ASSESSING THE SHALLOW GROUNDWATER SYSTEM AS A POTENTIAL FACTOR IN GENERATING STORM-WATER RUNOFF ON A NORTH CAROLINA BARRIER ISLAND

By:

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The town of Emerald Isle, located in North Carolina’s Outer Banks, experiences significant storm-water runoff and flooding problems during the fall and winter months. The topography of the island influences drainage patterns as well as the position of the water table. The goal of this study was to determine if the shallow groundwater system is responsible for storm-water runoff on the island. Two hypotheses were developed to test the relationship between the water table and storm-water runoff. The first hypothesis states: the water table rises above the land surface during periods of high precipitation, which leads to storm-water runoff in the town. The second hypothesis states: low infiltration rates in the swales of the island impede water from recharging the Surficial aquifer. The first hypothesis was tested by monitoring the position of the water table in the Surficial aquifer over a 12-month period using a network of 15 shallow groundwater monitoring wells. Potentiometric surface maps of the aquifer show that the water table does breach the land surface during storm events that produce at least 25 mm of precipitation. The second hypothesis was tested by conducting infiltrometer tests to determine if low infiltration rates were retarding natural recharge to the groundwater system. These tests reveal that the soils located in small portions of the swales have the lowest infiltration rates on

the island, making it more likely for storm-water runoff to be generated. A 3D finite-difference groundwater model was then used to determine if pumping water from the aquifer during extreme storm events (e.g., hurricanes) would alleviate an elevated water table. Numerical and analytical modeling results suggest that pumping water from the aquifer may be impractical for the town to employ because it is only a short-term solution to the storm-water problem. Therefore, several structural best management practices (BMP's) are presented as alternative measures to reduce storm-water runoff. These structural BMP's are ideal for the needs of the town, and they include bioretention, level spreader-vegetative filter strips, and infiltration basins/trenches.

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A Thesis

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By:

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DEDICATION

This thesis is dedicated to my late grandmother, Norma Sisco. Although you passed before I began this journey, I know you would have been proud.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my family for giving me a seamlessly never-ending amount of support throughout this entire process. To my mother, father, and sister: you helped me more than you will ever know.

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I would like to thank Frank Rush and the Town of Emerald Isle for help funding this project, and allowing us to conduct research on a truly beautiful island. I hope these findings will benefit the town in the future.

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LIST OF SYMBOLS AND ABBREVIATIONS

m	Meters
r^2	Coefficient of determination
Sy	Specific yield
Δh	Change in hydraulic head
Δt	Change in time
K_x	Hydraulic conductivity in the x (horizontal) direction
K_y	Hydraulic conductivity in the y (horizontal) direction
K_z	Hydraulic conductivity in the z (vertical) direction
ΔS	Change in groundwater storage
ΔWL	Change in water level
GPM	Gallons per minute

CHAPTER 1: INTRODUCTION

The town of Emerald Isle, which is located on Bogue Banks (Fig. 1), experiences significant storm-water runoff during the fall and winter months. This is primarily a function of increased precipitation, the position of the water table, topography, geology, and the development of more impervious surfaces. A previous study by Moffat & Nichol Engineers (1997) found that the topography characterized by dunes and swales directly influences the hydrology and drainage patterns on the island. The construction of impervious surfaces such as roads, houses, and gutters has significantly altered the natural drainage patterns in Emerald Isle, (Moffat & Nichol Engineers, 1997). This increase in impervious area can reduce infiltration to the shallow aquifer system and lead to more storm-water runoff (Arnold and Gibbons, 1996). Rather than focusing solely on the storm-water runoff that Emerald Isle experiences, this study sets out to determine the influence of the shallow groundwater system on storm-water generation, as well as the relationship between the water table and the topography on the island.

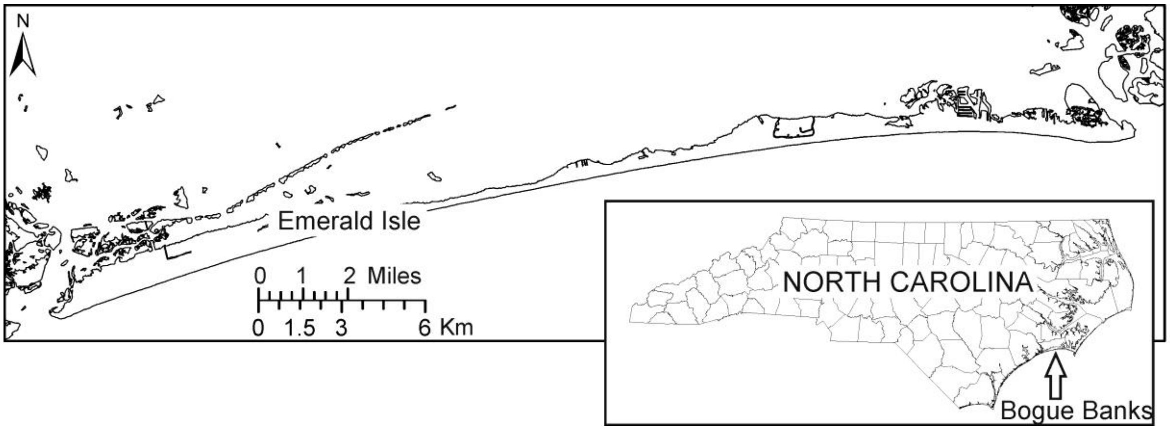

Figure 1: Map showing the Town of Emerald Isle on Bogue Banks. Inset: Arrow indicates the location of Bogue Banks off the coast of North Carolina.

