portion continues to grow. The barrier coasts are no exception. In spite of the risks, 1.4 million people have settled on the barrier islands along the East Coast of the United States, giving them a very high exposure to floods (Kron, 2005; Zhang & Leatherman, 2011). The barrier islands of Long Island, NY, are a typical example as they lay steps away from the ever-growing metropolis of New York City. The scope of this research is the Long Beach barrier island on the south shore of Nassau County. Being part of Greater New York, the island is highly urbanized and was seriously damaged after hurricane Sandy had passed by. Figure 3 shows the inundation depth of the floods on the island caused by Sandy's storm surge.



Figure 2 Inundation depths of the floods caused by hurricane Sandy. Source: FEMA

Direct floods caused by storms are not the only danger for the population living on barrier islands. As the groundwater table on these islands is directly related to the sea, sea level rise and climate change are very likely to elevate the groundwater table, possibly affecting the barrier islands on a permanent, large and broad scale (Masterson & Garabedian, 2007; Nuttle & Portnoy, 1992). Where the awareness and knowledge about coastal floods on barrier islands is increasing, little attention is paid to the effects of climate change on the groundwater systems of these islands.

¹ National Oceanic and Atmospheric Administration (NOAA)

The aim of this thesis research is to gain a broad and better understanding of the effects of sea level rise and climate changes on the groundwater system of barrier islands. This research focuses on changes in height of the groundwater table relative to mean sea level and how these changes have an impact on the barrier islands. The main question of this thesis research is: *how does the groundwater level of the Long Beach barrier island respond to sea level rise and climate change and how these changes can affect the City of Long Beach*? A brief overview of relevant processes and how they might endanger the island are given below and are illustrated by figure 6.

Groundwater levels on islands are directly related to mean sea level, surrounding the island. When the sea level rises, groundwater levels are likely to elevate as well (Masterson & Garabedian, 2007; Nuttle & Portnoy, 1992). A rising groundwater can induce structural long-term problems.

The zone between the groundwater level and the surface is called the unsaturated zone and is depicted in figure 4 and 5. Other to the pores beneath the groundwater level that contain water only, pores in this zone contain water as well as air. The presence of air makes this zone vital for organisms and trees and also humans use this zone extensively during construction of buildings and infrastructure and the cultivation of plants and crops.

In addition, as the pores in this zone are not completely filled with water, the zone has the ability to store water during heavy rainfall or floods. However, when groundwater levels rise the amount of rain water the zone can store decreases inversely proportional with an increase in groundwater level induced by sea level rise (figure 4 & 5). A thinner unsaturated zone means decreased unsaturated zone storage and an increase in soil moisture content (the amount of moisture in the soil). A higher volumetric moisture content of the soil can lead to extra surface runoff of water, putting extra pressure on the sewer systems and storm water drainage system (Hendriks, 2010).



Figure 3 groundwater level and unsaturated zone under normal conditions



Figure 4 groundwater level and unsaturated zone under conditions with a higher groundwater level

Furthermore, higher groundwater tables and sea level rise can severely damage subsurface infrastructure, basements and pools, often constructed within the unsaturated zone. Once the groundwater table rises to the vicinity of the subsurface (infra)structures, buoyancy forces cause uplift or deformation and destruction might occur.

Also, higher groundwater levels can affect urban nature. Trees and organisms are able to live in the unsaturated zone because air is present. Rising groundwater pushes the air out of the soil and highly saturated soils might affect the growth of the trees and plants due to anaerobic conditions. Highly saturated soils can also foster fungal growth which might impair plants and tree trunks (Nash & Graves, 1993; Predick, Gergel, & Turner, 2007). A rise of the groundwater table also reduces the habitat of smaller organisms living in the soil.

As humans extensively use the surface and the unsaturated zone, chances of contaminants percolating into the unsaturated zone are substantial, especially in urban areas. Often, contamination is trapped in pores or attached to soil particles. When the groundwater level rises, the contaminants get into contact with water and can either be dissolved (through dispersion and diffusion) or are transported into the groundwater flow direction, spreading the contaminants over a larger area.

Another problem that might occur is caused by the current storm water management system which discharges directly into the bay through a simple pipe system with a slight gradient. Sea level rise and unusual tides will submerge the pipe outlets, causing backfloods and failure of the storm water management system. During storms, more surface water has to be drained with a system that becomes less effective as a result of sea level rise and unusual tides.

To assess the vulnerabilities of the Long Beach barrier island, an urban vulnerability assessment is carried out supported by a theoretical background and site description. In the vulnerability assessment the problems and processes stated above will be outlined and explained in more detail. In addition, an analytical and numerical analyses is carried out to evaluate how the groundwater reacts on sea level rise and a changing climate. These analyses are used as a tool to get a better understanding of the groundwater system beneath the Long Beach barrier island and to evaluate how vulnerable the island is to climate changes and sea level rise from a groundwater perspective.



Figure 5 Approach taken in this study. First an analytical assessment of the possible changes in groundwater level will be made. Subsequently a numerical model will be developed to understand the current groundwater system. Then, an urban vulnerability assessment is carried to research how changing groundwater levels can possibly affect the City of Long Beach. After that scenarios are applied to the groundwater model to predict future groundwater changes.



Figure 6 Schematic overview of relevant processes and possible dangers

2. Site description and theoretical background

This chapter provides the theoretical background of all relevant aspects related to changes in groundwater level induced by sea level rise and climate change. The chapter starts off with a general description of the island, followed by a brief description of the genesis of the island. Subsequently, the hydrogeology and hydrology of the island are explained in more detail. Then the current climate and climate changes are discussed.

2.1 Geographical location and brief history of the island

The Long Beach barrier island lies on Nassau County's south shore. It's surrounded by the Atlantic Ocean on its south shore and Reynolds Channel on its north shore. The first anthropogenic developments on the island occurred in the late 1800s with the building of a large summer resort. Later, in the early 1900s, William Reynolds ensured a solid building ground that would form the basis of an industrial scaled rework of the island. He dredged Reynolds Channel and used the dredged material to fill and cover the original marshes that formed the backside of the island.

The development of the Long Beach barrier island occurred in four stages. The first stage is the development of the luxury hotel and resort in the period of 1908-1919. At this time, the first sewer system was also constructed. Further development took place during 1919-1929 (Post WWI). During these first two phases of development, the island was generally inhabited during summer months. In the period of 1930-1945 (Post Depression) the island became inhabited all year long and further development took place aft.er World War II.

Currently four municipalities are present on the island, namely Atlantic Beach, Long Beach, Lido Beach and Point Lookout. Their combined population is about 40.000 (Census, 2013). The island falls under the administration of Nassau County. The island lays steps away from New York City and is for a large part inhabited by commuters that work in New York City.

2.2 Morphologic history

During the Last Glacial (110.000 – 12.000 years ago) the sea level was tens of meters lower than today as large amounts of water were locked up in glaciers and ice caps (Lambeck & Chappell, 2001). As the earth started to warm up in the Holocene transgression, glaciers and ice caps started to melt and sea levels began to rise steadily. During this steady rise barrier islands developed. Two processes, both directly related to the rate of sea level rise, are believed to be the main drivers in the development of Long Islands' barrier islands.

The first process is called "shoreface retreat". Shoreface retreat implies that barrier islands continuously migrate landwards with sea level rise. The main mechanisms driving this process are shoreface erosion and washover of the landward sides where the barrier inlets play an important role (Johnson, 1919; Swift., Sanford, Dill, & Avignone, 1971; Swift., 1968). During the landward retreat the sediment in between the barrier islands and the main land (backbarrier sediments) are completely eroded by wave action until the barrier island is connected to the main land. This process is illustrated in Figure 7.

The other process is "barrier drowning". While the sea level rises, the barrier islands remain in place. The lagoon in between the barrier and the main land widens and deepens. Ultimately, the sea level causes the breaker zone to reach the top of the barrier and drown it. The breaker zone (zone where the waves brake) moves to the new shoreline landwards where new barriers develop (Sanders & Kumar, 1975; Sanders, 1963). The rate of sea level rise and sediment supply are important drivers in the behaviour of barrier islands (Kraft., 1971; Sanders & Kumar, 1975). Rapid sea level rise favours barrier drowning where slow sea level rise favours shoreface retreat.

Seismic evidence indicates that Long Island's barrier islands have been formed on a Pleistocene barrier ridge ±9000 years ago, 7 kilometres off shore from their current location (Figure 8). The size of that ridge is about the same size as the current barrier extent of Long Island (Rampino & Sanders, 1977, 1980; Sanders & Kumar, 1975). ±7500 years ago, when the sea rose to -16 MSL the ridge was drowned and the breaker zone shifted 5 kilometres landwards. New barrier islands formed at this new shoreline that continuously migrated towards their current location with approx. 63 cm/year over a period of ±5000-6000 years. The islands have migrated approximately 2 kilometres over this period to their current position (Shepard & Wanless, 1971). Figure 7 gives a chronological overview of the development of the Long Island barrier islands.

It is unclear for how long the Long Beach barrier island has been in its current position, but on the basis of the historical speed of movement, the island should have stagnated some 500-1500 years ago. Research done at the central part of Fire Island, one of the barrier islands a few kilometres to the right of the Long Beach barrier island, showed a similar stagnation point. That island hasn't migrated for the last 1000 years (Leatherman, 1985).

Current sea level rise accounts for less than one foot of annual erosion, being a high estimate (Tanksi, 2012). However, future sea level rise could either accelerate the migration of Long Islands' barrier coast or drown it. But the current projected increase in sea level rise would not significantly change the shoreline as is shown by Tanksi (2012). In the early 1900's the use of artificial fill to cover the marsh deposits and natural inlets lead to a static situation where the natural tidal dynamics of the marsh systems was removed.

In addition beach nourishments and the construction of groins in the 40s and 50s have led to a compensation of shoreface erosion and the barrier islands have been "locked" into place. A coastal protection study dating from 2009 and commissioned by the City of Long Beach even indicates that the beaches grow in size due to accretion of sand brought in by ocean currents.²

² City of Long Beach Local Waterfront Revitalization Program, 2009



Figure 7 Chronological schematization of the Long Island barrier islands development. Two processes are believed to be the main drivers behind the Long Island barrier islands migration; barrier drowning and shoreface retreat. Due to decreasing sea level rise the migration slowed down. Nowadays, the Long Beach barrier island is locked into place and is highly urbanized.





Figure 8 Illustration showing the Pleistocene ridge and the further movement of the barrier islands. (Michael R. Rampino & Sanders, 1980)

2.3 Hydrogeology of the Long Beach Barrier Island

The Long Beach Barrier island is underlain by deposits originating from the Late Cretaceous (100.5-66 Ma) and Pleistocene (2.58 – 0.0117 Ma). The deposits thicken to the south and southeast, following the contours of the bedrock. (McClymonds & Franke, 1972). Fresh groundwater flows through four aquifers, namely; the upper glacial, the Jameco, the Magothy and the Lloyd. A brief chronological description of the stratigraphy follows. The main characteristics of these aquifers and their aquitards are given in table 1

The Lloyd aquifer is the oldest and deepest of the four aquifers dating from the Late Cretaceous (100.5-66 Ma) on a depth of ±290 m and thickness of ±120 m. The aquifer has a relatively low permeability with an average hydraulic conductivity ranging from 12 to 20 m/d (McClymonds & Franke, 1972; Soren, 1971). The anisotropy is 10:1 (Chu, 2006; Smolensky, Buxton, & Shernoff, 1989). The aquifer is overlain by thick confining clay named Raritan clay. This layer has a very low vertical hydraulic conductivity of 0.003 m/d. The Lloyd is the only drinking water source for the islands drinking water supply, but due to its depth, plays an unimportant role in the height and shape of the water table. The Lloyd is recharged on Long Island, just north of the groundwater divide (Chu, 2006).

The Lloyd and Raritan clay are overlain by the Magothy aquifer that has a thickness of approximately 213 m. Its average horizontal hydraulic conductivity is ± 15 m/d. The Jameco aquifer lies directly on top of the Magothy and is defined as a different layer due to its very high hydraulic conductivity (76 m/d). The Jameco and Magothy are overlain by Gardiners Clay that has an average vertical hydraulic conductivity of approximately 0.003 m/d (Smolensky et al., 1989). With a thickness up to 30 meters, the Gardiners clay acts as a hydrological base and makes that the aquifers beneath have very little influence on the groundwater level.

The upper glacial aquifer is a unconfined aquifer and is composed of sand, gravel and boulders (Smolensky et al., 1989). The deposits are the remains of the glacial moraine system that underlies the whole of Long Island. The Long Beach barrier island is situated on this large outwash plain that consist of sand, fine to very course and gravel, pebble and boulder sized. The average horizontal hydraulic conductivity is very high with values of ± 80 m/d. The upper glacial contains a clay layer called "20-foot clay". This clay layer is an inter-glacial deposit with a vertical hydraulic conductivity of 0.003 m/d. The layer is ± 3 meters thick and is positioned at an average of 9m below the surface. This clay layer is expected to have a large effect on the height of the groundwater above mean sea level. Parts of this layer have been eroded in the last ice age. Figure 9 shows the presence of the 20-foot clay layer in the vicinity of the island.

The most recent deposits, stemming from the Holocene, consist of salt marsh deposits and sandy shoreline deposits. The thickness of these recent deposits varies across the island ranging from $\pm 3 - 6$ m. The sandy shoreline deposits have a good permeability, where the marsh deposits have a very poor permeability or around 0.01 m/d. The topsoil consists of a mixture of marsh remains and beach sand dredged from Reynolds Channel, this top layer is expected to have a conductivity of approximately 20 m/d, based on typical values.

Geological layer	Туре	Thickness	Horizontal/vertical conductivity	Anisotropy
Lloyd	Confined aquifer	±120m (393ft.)	12 – 20 m/d	10:1
Raritan	Confining aquitard	±91m (300ft.)	0.003 m/d (vertical)	
Magothy	Confined aquifer	±213m (698ft.)	15 m/d	10:1
Jameco	Confined aquifer	±30m (98ft.)	76 m/d	10:1
Gardiners	Confining aquitard	±30m (98ft.)	0.003 m/d (vertical)	
Upper glacial	Unconfined aquifer	±30-50m(100-	80 m/d	10:1
		165ft.)		
20-foot	Discontinuous aquitard	±3m (9.8ft.)	0.003 m/d (vertical)	

Table 1 Main characteristic of the 5 aquifers and their aquitards beneath the Long Beach barrier island



Figure 9 Presence of 20-foot clay beneath Long Beach barrier island

Table 2 shows the groundwater levels observed during spring and fall over the period of 2000 – 2003.

Table 2 Phreatic (shallow) groundwater	levels at	Long Beach,	Atlantic Beach	and I	Point	Lookout	throughout
2000 - 2003 in spring and fall (USGS)							

		2000		2001		2002		2003	
Monitoring well no.	Location	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
N-12609	Long Beach	1.09 m (3.57 ft)	1.14 m (3.74 ft)	1.11 m (3.64 ft)	0.93 m (3.05 ft.)	0.86 m (2.82 ft.)	1.16 m (3.81 ft.)	1.21 m (3.97 ft.)	1.04 m (3.41 ft.)
N-09474	Atlantic Beach	2.31 m (7.58 ft.)	1.19 m (3.90 ft.)	1.80 m (5.91 ft.)	0.79 m (2.59 ft.)	0.71 m (2.33 ft.)	1.00 m (3.28 ft.)	0.95 m (3.12 ft.)	1.01 m (3.31 ft.)
N-10130	Point Lookout	1.87 m (6.14 ft.)	1.87 m (6.14 ft.)	1.78 m (5.84 ft.)	1.52 m (4.99 ft.)	1.78 m (5.84 ft.)	1.84 m (6.04 ft.)	1.55 m (5.09 ft.)	1.50 m (4.92 ft.)

2.4 Hydrology and salinity

The upper glacial, Jameco and Magothy aquifers are contaminated with saltwater in the vicinity of the island. This is also the reason that coastal communities such as Long Beach are allowed to pump up water from the Lloyd as it provides the only source for potable water. Figure 10 shows the isochlors for this shallow saltwater wedge in parts per million. At a depth of 45m the concentrations range from 16200 - 12200 ppm at Far Rockaway (just north of the Long Beach barrier island), 12900 ppm at Atlantic Beach, 3600 ppm at Long Beach and 4 ppm near Lido Beach. Water with chloride values higher than 300 is considered to be brackish (Table 3).

Table 3 Division of water types by Chlorine concentration. Source: Stuyfzand (2012)

Туре	Concentration
Fresh	0 – 300 mg Cl/L
Brackish	300-10000 mg Cl/L
Salt	10000-20000 mg Cl/L
Hypersaline	>20000 mg Cl/L



Figure 10 Isolines for chloride concentrations (ppm) Red is saltwater, orange is brackish and blue is freshwater. source: Lusczynski & Swarzenski, 1966

2.5 Coastal groundwater system and hydrologic fluxes

The freshwater system on islands in general is defined by the inflow of freshwater through precipitation and the outflow of freshwater through groundwater discharge to the sea, evapotranspiration and surface runoff. Precipitation and potential evapotranspiration are controlled by climatic conditions and vegetation. The actual evapotranspiration is influenced by the actual supply of water, vegetation and the initial wetness of the soil. Precipitation and evapotranspiration are the largest fluxes in the water system on the island and are very important when assessing the groundwater system.

Due to the density difference between fresh- and saltwater, the freshwater floats atop of the denser saltwater and forms a so-called freshwater lens, depicted in Figure 11. This figure also shows the typical flow pattern within a freshwater lens.



Figure 11 Schematization of a typical freshwater lens

The density of saltwater is dependent on temperature and the amount of solutes. In general, saltwater contains sodium (Na), chlorine (Cl), carbon trioxide (CO_3), sulphate (SO_4), and manganese (Mg) in various amounts. The density of most surface seawater ranges between 1022 and 1028 kg m⁻³ at 20°C. As mentioned earlier, groundwater beneath the Long Beach barrier island varies from fresh to brackish and with a lower density, 1000 kg m⁻³ to 1021 kg m⁻³ (Figure 10 Lusczynski & Swarzenski, 1966).

2.5.1 Recharge and surface runoff

The recharge of the aquifers is strongly influenced by the type of surface and the initial moisture content of the soil. The Lloyd aquifer is scantily recharged by precipitation on the island because thick clay layers overlie it and its recharge area, a narrow corridor (800 meters) along the groundwater divide of Long Island, is relatively small (Chu, 2006).

The island is urbanized and characterized by highly impervious surfaces such as asphalt roads, concrete sidewalks, parking lots, homes and other types of buildings. Figure 12 shows the imperviousness of the island's surface. A substantial part of the island's surface is highly or extremely impervious; meaning that 60-100% of precipitation is captured by the storm water drainage system and discharged into the bay instead of infiltrating into the soil and shallow aquifers. Furthermore, the high level of urbanization results in compaction of the topsoil. This means that the pores in the topsoil become smaller and that the infiltration rate decreases. Besides that, the water holding capacities of the soil decrease as smaller pores are available for retention.

In areas with little to no pavement the initial moisture content of the soil determines the amount of surface runoff. Very moist soils are less able to store extra water, because large parts of the pores are already filled with water. During a normal rain event, the infiltration capacity of the soil is not exceeded and the infiltration rate is equal to the amount of precipitation. However, during heavy downpours, packing of the soil surface by rain, swelling of the soil and the in wash of fine materials occur and cause a decrease in surface porosity in the upper millimetres of the soil. During such a heavy rainfall event, the surface of the soil seems saturated and water starts to pond (Hendriks, 2010). During ponding, the infiltration capacity is limited to the maximum infiltration rate (hydraulic conductivity) of the soil and the excess water starts to flow over land. Excess overland flow is either discharged into the bay caught by the storm water drainage system or infiltrates after some time.

Furthermore, the recharge is influenced evapotranspiration. This is the sum of evaporation and plant/tree transpiration. This flux occurs predominantly during daylight hours and has a strong spatial variability. Studies show that evapotranspiration is estimated to be as high as 70% of annual precipitation in the U.S. (Trout & Ross, 2006). For the Long Beach barrier island evapotranspiration flux contains

approximately 60% of annual precipitation (Steenhuis, Jackson, Kung, & Brutsaert, 1985). However, evapotranspiration is strongly related to air temperatures and is highest during summer months (Figure 13). In July, evapotranspiration even exceeds the amount of precipitation and no recharge takes place.



Figure 12 Imperviousness of the Long Beach barrier islands' surface. Source: U.S. Geological Survey (USGS)

2.6 Current climate and climate change scenarios

2.6.1 Current climate

The Long Beach barrier island is situated in a region with a climate described by Köppen as a warm continental climate, with precipitation throughout the year and the hottest month having an average temperature above 22°C (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). Data from the JFK international weather observation station was used to assess the current climate of the Long Beach barrier island. The weather station is situated within 7 kilometres of the island and represents the climate on the island sufficiently. Figure 13 shows the average temperature and precipitation values for the period 2000-2014. The temperature varies greatly from season to season with temperatures ranges of 0-5 degree Celsius in winters and 20-25 degrees Celsius in summers.

The evapotranspiration values are based on data from the New York City Central Park weather observation station over the period of 1975-2004. The average amount of precipitation, annually, is around 1090 mm, whilst around 650 mm leaves the system through evapotranspiration. Evapotranspiration is strongly related to the temperature throughout the year and the type of vegetation. Especially during spring and summer, evapotranspiration values are high, mainly due to high temperatures and the active growing season of vegetation (Wagle & Kakani, 2014).



Figure 13 Temperature and precipitation are based on data from the John F. Kennedy International Airport weather observation station over the period of 2000 – 2014. Evapotranspiration data is based on data from the New York City Central Park weather observations

2.6.2 Climate changes

Sea level rise

According to the NPCC's latest Climate Change report, sea level at The Battery, NY rose with about 3 cm per decade over the period of 1900-2013 (Horton, Little, et al., 2015). This trend is likely to accelerate in the future due to the anthropogenic and climatic changes mentioned in the introduction. Table 4 shows the projected relative sea level rise in New York City (the Battery) for 2020, 2050, 2080 and 2100, as presented in Chapter 2 of the NPCC 2015 Climate Change Report,

The results are based on 24 global climate models (GCMs) and 2 representative concentration pathways (RCPs). In this thesis, these scenarios are referred to as a cautious, moderate and extreme scenario. The projections are based on percentiles. For instance, the extreme scenario is based on the 90th percentile of the model outcomes obtained by Horton et al. (2015). 67 out of 70 projections are the same of lower than. Geologic subsidence, groundwater mining, urban runoff and impoundments of reservoirs have been taken into account in these projections. The projections are embedded with uncertainties such as modelling constraints, the random nature of parts of the climate system and limited understanding of some physical processes. The projections must not be mistaken with probabilities.

	Business as usual	Cautious	Moderate	Extreme
2020s	0.06 m	0.025 m	0.1 – 0.2 m	0.25 m
2050s	0.15 m	0.23 m	0.28 – 0.53 m	0.76 m
2080s	0.24 m	0.33 m	0.46 – 0.99 m	1.47 m
2100	0.30 m	0.38 m	0.56 – 1.27 m	1.90 m

Table 4 Observed and estimated sea level rise. (Horton, Little, et al., 2015)

Temperature changes

The NPCC states that higher temperatures are extremely likely for the New York metropolitan area (Horton, Bader, et al., 2015). Table 5 shows the projections based on the NPCC's report. Higher temperatures will result in more evapotranspiration and could change precipitation patterns.

Temperature baseline (1971-2000) <i>12.2 ℃</i>	Cautious scenario	Moderate scenario	Extreme scenario
2020s	0.8	1.1 – 1.6	1.8
2050s	1.7	2.3 - 3.2	3.7
2080s	2.1	2.9 - 4.9	5.7
2100	2.3	3.2 - 5.8	6.7

Table 5 Temperature changes following the NPCC 2015 Climate Change report

Precipitation changes

Precipitation in general varies greatly from year to year. Therefore, the projections shown are relatively small compared to the year-by-year variability (Horton, Bader, et al., 2015). The NPCC projects that annual precipitation will increase over time and these increases will be greatest in winter months. Table 6 shows the projected seasonal changes until 2080 as shown in the NPCC 2015 Climate Change Report. Table 7 shows annual changes until 2100 and is based on the model outcomes of the NPCC 2015 report.

	Low estimate	Middle range	High estimate
	(10th percentile)	(25th to 75th percentile)	(90th percentile)
(a) 2020s			
Winter	-3%	+1% to +12%	+20%
Spring	-3%	+1% to +9%	+15%
Summer	-5%	-1% to $+11%$	+15%
Fall	-5%	-2% to $+7%$	+10%
(b) 2050s			
Winter	+2%	+7% to +18%	+24%
Spring	-1%	+3% to +12%	+18%
Summer	-9%	-5% to $+11%$	+18%
Fall	-2%	+1% to +10%	+14%
(c) 2080s			
Winter	+4%	+10% to $+25%$	+33%
Spring	-1%	+4% to $+15%$	+21%
Summer	-10%	-5% to $+18%$	+23%
Fall	-7%	-1% to $+11%$	+18%

Table 6 Projected seasonal changes in evapotranspiration as shown in the NPCC 2015 Climate Change Report.Source: Horton, Bader, et al., 2015

Table 7 Increase in average annual precipitation. Source: Horton, Bader, et al., 2015

Precipitation baseline 1273 mm (1971-2000, Central Park)	Cautious	Moderate	Extreme
2020s	-1%	+1% - 8%	+10%
2050s	+ 1%	+4 - 11%	+13%
2080s	+ 2%	+5 - 13%	+19%
2100	-6%	-1% - +19%	+25%

The NPCC also reports that the number of days with more than 25.4 mm of rain will increase in the future. Table 8 is based on historical rainfall data and a ranking of 70 model outcomes (35 GCMs and 2 RCPs). It is expected that heavy rainfall events will occur more frequent with increased intensity and duration. The model projections are based on data obtained from weather stations in Central Park, NY. However, the region of the Long Beach barrier island experiences significantly less heavy rainfall events above 25.4 mm a day. Based on historical data from the John F. Kennedy International Airport weather station (NY US COOP: 305803) the average of days with heavy rainfall above 25.4 mm over the period of 1971-2000 is 10.66 days. It is likely that this region will also experience less heavy downpours in the future.

Baseline (1971 -2000, Central Park)		Cautious scenario	Wet scenario	Extremely wet scenario
	2020s			
	At or above:			
13	25.4 mm	13	14 - 15	16
3	50.8 mm	3	3 - 4	5
0.3	101.6 mm	0.2	0.3 - 0.4	0.5
	2050s			
	At or above:			
13	25.4 mm	13	14 - 16	17
3	50.8 mm	3	4	5
0.3	101.6 mm	0.3	0.3 – 0.4	0.5
	2080s			
	At or above:			
13	25.4 mm	14	15 – 17	18
3	50.8 mm	3	4 – 5	5
0.3	101.6 mm	0.2	0.3 – 0.5	0.7

Table 8 Future annual extremely wet rainfall events (number of events per year) Source: Horton, Bader, et al., 2015

Storm surges

During hurricanes and nor'easters, local sea levels rise very sudden. This phenomenon is caused by a strong decline in atmospheric pressure and inward swirling winds that cause an uplift of the water. Such storm surges can cause severe damages along the coast as the waves attack higher up the beach and cause erosion (Tanksi, 2012). Extreme surges can cause widespread floods, comparable with the floods that occurred during hurricane Sandy (figure 2). Depending on the size of the storm, surges can last for hours up to days. For example Sandy's surge lasted for 2-3 days, where the peak of this surge endured for 12 hours with a height of 4 meters above MLLW (Mean Lower Low Water) (figure 14). Hurricanes, tropical cyclones and Nor'easters are expected to become more intense in the future and storms with the likes of Sandy will become the new norm in the future (Yaukey, 2014).



Figure 14 Sandy's storm surge measured at The Battery. Source: NOAA

In a barrier system, storm surges last longer where the barrier-inlets play an important role. Figure 15 depicts the Long Beach barrier island. During a storm, the storm surge will cause higher sea levels on the ocean side of the island causing landward flow of the water, depicted in Figure 15 (upper). As the barrier-inlets are relatively narrow they function like a funnel, impeding the water flow to the bay side of the island. This results in a temporal difference in sea level between the Atlantic Ocean and the bay. After a given period, the water level in the bay equals the surge-level of the Atlantic Ocean.

When the storm has passed, the sea level on the ocean side rapidly decreases to its normal level. As the barrier inlets function as a funnel, this phenomenon results in a difference in sea level but vice versa where now the water flow is in the seaward direction, depicted in figure 15 (lower). This process causes the barrier island to be exposed to higher sea levels for a longer period of time than the mainland often resulting in longer lasting floods on the islands. In addition, during Hurricane Sandy, strong North Eastern winds resulted in even higher sea level on the bay side of the island (Figure 16 and 17³).

In addition, surge levels might have an effect on the groundwater level of barrier islands. It is already known that tidal fluctuations influence the height of the groundwater level. (Ataie-Ashtiani, Volker, & Lockington, 2001; Masterson & Garabedian, 2007; Raubenheimer, Guza, & Elgar, 1999; Xun, Chuanxia, Yanyan, Bin, & Yecheng, 2006). Storm surges might have a similar effect on the groundwater level. Where the groundwater level could be raised for a certain amount of time, depicted in figure 18. Tidal influences diminish land inward from the shoreline, meaning that the influence is likely to take place at the edges of the barrier island (Raubenheimer et al., 1999). In this process, geological properties of the soil play an important role in the extent of the fluctuation land inward.



Figure 15 The role of barrier inlets and the development of water levels during a storm surge

³ Living with the Bay: A Comprehensive Regional Resiliency Plan for Nassau County's South Shore. Design proposal, submitted March 25 2014.



Figure 16 A model developed in Delft3D (Deltares, Living with the Bay design proposal, 2014)) shows that strong North Eastern winds resulted in water levels 4 meters above MLLW



Figure 17 After the hurricane has past water levels in the bay remain higher for several hours (Deltares, Living with the Bay design proposal, 2014),



Figure 18 Schematization of the temporal response of the groundwater level of barrier islands to storm surges

3. Methods

3.1 Urban Vulnerability Assessment for the City of Long Beach

3.1.1 Effects on subsurface structures

The sewer system for the City of Long Beach is approximately 80 kilometers long and services the whole of Long Beach and a part of Lido Beach (\pm 3 kilometers). Most of the collector pipes have a diameter of \pm 15 centimeters. Older pipes are composed of clay tile or concrete, newer pipes of reinforced concrete, transite and PVC. The pipes have a diameter of 120 centimeters when entering the treatment facility. The system flows by gravity with gradual slopes. The City of Long Beach has three pumping stations originating from 1940, 1955 and 1958, of which two stations have seriously deteriorated.

According to a replacement feasibility study commissioned by the City of Long Beach⁴, the collecting system is in very bad shape. Problems include:

- Cracks and open joints and substantial parts of the system lying beneath the groundwater table have led to excessive infiltration;
- The buildup of grease;

⁴ Long Beach Sewage Treatment Plant Aternatives Feasibility Study - 2009; commissioned by the City of Long Beach, prepared by Dvirka and Bartilucci Consulting Engineers

- Many pipes and manholes have deteriorated and lost their slope leading to backflow;
- General sewer failure due to tree root invasion, breaks and degradation of pipe material occur;
- Pumping capacity of pumping stations is not expedient, leading to surcharge upstream.

A common problem related to rising groundwater levels is the uplift of subsurface infrastructure and inground structures such as pools and manholes. Because of their relative light weight compared to their surroundings and acting buoyancy forces these structures are prone to uplift.

Subsurface infrastructure

When groundwater rises to the vicinity of the subsurface infrastructure, buoyancy forces start to act. If the upward hydrostatic force of the groundwater exceeds the weight of the pipes and soil, deformation and uplift occurs. The vertical hydrostatic uplift force can be calculated with equation 1, where *U* is the uplift force in kg per linear meter of pipe, *D* being the outside diameter of the pipe and δ_w the unit weight of water in kg/m³.

$$U = \frac{\pi}{4} D^2 \delta_w \quad (1)$$

In order for the sewer pipe to remain in place the soil overburden and the weight of the pipe must equal the upward vertical hydrostatic force (equation 2). The weight of the pipes varies greatly as many types of materials are used for the construction of subsurface infrastructure such as sewer and drainage lines, water supply pipes and gas pipes. As most of these materials are relatively light compared to their surroundings, they have to be installed on a certain depth to prevent uplift during higher groundwater levels.

$$U = W_{soil} + W_{pipe}$$
 (2)

The weight of the soil overburden W_{soil} (kg/linear meter of pipe) can be calculated with equation 3 where, δ_{dry} is dry unit weight of the soil (kg/m³), H_{dry} is depth of dry soil (m), H_{sub} is depth of saturated soil over top of pipe (m), δ_{sat} is the saturated unit weight of the soil (kg/m³), $\delta_{sat} - \delta_w$ is submerged unit weight of the soil (kg/m³).

$$W_{soil} = \delta_{dry} H_{dry} D + (\delta_{sat} - \delta_w) (H_{sub} + 0.1073D) * D$$
 (3)

For example, when the groundwater level is at the surface, a concrete pipe with an outer diameter of 15 centimetres and a weight of 25 kg/meter needs a cover of only 0.07 metres. In case of the Long Beach barrier island, substantial parts of the subsurface infrastructure are already situated in groundwater and will thus, fortunately, not be affected by uplift or deformation by buoyancy forces.

Table 9 shows typical sewer replacement costs. These costs are based on experiences of people that had to replace sewer lines. The exact costs of replacing sewer lines can vary greatly as soil conditions; surface conditions and wages play a role in the costs.

Table 9 Typical replacement costs of	sewer lines. Source:	home.costhelper.com,	assessed in October 2015.
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Method	Main sewer pipe	Tributary sewer pipe	Manhole
Replacement by trenching	\$50 - \$250/ft.	\$ 105/ft.	\$4600
Trenchless replacement	\$60 - \$200/ft.	\$3.500 - \$20.000/ft.	d.n.a.

Manholes, pools and basements

The same principle applies to manholes and pools but requires a slightly different approach where the sliding resistance must be taken into account. In order for the manhole to start floating, the buoyancy forces must exceed both the weight of the manhole and the sliding resistance. Sliding resistance is defined as the resistance to sliding of one mass to another, in this case concrete and soil. The sliding resistance between non-similar substances is given by equation 4, with P being the total pressure exerted on the manhole (equation 5), *f* is the friction coefficient and $(\pi)(B_d)$ represents the circumference of the manhole. Values for *f* depend on soil material, manhole material and compaction levels. Typical values of *f* for silts are about 0.35, for coarse-grained gravels 0.55.

$$R_{sliding} = P(f)(\pi)(B_d) \quad (4)$$
$$P = \left[\left(K_a \left(\delta_{dry} + (\delta_{sat} - \delta_w) \right) \right) H \right] \left(\frac{H}{2} \right) \quad (5)$$

P, defined by equation 5, depends on $\delta_{dry} + (\delta_{sat} - \delta_w)$ being the combined weight of dry soil and submerged soil, K_a being the active lateral earth pressure (dimensionless) increasing with depth *H*.

So for the manhole to stay in place the sliding resistance and weight of the manhole must be equal or greater than the vertical hydrostatic uplift force, resulting in equation 6. The forces exerted on the manhole are depicted in figure 19

$$U = R_{sliding} + W_{manhole}$$
 (6)



Figure 19 Overview of acting forces on manhole or pool

If the basements or crawl spaces of homes and other buildings are not properly sealed, groundwater could seep into these spaces and cause water damage. The replacement and repair/adjustment costs for

foundations, pools and basements are provided in table 10. These costs are based on experiences from homeowners that made such costs.

Table 10 Typical costs for the replacement, repairs and adjustments of foundations, pools and basements. Source: homeadvisor.com, assessed in October 2015.

Туре	Costs
Foundation repairs	\$1700 - \$5800
Pool repairs	\$250 - \$11600
Waterproofing of basements	\$2100 - \$5800

Effects of replacement on the groundwater level

The majority of the subsurface infrastructure is constructed in the 60's. During the construction of the subsurface infrastructure these forces, most likely, have accurately been taken into account for the situation at that time. However, climate change, most likely, has not been reckoned with. Therefore, in case of structural groundwater rise due to sea level rise, the construction requirements used at the time might become insufficient resulting in uplift, causing deformation or destruction of the infrastructure.

As previously mentioned large parts of the islands sewer system is outdated and leaks. The most obvious

Figure 20 Lifted manhole

Figure 21 Lifted pool

proceeding is to replace those systems with non-leaky laterals. Replacement plans are already on the table (Crystal, Mcnally, & Lake, 2014; Kohan & Licatesi, 2014; Quinn, 2014). It is important to emphasize that replacing leaky sewer laterals will have a large impact on the height of the groundwater table. As leaky sewers can drain excessive amounts of groundwater the height of the water table occurs lower than it would naturally be. Replacing such leaky sewers can thus raise groundwater levels and should be carefully evaluated before proceeding. A possible solution is to replace leaky laterals with non-leaky sewers and place a drainage pipe on top of the sewer to maintain a certain groundwater level.

3.1.1 Effects on surface pavement

During the winter, temperatures frequently drop below 0°C. The JFK-weather station reported 86 days below zero degrees Celsius (32 degree Fahrenheit) in 2014. If groundwater levels rise within approximately 70 cm of the surface frost heave can occur. With freezing temperatures, water rising from the capillary fringe just beneath the surface of roads and sidewalks rapidly freezes creating ice lenses in the subsurface. These lenses cause local uplift and deterioration of the pavement (figure 23). When temperature rises above 0°C and the ice lenses start to melt, holes are left behind that ultimately lead to potholes. Frost heaving can even cause more damage in areas where frost susceptible soils are alternated with non-frost susceptible soils, as depicted in figure 22. As roads are often low-lying areas in the



landscape, groundwater levels are more likely to rise within 70 cm beneath roads, than in other higher lying areas.

Frost heaving can also occur beneath buildings causing damage to the foundation. The City of Long Beach's Department of Public Works already suffers from an excessive amount of potholes in roads that are very expensive to fix. The exact costs for the City of Long Beach are unknown. The repairs of state owned roads in Nassau County have cost the state approximately 1.3 million USD in 2014⁵.



Figure 22 Frost heave in areas with partially susceptible soils



3.1.2 Storm water drainage

The storm water management system on the island is separated from the sanitary sewer. It consists of old open street gutters and a newer underground system, both discharging directly into Reynolds Channel. The street gutters are grouped to form a catchment, where each catchment has its own outfall point. Figure 24 shows the outfall locations of the drainage system for the City of Long Beach.

According to the Nassau County Drainage Requirements, the system has to provide storage for 8 inch of runoff from its tributary area. However, the 2014 NY Rising Community Reconstruction Plans reports of the City of Long Beach, Lido Beach, Point Lookout and both the villages of Atlantic Beach and East Atlantic Beach state that the storm water drainage system works improperly (Crystal et. al. 2014; Kohan & Licatesi, 2014; Quinn, 2014) . The reports for Lido Beach and Point Lookout indicate that the drainage system was not intended for the current amount of development and is undersized. All the reports indicate that a lack of structural maintenance causes the systems to be blocked by debris. The blocking by debris may result in a much smaller drainage capacity than the requirements stated in the Nassau County Drainage Requirements.

⁵ http://www.longislandpress.com/2014/03/09/long-island-potholes-worse-than-last-year/



Figure 24 Storm water drainage outfall points. Source: Coastal Protection Study for the City of Long Beach: Bayside Flood Protection Plan, 2009

Furthermore, the reports state that the elevation of the island causes the slope of the pipes to be insufficient. Because of this, water remains in the system instead of being drained, resulting in streets that are frequently flooded. In addition, backflow into the street occurs during unusual tides and storms. In the City of Long Beach, "Tide flex" valves are installed on some of the outfall pipes in order to prevent backflow from the bay (Figure 25). However, again, a lack of maintenance causes the valves to get clogged by seaweed and algae, or to be held open by debris coming from the system.



Figure 25 Tideflex valve to prevent backflow.

Especially during hurricanes and North Easters, when surges and heavy downpours occur, the system turns out to be inappropriate. The outfalls are submerged by the surge during a time that they are needed to drain unusual amounts of rain, inevitably leading to floods. According to the Lido Beach and Point Lookout 2014 Community Reconstruction Plan report the storm water system was severely damaged during hurricane Sandy in 2012. The hurricane overloaded the system and sand and debris washed into

the system. Currently, as the report states, the system is already overwhelmed by minor rainfall events. All the Community Reconstruction reports thus propose an update of the storm water management system for the current needs.

3.1.3 Effects on plants and trees

A highly saturated soil can affect trees resulting in a wide range of symptoms. The occurrence of symptoms can strongly vary between species, but also within the same species depending on climate and local differences in soil.

Root-zone aeration and microbial ecology

When soils become completely or highly saturated, the air in the soil is replaced by water. An ideal soil condition for the growth of trees and plants generally consists of 50% solids, 25% water and 25% air. However, due to compaction, most soils contain 10-30% air filled pores.

A very important factor in tree and plant growth is a consistent supply of large amounts of oxygen (O_2) for the respiration of the root system. However, urban soils are already strongly compacted, so oxygen supplies are generally not favourable for optimal growth. A higher saturation would further reduce favourable conditions. When oxygen levels drop below 10%, intolerant species may die as a result of prolonged oxygen stress. Some plants tolerate saturated conditions and are able to make physiological and anatomical adaptations to allow them to cope with low oxygen levels (Unger, Kennedy, & Muzika, 2009).

But not only does a near-saturated soil influence the oxygen supply, also the chemistry of the soil changes radically as the gas exchange with the atmosphere stagnates. In sufficiently aerated soils, oxygen used by soil organisms is easily replaced. But in highly saturated soils, the oxygen cannot be replaced and ultimately this will lead to anaerobic conditions in the soil where other gases, produced during metabolic activity of soil organisms, mainly CO_2 and ethylene, accumulate in the soil (Atwell, Kriedemann, & Turnbull, 1999). Once the soil is anaerobic, bacteria that favour these conditions flourish. These bacteria produce energy by catabolism and reduce iron (Fe³⁺), manganese (Mn⁴⁺), and sulphate (SO₄²⁻). The reduced forms of these elements, Fe²⁺, Mn²⁺ and hydrogen sulphide (H₂S) are very soluble and toxic for trees and plants (Atwell et al., 1999; Unger et al., 2009). Also gaseous N₂ and ammonium (NH₄⁺) become dominant and after long anaerobic conditions methane is produced. This chemical change in the soil affects the growth of intolerant species.

Without oxygen, plants and trees lose 85-95% of their capacity to produce energy and their growth stagnates (Atwell et al., 1999). Symptoms generated in anaerobic conditions are leaf chlorosis (yellowing of leafs), defoliation, reduced leaf size and stagnated shoot growth, epicormic sprouting, crown dieback and in the worst case plants and trees will die.

Insects and Diseases

When soils are saturated, water molds are able to attack trees and plants. Water molds cause leafs to become brown and branches and trunks to become moist, leading to decay. Other fungi can cause areas of killed bark on the stem and branches of trees.

In saturated conditions, biochemical defence mechanisms of trees might be triggered; releasing sugar, carbohydrates and other nutrients that attract insects and can cause fungal pathogen attacks (Iles & Gleason, 2008). Examples of insects attacking water stressed trees are phloem and wood borers, who weaken the trunks and branches and can cause the tree to die.

Saltwater Intrusion and floods

Saltwater can affect plant and tree growth in two ways. First it reduces the water uptake by plants. Second, high concentrations of salts can be toxic and reduce growth significantly and can ultimately lead

to the death of plants and trees. As Figure 10 shows, the upper glacial is locally contaminated with saltwater. Higher sea levels may cause a different flow pattern and a different interaction between saltwater and freshwater. Although this research does not focus on changes in the amount of saltwater encroachment, or differences in flow patterns, the presence of saltwater and its effect on vegetation cannot be neglected in a coastal area.

Common Species of Trees and Plants on the Long Beach barrier island

Table 11 is based on a Tree Replanting Master Plan commissioned by the City of Long Beach and provides an overview of common tree species that have recently been replanted on the Long Beach barrier island. This replacement has cost around 1.3 Million USD⁶.

The water tolerance is based on several fact sheets found in horticulture databases of the USDA Forest Service and the University of Florida. Furthermore, the Ellenberg F-moisture values are given for the species mentioned in the Ellenberg database. Based on the factsheets, the species not mentioned in the Ellenberg were given an Ellenberg equivalent. It is important to emphasize that the equivalent values are based on the water tolerance mentioned in factsheets and is not based on the Ellenberg method.

Botanical Name	Common Name	Tolerance to water lodged soils	Ellenberg F-Moisture Value
Acer Rubrum	Red Maple	Very tolerant	9, equivalent
Carpinus betulus	European Hornbeam	Intermediate/intolerant	5
Ginkgo biloba	Ginkgo	Intermediate	7, equivalent
Gleditsia triacanthos	Honeyclust	Intermediate	7, equivalent
Pinus thunbergii	Japanese Black Pine	Intermediate	7, equivalent
Quercus coccinnea	Scarlet Oak	Intermediate/intolerant	5, equivalent
Quercus bicolor	Swamp White Oak	Very tolerant	9, equivalent
Quercus robur	Columnar English Oak	Intermediate/intolerant	5
Quercus phellos	Willow Oak	Very tolerant	9, equivalent
Styphnolobium	Saphora	Intermediate/intolerant	5, equivalent
japonicum			
Taxodium disticum	Bald Cypress	Very tolerant	9, equivalent
Tilia	Linden	Intermediate/intolerant	5, equivalent
Ulmus americana	Elm	Intolerant	3-5
Zelkova serrata	Zelkova	Intermediate	7
Acer campestre	Hedge Maple	Intermediate/intolerant	5
Crataegus crus-galli inermis	Thornless Hawthorn	Intermediate/intolerant	5
Koelreuteria paniculata	Golden Rain Tree	Intermediate	7
Prunus	Cherry	Intermediate	7
Syringa reticulata	Ivory Silk Japanese Tree Lilac	Intermediate	7
Quercus x warei	Kindred Spirit Oak	Intermediate	7

Table 11 Common species. Based on the City of Long Beach Tree Replanting Master Plan

3.1.4 Brownfields and urban runoff

Brownfields are very common in dense urban areas. According to an investigation carried out by Gannett Fleming⁷, possible brownfields are present in the City of Long Beach (figure 26). Most of the industries in

⁶ longbeachny.gov

⁷ City of Long Beach Brownfield Opportunity Areas (BOA) - Pre Nomination Study, 2009
this area hold permits that allow them to produce, work with, or treat hazardous substances and pollutants. Therefore, the area has been assigned a brownfield status. Yet, no research has been conducted that confirms contamination in this area.

When hazardous substances infiltrate into the soil they can ultimately reach the groundwater and pollute it. The hazardous substances generally form a plume. When groundwater levels rise in the vicinity of a brownfield the hazardous substances within the plume can leach into the groundwater more easily and start to migrate, possibly affecting trees and plants and possibly become a serious public health issue. In addition, changes in the shape of the groundwater level can results in higher groundwater velocities that might accelerate the leaching process. In case of the Long Beach barrier island, where the groundwater divide lies in the middle of the island, groundwater beneath the Brownfield Opportunity Area flows towards Reynold's Channel. During its journey towards Reynolds Channel, contaminated groundwater can infiltrate into leaky sewer pipes, ultimately reaching the treatment facility, be taken up by trees and plants, be vaporized or be discharged directly into Reynolds Channel through the storm water drainage system.



Figure 26 Brownfield Opportunity Area assigned by the City of Long Beach

3.2 Assessment on groundwater level change

Based on the findings of Nuttle & Portnoy (1992), McCobb & Weiskel, (2003) and Masterson & Garabedian (2007) it is expected that the water table will rise along with mean sea level. If the groundwater level is deep enough and precipitation surplus remains the same, no change will occur in the height of the water table above mean sea level whilst the unsaturated storage will decrease and groundwater levels will rise relative to the land surface. McCobb and Weiskel (2003) showed that groundwater levels have risen with similar amounts as sea level on Cape Cod, a coastal area with the likes of the Long Beach barrier island. Of course, changing climatic conditions could change this rate for instance due to more evapotranspiration or less precipitation. To investigate the sensitivity of Long Island groundwater levels to sea-level rise and/or climate change, two numerical approaches will be outlined supported by an analytical approach.

3.2.1 Analytical groundwater assessment

The shape and height of the water table and the size of the freshwater lens depend on mean sea level, the density difference between salt and fresh water, the amount of in- and outflow of freshwater, the hydraulic properties of the soil and the width of the island.

The hydraulic freshwater head (piezometric head (\emptyset)) of an aquifer is the sum of the elevation head (z) and the pressure head (h). The hydraulic heads of the aquifers can be used to determine the flow direction and the height of the water table in phreatic aquifers. A freshwater column has a specific pressure at any given point (x, y, z). The pressure increases as a function of depth. Only for saltwater, as it is denser, the pressure at any given depth, is higher. In other words, pressure at elevation z is lower in freshwater than in saltwater.

In coastal areas, the height of the water table above mean sea level and the depth to the fresh/saltwater interface can be estimated using the Badon Ghijben-Herzberg principle, where the vertical pressure is assumed to be hydrostatic and freshwater and saltwater do not mix. This principle can be used together with Darcy's law and the continuity equation to derive an analytical solution for the thickness of the lens, equation 9 (Van Dam, 1983). Subsequently, the density difference is taken into account (equation 8) and the height of the water table can be computed (equation 7).

$$h = \delta H \quad (7)$$
$$\delta = \frac{\rho_s - \rho_f}{\rho_f} \quad (8)$$
$$H = \sqrt{\frac{xN(-x+L)}{\delta K(1+\delta)}} \quad (9)$$

where:

$$\begin{split} h &= groundwater \ table \\ H &= t \ hickness \ of \ the \ lens \ relative \ to \ mean \ sea \ level \\ \delta &= relative \ density \ difference \ between \ fres \ h - \ and \ saltwater \\ \rho_s &= \ density \ of \ saltwater \ (ranging \ from \ 1022 \ to \ 1028 \ kg \ m^{-3}) \\ \rho_f &= \ density \ of \ fres \ hwater \ (1000 \ kg \ m^{-3}) \\ x &= \ horizontal \ coordinate \ on \ the \ island \\ N &= \ rec \ harge \ rate \ \left(\frac{m}{d}\right) \\ L &= \ widt \ h \ of \ the \ island \\ K &= \ hydraulic \ conductivity \end{split}$$

Although this solution gives a sound understanding of the aspects influencing the freshwater lens, it is important to emphasize that aspects such as the miscibility of salt and freshwater are disregarded. Furthermore, in reality, the vertical pressure is not hydrostatic due to vertical flow resistance, for instance induced by layers with a very low conductivity. Significant vertical resistance might affect the shape of the freshwater lens on the outflow sides (Pauw, 2015). Pressure gradients might develop as a result of impermeable layers such as the Gardiners and 20-foot clay underlying the barrier island.

The influence of such an impermeable layer on the groundwater level above mean sea level can be computed with the use of equation 10 (Bakker, 1981). This equation takes a hydrological base into account, for instance a very impermeable clay layer.

 $h^{2}(x) = \frac{N}{k} \left(\frac{L^{2}}{4} - x^{2} \right) + \frac{41}{40} H_{s}^{2}$ (10)

where:

h = groundwater level relative to *h*ydrological base

 $H_s = depth of fresh water lens relative to mean sea level$ x = distance to the middle of the islandN = recharge rate (m/d)L = width of the islandk = hydraulic conductivity

the groundwater level above mean sea level h_g is calculated by subtracting H_s from h.

3.2.2 iMod

iMod is an accelerated, easy to use MODFLOW version made by Deltares. It stands for interactive modelling and facilitates large, high-resolution 3D MODFLOW groundwater computations. iMOD allows input data to be stored at its own resolution. Clipping data to any pre-defined area of interest or pre-processing it to any model grid resolution is not needed. Resolutions of parameters can differ and the distribution of the resolution of one parameter can also be heterogeneous and the spatial extents of the input are allowed to differ. iMOD is able to perform up- and downscaling in case the resolution of the simulation is differs from data resolution (Vermeulen, 2006). The easy to use interface and swift views of model input and output helps the public, stakeholders and regulators to understand and trust the model as a valid decision support tool. For instance, iMod results can be plotted on a map, which can be very helpful when advising policy makers as it gives a clear overview of where problems might occur in any given area. Policymakers are able to use these maps in their policy-making processes.

The model uses so-called .IDF (Data Files) and .IPF files (Point Files). The .IDF files generally contain the hydrogeological properties of the subsurface such as the porosity, hydraulic conductivity and vertical resistance as well as the elevation of the surface, the land use of the island and the permeability of the surface. The .IPF files contain bore logs and groundwater heads on a specific coordinate with specific depth. The .IPF files can be used to construct the subsurface geology based on the layer extinction found in the bore logs.

Structure of the model

The hydrogeological stratification of the subsurface built in iMod is based on hydrogeological plates and maps provided by the USGS and found in literature. In the model, the top and bottom of each layer are defined as well as their conductivity (Chu, 2006; Doriski & Wilde-Katz, 1983; McClymonds & Franke, 1972; Smolensky et al., 1989; Soren, 1971). The surface of the island is defined by elevation data of the island (USGS). Figure 27 gives an overview of this stratiphication and the structure of the iMOD model.



Figure 27 3D-view of the model in iMOD

The recharge is defined by:

where precipitation is based on data from the New York JFK International Airport weather station data (lat/lon 40.63861, -73.76222: COOP:305803). Evapotranspiration data is based on potential evapotranspiration data provided by the Cornell University and reduced with 20% during summer months (see paragraph 3.3). Surface runoff is defined by data on the imperviousness of the soil provided by the USGS and depicted in figure 12.

Mean sea level has been assigned a constant head of 0 meaning that the head remains constant throughout the calculations. The island with its subsurface has been assigned a boundary "1", meaning that the head changes throughout the calculations. Subsequently the model makes its calculation with MODFLOW, changing the groundwater level on the island under influence of a higher sea level or changing climate. Figure 28 gives an impression of the results of such a model.



Figure 28 Impression of iMod results

Density differences and iMod

On islands surrounded by the sea, freshwater floats atop of denser saltwater. The height of the groundwater table on the island is defined by mean sea level, the amount of in- and outflow of freshwater, the hydraulic properties of the soil and the density difference between salt- and freshwater. iMOD is typically used for fresh groundwater modelling and does not incorporate density differences. Based on literature regarding groundwater modelling in coastal areas, disregarding density differences seems unwise (Oude Essink, 2001; Oude Essink et al., 2010; Oude Essink & Schaars, 2002; Pauw et al., 2012). However, modelling the interaction between salt- and freshwater is time costly, complicated and beyond the scope of this research because this study solely focuses on a change in height of the water table and not on changes in the groundwater flow pattern and freshwater-saltwater interface. iMod in combination with MODFLOW-SEAWAT is able to account for these density differences.

Due to technical issues and the time scope of this research, the iMod SEAWAT module could not be used in this study. Although the model built in iMod does not properly work yet, the gathering of data and the model building process in iMod has been an essential and time-consuming part of this study. It helped in understanding the groundwater system of Long Beach Barrier Island and the data gathered provides a solid base for further model development. However, to be able to answer the main research question stated in the introduction a different, less time-consuming approach has been chosen that is also able to incorporate density difference. This approach will be elaborated in the following paragraph, 3.2.3.

3.2.3 PMWIN

PMWIN is a non-commercial MODFLOW interface. The system supports quite a few groundwater and solute transport related codes such as MODFLOW, MT3D, MT3DMS, MOC3D, and PMPATH. In this study MOCDENS3D will be used (Oude Essink et al., 2010; Oude Essink & Schaars, 2002; Oude Essink, 1998; Pauw et al., 2012). MOCDENS3D is a three-dimensional method-of-characteristics groundwater flow and transport model and will be used to incorporate density differences (Konikow, Goode, & Hornberger, 1996; Gualbert H.P. Oude Essink, 1998). PMWIN is able to model in 3D, but this is very time-consuming and asks for a solid modelling experience. For the time scope of this study a 2D model has been built. Thus, it important to emphasize that this model does not account for the whole island, as iMod would have done. The 2D approach uses intersects of the island with a site-specific hydrogeological stratification and the outcomes are only valid on these specific intersects.

Structure of the model

The model that was developed is illustrated in figure 29 and will be discussed below.

A model grid of 330 by 70 cells is used. The width of a cell is 10 meters and the height 0.5 meters. The Gardiners clay layer has been set as the bottom of the model as this aquitard acts as a hydrological base and the aquifers beneath this clay layer play a negligible role in the height of the water table.

The model represents a cross section of the island plus its surrounding water bodies with a width of 3300 meters and depth of 35 meters. The middle 130 cells of the first row have been assigned an active status, being the maximum width of the barrier island. The rest of the cells in the first row, together with the side columns of the model have been assigned a General Head Boundary to allow head-dependent flow on the borders of the model.

The geological data gathered in the iMod model process and also used for the PMWIN approach is unfortunately of a low resolution as they are predominantly obtained from old geological maps, which is sufficient for the deeper geology, but become insufficient for the topsoil. The topsoil is crucial when modeling and assessing groundwater levels and requires higher detail. More detailed data such as driller logs were not available for the island, at least not in large numbers to obtain a sound overview of the topsoil. Therefore assumptions have been made on the type of materials and k-values found in the topsoil. Typical k-values found in the marsh deposits of the Dutch Wadden islands were used. It is known that the topsoil consists of a mixture of beach sands, marsh deposits and other organic material. But the exact thickness of this layer across the island is unknown.

The average hydraulic conductivity of the upper glacial has been set to 80m/d with an anisotropy of 1:10 and an effective porosity of 0.25 (Smolensky et al., 1989). The vertical resistance of the 20-foot clay has been set to 0.003; effective porosity to 0.3, being a typical value for clay (Smolensky et al., 1989). The marsh deposits have been assigned a hydraulic conductivity of 0.01 with anisotropy of 1:10 and effective porosity of 0.3. These values are based on the typical characteristics of marsh deposits found on the Dutch Wadden islands, which have a similar genesis. The dredged materials used to cover the marsh deposits, generally beach deposits, are assigned typical values. The hydraulic conductivity is set to 20 m/d with anisotropy of 1:10, effective porosity to 0.25.



Figure 29 Structure of the model in PMWIN

Accuracy

To test the accuracy of the model, data of the only observation well in the vicinity of Long Beach has been used together with precipitation and evapotranspiration data from this period. Unfortunately, the data from the observation well covers only a period of three years from 2000-2003. Therefore, the model run will only give a very rough indication of the accuracy of the model.

A simulation period is 1995 – 2010 is used and the model outcomes for 2000-2003 are depicted in Figure 30. The model outcomes for spring and fall in the year 2000, spring in the year 2011 and spring in the year 2003 match with only a slight margin of error. The model fails to simulate the right groundwater level for fall 2001, spring 2002 and fall 2003. This could be caused by inaccuracy of the precipitation and evapotranspiration data used or could be caused by assumptions made in the model, such as too homogeneous hydraulic conductivities. Again, the very small amount of reference data limits the value of this accuracy test and only gives a rough indication of the models accuracy.



Figure 30 Model performance

Historical lens development

To simulate the historical development of the lens the initial chloride concentration of the groundwater has been set to 17000 mg/L (saltwater), where the longitudinal dispersion is 0.1 and the transverse dispersion 0.01. The diffusion coefficient has been set to 0.0000864. Courant number has been set to 1. The recharge rate is based upon historical precipitation and evapotranspiration data, presuming that these have been constant over the last 500-1000 years. The recharge rate has been modelled using infiltration wells placed over the width of the island with an injection rate of 0.01, representing 1 mm of average daily aquifer recharge. Paved surfaces, storm water runoff and leaky sewer laterals have not been taken into account as the lens started to develop some 500-1000 year ago, long before the first settlements. The chloride concentration of the recharge has been set to 20 mg/L. The simulation period is 600 years.

Influence of density differences

A model run with freshwater parameters is computed to evaluate the effect of density differences. Instead of 17000 mg/L, an initial concentration of 300 mg/L has been set where the injection well has a concentration of 20 mg/L. The model outcomes were compared to the fresh/salt simulation to evaluate the influence of the density difference on the height of the groundwater table above mean sea level.

Future climate simulation

To simulate future climate changes, a few adjustments have to be made to the input parameters. Paved surfaces have been taken into account, leading to lower recharge values. A 50/50 ratio has been used, where it is assumed that 50% of the rain is discharged into the bay through the storm water drainage system. Furthermore, reports indicate that a substantial part of the sewers on the island are leaky and drain groundwater. To simulate these leaky sewer laterals, the MODFLOW drain package has been used (Harbaugh, Banta, Hill, & McDonald, 2000). The drains are located 1 meter above mean sea level, which is the approximate depth of the pipes. It is difficult to assign a representative value for the hydraulic conductance of the drain based on the information found on leaky sewer laterals. An assumption has been made that the entrance resistance of the leaky sewers equals the conductivity of the surrounding material, being 0.25 m/d. The lens developed in the model described paragraph 3.1.1.1 will be used as the initial concentration distribution for the future climate simulations.

Storm surges

To evaluate the effect of a storm surge on the groundwater level, the surge data from Sandy depicted in figure 10 were generalized and used as "general head boundary conditions". It was assumed that such a surge will not flood the island (e.g. due to a levee). This model run has a timespan of 7 days and all other parameters remain constant. Table 12 shows modelled sea level increase in general head in the Atlantic Ocean and Reynolds Channel, where the water level in Reynold's Channel rises with a one day lag due to the funnel effect of the barrier inlets explained in paragraph 2.6.2.

	Height of surge in Reynold's Channel (m)	Height of surge in the Atlantic Ocean (m)
Day 1	0	0
Day 2	0	2
Day 3	2	4
Day 4	4	4
Day 5	4	2
Day 6	2	0
Day 7	0	0

Table 12 Generalized Sandy storm surge

3.3 Scenarios

Based on the projections presented in the NPCC 2015 Climate Change report, a cautious, moderate and extreme scenario were composed. The scenarios cover a period of 80 years for the 2020s, 2050s, 2080s and 2100. The parameters used in the cautious scenario correspond with the low estimate (10th percentile) NPCC model outcomes, the moderate scenario with the middle range (25th to 75th percentile), and the extreme scenario corresponds with the high estimate (90th percentile).

Future sea levels used in the scenarios are identical to those stated in the NPCC 2015 Climate Change Report, depicted in table 4. The future sea levels were modelled as a "general head boundary" and increase over the projected time period throughout the model runs.

Future precipitation amounts are computed based on average daily precipitation data obtained from the JFK International Airport weather station over the period of 1981-2014 and monthly precipitation increases as stated in the NPCC Climate Change report 2015. The development of precipitation in winter

and summer months is depicted in figure 28 - 30. The graphs cover the development from present to 2100.

Future potential evapotranspiration estimates for each month are based on daily potential evapotranspiration estimates for the JFK International Airport over the period 1981-2014. For each month, average potential evapotranspiration values have been plotted against average temperature records. The monthly relation between temperature and potential evapotranspiration are depicted in annexes 1-12. These relations are used to compute future evapotranspiration as a function of future temperature changes using equation 11, where β represent the relation between temperature and evapotranspiration for each month. Or in other words; β represents the slope of the regression lines plotted in annexes 1-12.

$$ET_{future} = ET_{2014} + \beta (T_{future} - T_{2014})$$
(11)

For winter, spring and fall it is assumed that the actual evapotranspiration equals the potential evapotranspiration. Potential evapotranspiration increases significantly in summers, such that it is not likely that the actual evapotranspiration is equal. For the summer months it is assumed that actual evapotranspiration is 20% lower than the potential evapotranspiration. The development of evapotranspiration is also depicted in figure 31-33.



Figure 31 Average daily precipitation and evapotranspiration projections for summer and winter months in a cautious scenario



Figure 32 Average daily precipitation and evapotranspiration projections for summer and winter months in a moderate scenario



Figure 33 Average daily precipitation and evapotranspiration projections for summer and winter months in an extreme scenario

4. Results & Discussion

The results presented in this chapter must be carefully interpreted. As emphasized in this study, groundwater systems are complex systems where many processes intertwine. To properly understand and evaluate such systems, extensive hydrologic knowledge and field experience is needed. The use of models can be very helpful in understanding groundwater systems, but is also accompanied by uncertainties. When building a model, assumptions have to be made on various topics. These assumptions, if not made carefully, can affect the model outcomes such that they represent anything but reality. The assumptions in this study are deliberate and are made in agreement with experts in the field of hydrology.

4.1 Analytical results

Table 13 gives the groundwater levels on the island following the Badon Ghijben-Herzberg principle of freshwater lenses. Aforementioned in paragraph 2.4 and 3.2, density differences play an important role in coastal groundwater systems and can seriously influence the height of the groundwater table above mean sea level. Table 15 gives the groundwater level on the wider parts of the island under conditions with a homogenous K-value throughout the subsurface of 80 m/d (Upper Glacial). As the density of saltwater increases, the groundwater level rises slightly and the fresh/salt interface gains height and the lens becomes smaller. Due to a very high K-value of 80 m/d, the groundwater level does not react strongly to the changes in density.

Table 13 groundwater levels following the Badon Ghijben-Herzberg principle with different densities of saltwater, where *h* is the groundwater level above mean sea level, *H* is the thickness of the lens relative to mean sea level, ρ_s is the density of saltwater (1022 to 1028 kg m⁻³), ρ_f is the density of freshwater (1000 kg m⁻³), *x* is the middle of the island (675m), *N* is recharge (0.0015 m/d), *L* is the width of the island (1350 m) and *K* is hydraulic conductivity (80 m/d).

	ρ _s 1022	ρ _s 1024	ρ _s 1026	ρ _s 1028
h (m above M.S.L)	0.43	0.45	0.47	0.48
H (m below M.S.L)	20.5	18.6	17.9	17.2

When decreasing the K-value to 30 m/d, groundwater level rises and the influence of density differences slightly increases with 1 cm per 2 $kg m^{-3}$ increases in density (table 14). According to these results, density differences do not have a large impact on the height of the groundwater level compared to other parameters, such as the K-value. As already mentioned in paragraph 3.2.1 this solution disregards aspects such as the miscibility of salt and freshwater. Also, in reality the vertical pressure is not hydrostatic due to vertical flow resistance, for instance induced by layers with a very low conductivity.

Table 14 Groundwater level following the Badon Ghijben-Herzberg principle with different saltwater densities. The hydraulic conductivity K is 30 m/d. All the other parameters are identical to the ones described in the caption of table 7.

	ρ _s 1022	ρ _s 1024	ρ _s 1026	ρ _s 1028
h (m above M.S.L)	0.70	0.73	0.76	0.79
H (m below	31.8	30.4	29.2	28.1
M.S.L)				

Table 15 shows the height of the groundwater table when following Bakker's equation (1981), where a hydrological base is included. The hydrological base is set to 6 meters (average depth of the 20-foot clay layer) and 30 meters (average depth of the Gardiners clay) respectively. The outcomes show that the depth of a hydrological base has a large influence on the height of the groundwater level. In reality, the 20-foot clay layer is discontinuous and not thick enough to act as a hydrological base, the Gardiners clay with a thickness up to 30 meters does. The hydrological base obstructs the lens from reaching greater depths and increases the horizontal groundwater movement. In this analytical approach, the k-value does not have a large influence on the height of the water table whilst in reality this is an important parameter.

Table 15 groundwater level under circumstances with an hydrological base (Bakker, 1981), where h_g is the groundwater level above mean sea level, H_s is the depth the the hydrological base, x is the distance to the middel of the island, N is recharge (0.0015 m/d), L is the width of the island (1350 m) and K is the hydraulic conductivity of 80 m/d)

Depth to hydrological base <i>H_s</i> (m below M.S.L)	6 (20-foot)	30 (Gardiners clay)
h_g (m above M.S.L)	0.08	0.37

4.2 Numerical results: PMWIN

Lens Development

The results presented by Leatherman (1985) indicated that the Long Beach barrier island has stopped migrating some 500-1000 years ago. The current freshwater lenses beneath the island possibly date back to this period. Figure 32 shows that the lens computed in PMWIN is in a steady state after 600 years. The streamlines show a typical flow pattern that can be found within freshwater lenses and that is depicted in figure 11. First the water flows downwards and when reaching the denser saltwater it is forced upward. The fresh/saltwater interface clearly lies on top of the 20-foot clay layer at a depth of 15 meters. The clay layer limits further development of the lens due to its very low hydraulic conductivity and gives the lens its flattened appearance on the bottom.

As Figure 9 indicates, the 20-foot clay layer is interrupted beneath parts of the City of Long Beach and between Long Beach and Point Lookout. The lens development is likely to advance to greater depth in areas where the 20-foot clay layer is absent. Figure 33 shows the lens development in areas without the 20-foot clay layer. What strikes, is the relative small portion of freshwater with concentrations between 0 and 300 of chloride (mg/L) in comparison to the transition zone. Theoretically, it is expected that a clay layer limits the size of the freshwater lens, thereby decreasing the freshwater portion, and thus the freshwater portion in a situation without a clay layer would increase. This model shows partly contrary results. The mixing zone indeed reaches greater depths, but the freshwater portion does not significantly increase. The reason for this can be found in the thicker transition zone where a substantial part of the freshwater starts to mix with the saltwater. In the situation with a clay layer, the vertical water movement is slowed down in the vicinity of the clay layer and turns into horizontal movement. This is also the reason why the transition zone is relatively narrow, as the longitudinal dispersion coefficient (1 m) plays a less important role than the transverse dispersion (0.1 m). In the situation without a clay layer, the water movement is predominantly vertical, to greater depth, as the clay layer does not obstruct it. Here, the longitudinal dispersion coefficient (dispersion in the flow direction) plays a more important role than the transverse dispersion (perpendicular to the flow direction). This results in a wider transition zone with a smaller portion of water with a chloride concentration between 0 and 300 mg/L.

The Badon-Ghijben Herzberg principle indicates that a larger lens would result in a higher groundwater table with a ratio of 1:40. But because the freshwater portion in the lenses is approximately the same, there's no difference in height of the groundwater table in areas without the 20-foot clay layer compared to areas with 20-foot clay presence. The maximum groundwater level is in both situations 2 meters above mean sea level.



Figure 34 Lens aft.er 250 years in a steady state



Time= 600 yr

Figure 35 Lens development in areas without 20-foot clay layer



Figure 36 Lens development on the narrow parts of the island

Figure 34 depicts the lens development on the narrower parts of the island. As the analytical results in paragraph 3.2.2 already indicated, a smaller lens would develop beneath these narrow parts of the island. The model outcomes in PMWIN indeed correspond to the analytical results. Where on the wider parts of the island the freshwater lens reaches depths of around 12-15 meters, the lens on narrow parts of the island reaches a depth of around 8-9 meters. This smaller lens does not reach the 20-foot clay layer and this clay layer does thus not affect its shape. Also the maximum groundwater level is lower on these narrow parts, with a height of 0.82 meters above mean sea level compared to 2 meters on the wider parts of the island.

The influence of density differences on the groundwater table

Figure 35 shows the model outcomes of a density dependent and independent simulation of the groundwater level in areas where the 20-foot clay layer is present. Both model outcomes simulate steady state flow and use identical parameters. The x-axis represents the width of the island with Reynolds Channel on the left side and the Atlantic Ocean on the right side. The red line represents the groundwater table in a density dependent groundwater system. The maximum groundwater level in this situation is 2 m. The blue line represents the groundwater table in a freshwater system without density differences where the maximum water level is 1.913 m. Thus, the model indicates that density differences induce a 10 cm raise in the groundwater level, which is relatively small. The clay layer seems to dampen the effect of the density difference in this situation. As described in paragraph 2.3, the 20-foot clay layer is not present beneath some parts of the island and here the differences in groundwater level would are larger. Figure 36 shows the groundwater levels in a density dependent and independent simulation. It is indeed the case that the clay layer dampens the effect of the density differences; in this situation the difference is 20 cm.

In both situations (with and without presence of the 20-foot clay layer), the maximum level is 2 meters above mean sea level and no difference in the convex shape of the groundwater table can be observed. The model outcomes show that the effect of density differences is bigger in areas without the shallow 20-foot clay layer.



Figure 37 Groundwater levels in areas where 20-foot clay is present



Figure 38 Groundwater levels in areas where 20-foot clay is not present.

Storm surges

Figure 37 and 38 show the outcomes of the model run that simulates a Sandy like storm surge. Figure 37 shows the groundwater change on the narrow parts of the island, figure 38 the effect on the wider parts of the island. On day 2, when the surge comes in, the model outcomes show a clear response of the groundwater level to higher sea levels (2 meter), where especially the Atlantic side of the island experiences higher groundwater levels. On day 3, groundwater levels on the bay side of the island start to respond to the 2 meter increase in water level in the bay. This process continues as the surge increase, where the groundwater response can be observed approximately 160 meters off the shores. On day 6, when the sea level has returned to its normal level but the bay level is still at 2 meters, a groundwater peak on the Atlantic side of the ocean can be observed (illustrated by the orange line). On day 7, when storm surge is over, the groundwater level has risen across the island with approximately 10 cm. The fact



that the groundwater level responds so quickly is likely due to the high hydraulic conductivity of the upper glacial aquifer, which is 80 m/d.

Figure 39 The effect of a Sandy like storm surge on the on the groundwater level on the narrow parts of the island



Figure 40 The effect of a Sandy like storm surge on the on the groundwater level on the wide parts of the island

4.2.1 Influence of sea level rise and climate change on the groundwater level

The model outcomes presented in this paragraph are only valid on intersects with the same width (1350) and a similar hydrogeology (presence of 20-foot clay layer), depicted in figure 27. The City Of Long Beach is predominantly underlain with this hydrogeological stratification.

Cautious scenario

In this scenario unconfined aquifer recharge substantially decreases and is negative from \pm May to August due to increasing evapotranspiration and decreasing precipitation. Figure 28 shows that both summers and winters become drier due to less precipitation and an overall temperature increase of 2.3 °C by 2100. The effects of these climatic changes on the groundwater level based on the model outcomes are outlined below.

Figure 39 shows the groundwater level across the island during the winter months of 2014, the 2020s, 2050s, 2080s and 2100.

By 2030, this leads to a substantial decline in the groundwater levels found on the middle of the island, relative to mean sea level. This groundwater level decline is predominantly driven by climate change that leads to lower recharge rates. At the same time an increase in groundwater level can be observed on the shores of the island, where groundwater levels are predominantly driven by the sea level, which increases. Due to these processes the overall shape of the groundwater level becomes less convex over the years, meaning that the hydraulic head gradient decreases. While this happens, also the height of the groundwater level relative to mean sea level decreases. A lower hydraulic head gradient results in a reduction of groundwater flow velocity. Over the period of 2030 to 2100, groundwater levels start to rise again due to continued sea level rise, however, the maximum groundwater level of the island remains lower than the current levels as climate changes induces a less convex groundwater shape, making it flatter.



Figure 41 Groundwater levels in winter months under the conditions of a cautious scenario

Figure 40 shows the groundwater levels across the island in summer months. The figure clearly shows the same changes in the shape of the groundwater table, even more extreme; a strong decline of the groundwater levels on the middle of the island, and a substantial rise on the sides of the island. As the increase in evapotranspiration between 2030 and 2050 is even higher than in winter months, the decline in the groundwater levels on the middle of the island is even stronger in summer months, up to 30 cm by 2050.



Figure 42 Groundwater level in summer months under the conditions of a cautious scenario

Moderate Scenario

This scenario projects a temperature increase of 4.5 °C by 2100. Figure 29 shows the development of precipitation and evapotranspiration throughout this scenario. Increasing temperatures lead to substantially more evapotranspiration around the 2030s, especially in spring and summer, the active growing seasons of vegetation. Annual precipitation amounts from ± 1090 mm/year to ± 1200 mm/year, which is similar to present day amounts. Evapotranspiration values will increase to 1035 mm by 2080 and decline to 950 mm by 2100.

Figure 41 shows the groundwater levels in winter months for 2014, the 2030s, 2050s 2080s and 2100. Similar to the previous scenario, a reduction in hydraulic gradient can be observed. As the sea level rises more quickly in this scenario, groundwater levels on the shore also rise quicker. The increase in height of the water table on the sides of the island is more than 50 cm by 2100. Where on the middle of the island, the water table rises with ± 11 cm to a maximum groundwater level of 1.39 meters above mean sea level. The leaky sewer laterals that are incorporated in this model are increasingly visible in the shape of the groundwater level. As the groundwater level rises, leaky laterals start to drain more groundwater, creating smaller convex shape in the global shape of the groundwater level.



Figure 43 Groundwater levels in winter months under the conditions of moderate scenario

During summer months, the groundwater level significantly decreases (figure 42). The model projects that by 2100 the sea level rises with such heights that it exceeds the hydraulic groundwater heads on the island. This leads to a concave groundwater shape. A concave groundwater shape would mean that groundwater will flow in the direction of the island and this will lead to an inflow of seawater and an increase in saltwater intrusion in the upper aquifers of the island.



Figure 44 Groundwater levels in summer months under the conditions of moderate scenario

Extreme scenario

In this scenario, temperature increases with 6.7 °C by 2100. Figure 30 shows how precipitation and evapotranspiration change over time. Annual evapotranspiration increases significantly to 830 mm in 2030 to 1315 mm in 2100. Precipitation increases to 1370 mm in 2100. Both summers and winters become increasingly dry in the 2050s. Sea level rise is most extreme in this scenario, rising with 1.9 m by 2100. If no flood protection will be built, this rise will lead to a permanent flooding of significant parts of the island (depicted as the dark blue areas in figure 43). This permanent flood will make the island smaller and saltwater will infiltrate on the land surface raising the groundwater level. Under such circumstances the boundary conditions of the model do not apply and therefore, the groundwater level response in 2080 and 2100 are dashed as these model outcomes are not accurate.



Figure 45 The dark blue colour indicate the areas that would flood if no flood protection is built and sea level rise to 1.9m, projected in the extreme scenario

Aquifer recharge will decrease in the 2050s during winter months. Over the years the shape of the groundwater table will flatten out in both summers and winters, similar to the other scenarios, shown in figure 44 and 45.



Figure 46 Winter groundwater levels under the conditions of an extreme scenario.



Figure 47 Summer groundwater levels under the conditions of an extreme scenario.

4.3 Urban vulnerability assessment

The urban vulnerability of the City of Long Beach has been assessed using the changes in groundwater level presented in the previous paragraph. As mentioned above, the model outcomes presented in this paragraph are only valid on intersects with the same width (1350) and a similar hydrogeology (presence of 20-foot clay layer. The area depicted in figure 47, 48 and 49 has a width of approximately 1350 meter and the 20-foot clay layer is present, and thus our model outcomes are valid in this area. However, in reality the groundwater levels might differ under the modelled climatic conditions due to differences in the topsoil or perforations of the 20-foot clay layer that have not been taken into account in this model. To be able to model this more accurately and to be able to assess how the groundwater is spatially distributed, high resolution geological data is needed and a 3D-model approach should be developed to assess the vulnerability of the Long Beach barrier island more accurately.

Subsurface infrastructure, pools and basements

The model outcomes presented in paragraph 4.2.1 show that the seasonal changes in groundwater level become more extreme as a result of climate change. The groundwater cycles projected in the moderate and extreme scenario can cause increased stress on subsurface infrastructure as groundwater levels in winter might rise above the subsurface infrastructure and drop below the infrastructure in summer months. Depending on the exact depth and type of infrastructure, this might cause deformation of infrastructure or subsurface structures such as pools and basements as described in paragraph 3.1. Pools, which are very popular on the island, become more susceptible to uplift or damage with the projected higher groundwater levels. Especially during the winter when groundwater rise is greatest and pools are often emptied. The higher winter groundwater level projected by the model also can lead to a higher susceptibility of basements and crawl spaces to water damage and floods, especially if not properly sealed.

As described in paragraph 3.1.1, replacing leaky sewer system can have a large impact on the height of the groundwater level. Plans to replace the old and leaky sewers on the island are already on the table and this would stop the excessive groundwater draining on the island and will increase the groundwater level. Figure 45 shows how the groundwater level responds to the replacement of leaky laterals in a moderate scenario. According to the model outcomes, in a moderate scenario this would result in an increase of ± 1 meter by 2100, ± 0.5 meter by 2080 and ± 0.3 meters by 2050 and 2030 during winter months. As the location of leaky laterals and the exact amount they drain is unknown, the draining effect might be over or under estimated in this model. If so, this could result in a different response of the groundwater level.



Figure 48 groundwater levels in a situation where leaky sewer laterals are replaced and excessive drainage has stopped.

Surface pavements

The model outcomes in a moderate scenario by 2100 show that roads will become more susceptible to frost heave in the future, if the amount of days where temperatures drop below zero degrees Celsius remain the same. Figure 47 shows the areas where according to the model outcomes the groundwater level rises to within 70 cm below the surface. One can observe that this often happens below roads on the northern part of the island, which naturally has a lower elevation than the southern part. In some areas, the groundwater level rise in winters will reach the surface that might leads to floods, for instance on Eastern Pine Street, which has a low elevation.



Figure 49 Depth to groundwater table in a moderate scenario by 2100 where the width of the island is approximately 1350 meters and the 20-foot clay layer is present.

Plants and trees

As mentioned in paragraph 3.1.3, the City of Long Beach has commissioned a large tree-replanting scheme. The trees included in that scheme are six intermediate water intolerant and water intolerant species, depicted in table 11. The planned location of intolerant species areas with high groundwater levels is depicted in figure 48. The European Hornbeam, Scarlet Oak, Columnar English Oak, Linden and Hedge Maple are intermediately intolerant to highly saturated soils. The model outcomes indicate that these species are planned in areas that might experience higher groundwater levels in the future. The Elm, an intolerant species is also planned in this area. As described in paragraph 3.1.3, it is hard to give the likelihood of symptoms that might occur in waterlogged soils as this van differ from species to species and even within the same species.



Figure 50 Replanted tree species together with groundwater levels that would occur by 2100 in a moderate scenario

Storm water drainage system

As the sea level rises the storm water drainage will become less effective. The outlets currently discharge just above the sea level. Already, during storm surges the outlets are drowned and are not able to drain storm water as effectively as above water. If sea levels permanently rise, the outlets could also be permanently drowned. This would have large consequences for the City of Long Beach in times of heavy downpours, as these could lead to floods in that situation.

Brownfields

The City of Long Beach has a relatively large area with possible brownfields (depicted in figure 24). Figure 49 shows that these brownfields are located in areas that might experience higher groundwater levels by 2100. Migration of contaminants can occur over time, but this is hard to evaluate as the area is assigned a "possible brownfield" status. Although, the groundwater level increases, the model outcomes also showed that the hydraulic head gradient decrease, which results in a decrease in the speed of the groundwater flow towards Reynolds Channel. This could slow down the spread of contaminants.



Figure 51 Location of potential brownfield areas together with the groundwater level that would occur by 2100 in a moderate scenario.

5. Conclusion & recommendations

Their meagre elevation above the sea and their location in front of the mainland makes that Barrier coasts are among the most vulnerable areas when assessing climate change and sea level rise. Barrier coasts are very prone to floods and a first line of defence against the natural violence of hurricanes and nor'easters. This thesis aimed to gain a broad and better understanding of the effects of sea level rise and climate changes on the groundwater level of the Long Beach barrier island, where the main question is: *how does the groundwater level of the Long Beach barrier island respond to sea level rise and climate change and how these changes can affect the City of Long Beach*?

The study showed that climate change and sea level rise could have a great impact on the groundwater system of the Long Beach barrier island. As temperatures are expected to increase up to 6.8 $^{\circ}C$, the recharge of the aquifers on the island will decrease in the future. Less recharge would mean a decline in groundwater levels on the island. However, due to the fact that the groundwater level on islands is directly related to the sea level, and the sea level rises, groundwater levels will rise. Together, these two processes will lead to a less convex shape of the groundwater and a decline in the groundwater level relative to mean sea level. The groundwater level relative to the surface, also known as depth to groundwater, is expected to decrease especially in winters and this might cause groundwater related problems in the future. As evapotranspiration will increase in summers, groundwater level will increase in this season. The model outcomes show the seasonal differences in groundwater level will increase in the future.

According to the model outcomes, the most cautious climate change and sea level rise projections will result in a slight decline of the groundwater levels on the middle of the island during winter months by, 2100. This decline in the groundwater level is driven by climate change. On the shores, groundwater levels will rise as a result of sea level rise. Both these changes lead to a less convex shape and a decline in the groundwater level relative to mean sea level in both summer and winter months. This change in convex shape, or change in hydraulic head gradient will lead to a reduction in the groundwater flow velocity in the direction of the sea and Reynolds Channel.

The moderate sea level rise projections and climate change scenarios will increase groundwater levels both on the middle of the island and on the shores. Although climate change imposes the same change in the convex shape, groundwater levels on the middle of the island will rise and come closer to the surface. According to the model outcomes, the shores will experience an increase of the groundwater level up to 100 cm by 2100 in a moderate scenario, where the middle of the island experiences an increase of approximately 10 cm.

In an extreme scenario the groundwater levels at the shores experience a rise in groundwater level of approximately 70 cm by 2050 and the middle of the island approximately 20 cm. The sea level rise projections in the extreme scenario by 2080 and 2100 are very severe and will flood parts of the island permanently if no flood protection is constructed.

This study also shows that groundwater levels at the shores respond quickly to storm surges with the likes of Sandy's storm surge. The model outcomes show that the groundwater level increased approximately 80 cm, 70 meters from the shore during the peak of the surge. The model outcomes also showed that once the storm surge is over, groundwater levels remain higher in the order of 10 cm and quickly recovers afterwards.

Due to these changes in groundwater levels, the City of Long Beach might become more susceptible to groundwater related problems. The north side of the city has a lower elevation above N.A.D. (approximately 1.5 - 2 m) compared to the south side (approximately 3.5 - 4 m) and according to the

model outcomes, the north side of the city might experience more groundwater related problems than the south side of the island. As groundwater levels, in a moderate and extreme scenario, will come closer to the surface in the northern part compared to the southern part of the city, they might have a large impact on the subsurface infrastructure, urban nature and surface pavements in this area. Also, higher groundwater levels could increase leaching of soil contaminants at the potential brownfields of the city.

In addition, as the seasonal differences increase, the subsurface infrastructure of the city might be exposed to temporal buoyancy forces, possibly leading to more damage to infrastructure in the future. Leaky sewer laterals already cause significant and unwanted infiltration of groundwater in these laterals. Plans to replace these leaky sewers must be carefully evaluated, as the model outcomes show, that this will increase the groundwater level significantly. In addition, as the model outcomes show that in winters, groundwater levels significantly increase, uplift and damage to pools might occur as these are often emptied in winter months.

As the groundwater levels increase in the cold winter months, roads and other pavements become more susceptible to frost heave, creating potholes in the roads. According to the model outcomes, roads on the north side of the island are more susceptible as this part of the island.

This study also indicates that water intolerant and intermediately tolerant trees are planted in areas that might experience higher groundwater levels in the future. These trees might become more susceptible to leaf chlorosis (yellowing of leafs), defoliation, reduced leaf size and stagnated shoot growth, epicormic sprouting, crown dieback and in the worst case these trees could die. However, the impact on trees varies from species to species and even within species, so it is hard to assess the exact impact of saturated soils on these trees.

To get a better and more detailed overview of the magnitude of the groundwater related problem a few improvements have to be made in the model approach and input and more research has to be done on the urban vulnerability potential. As mentioned earlier, iMod in combination with the MODFLOW-SEAWAT module would be able to compute the changes in groundwater level in more detail and is able to add a spatial component that could potentially give better insights in where on the island future problems might occur. The recommendations are listed in the following bullet points.

Recommendations:

- 1. Detailed driller logs of the topsoil could help in increasing the accuracy of the model outcomes. 5 drill rows across the width of the island would be sufficient to get a better understanding of the topsoil of the island.
- 2. Detailed seasonal groundwater level data of the island could help in validating the model outcomes and can be used as initial input for the model. The boreholes mentioned above can be transformed into monitoring wells that can take measurements for phreatic groundwater as well as pièzometric heads of the deeper aquifers;
- 3. Gaining information on the amount of groundwater drained by leaky sewers could help in better understanding the effects of sewer replacement and how to cope with the problems caused by replacement.
- 4. Using this additional information in iMod and MODFLOW SEAWAT will be beneficial for the usability of the outcomes due to the spatial component.
- 5. More detailed numbers could be obtained on the costs of certain damages, for instance by means of interviews with insurance companies
- 6. Applying a full water balance equation for the island will also be beneficial in assessing the impact of higher groundwater levels on the island.

Besides answering the research question, this study has helped in better understanding the groundwater system and morphological origin of the Long Beach barrier island. Applying this type of assessment on more barrier islands could help in better understanding the effects of climate change and sea level rise on barrier coasts and could give better insights in potential damages.

6. References

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7. Appendix



Appendix 1



Appendix 2



Appendix 3



Appendix 4



Appendix 5



Appendix 6


Appendix 7



Appendix 8



Appendix 9



Appendix 10



Appendix 11



Appendix 12