Light Detection And Ranging (LiDAR) data show that the elevation of the island ranges from 0 m to 16.5 m (45 feet) above mean sea level (AMSL). The higher elevations represent dunes that lie parallel to the long axis of the island, while lower elevation swales are present in between these longitudinal dunes. The largest dunes are located in the south whereas the smallest dunes are in the northern parts of the island. According to studies conducted by other workers, the swales act as the natural discharge zones for the island (e.g., along Coast Guard Road) (Moffat & Nichol Engineers, 1997). These areas, particularly those located along Coast Guard Road (Fig. 2), experience periodic flooding events that impact the residents in that part of the town.

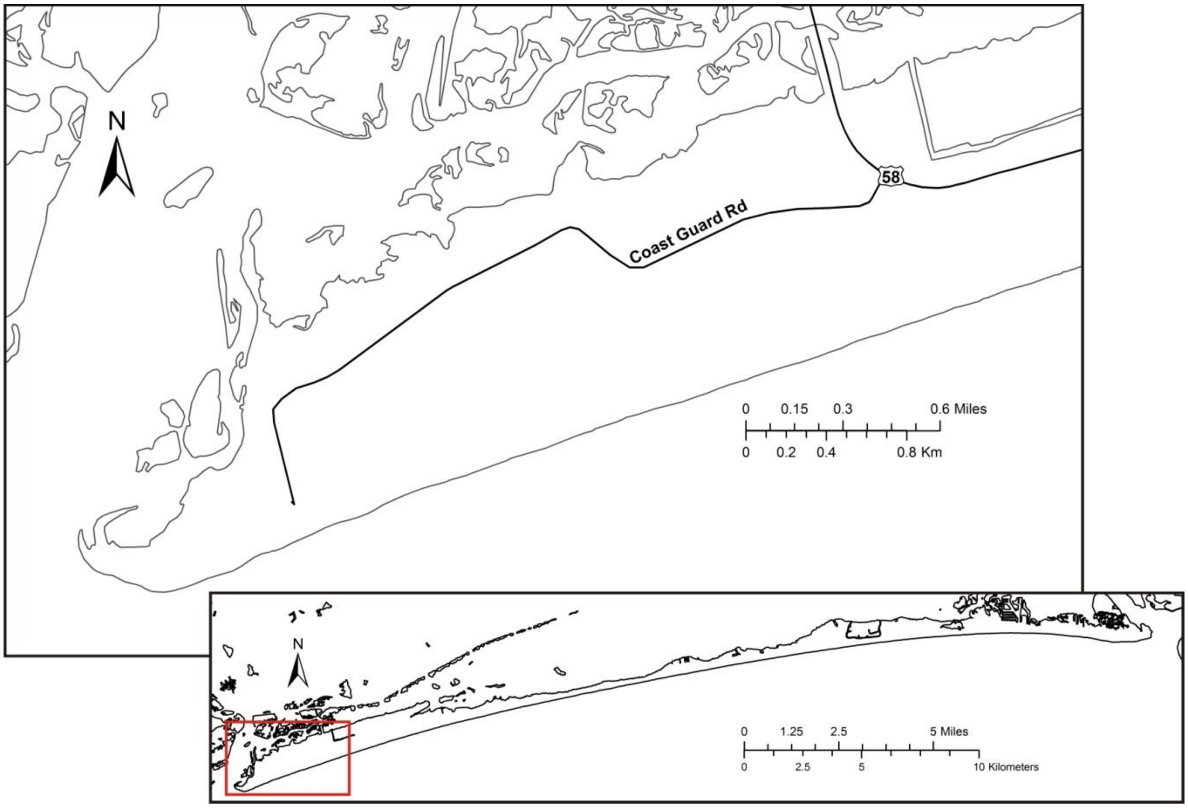

Figure 2: Map showing the study area on the western part of Emerald Isle in the vicinity of Coast Guard Road. Inset: Bogue Banks with a red outline identifying the study area.

1.1 Purpose and Scope

The goal of this study is to characterize the shallow groundwater system on the western side of Bogue Banks and determine how the system contributes to storm-water generation within the study area. Through the collection of water level, precipitation, and hydrogeologic data, the research will seek to accomplish the following objectives:

1) Derive and evaluate the physical properties of the Surficial aquifer.
2) Monitor the position of the water table and characterize groundwater flow patterns.
3) Estimate components of a water budget for the study area.
4) Determine the influence of the water table fluctuations on storm-water runoff.
5) Assess alternatives of managing storm-water problems and/or lowering groundwater.

The data that were collected were used to test two hypothesis related to the position of the water table and storm-water runoff. The hypotheses that were tested in the study are as follows: (1) the shallow water table rises above the land surface, particularly in the lower-lying swales, during periods of significant recharge, and (2) the infiltration rates of the soils reduce the recharge potential during storm events in low-lying areas. When infiltration rates impede the natural recharge of the soil, storm-water runoff has the potential to be generated.

1.2 Significance

Previous work (Moffat & Nichol Engineers, 1997) that looked at the groundwater system on the island did not utilize time-series data of groundwater level measurements, which are important for understanding spatial and temporal variations of groundwater flow. Not having these data can in turn affect the accuracy of a model that is created for characterizing the Surficial aquifer and providing solutions for storm-water management (Taylor and Alley, 2001).

Studying the configuration of the water table and the properties of the Surficial aquifer can reveal potential areas where flooding induced by a shallow water table may be expected. In addition to the groundwater table characteristics, other factors influencing groundwater levels in the Surficial aquifer must be considered. These include precipitation, evapotranspiration, runoff, and topography.

Depth-to-groundwater measurements are important to study for two main reasons: determining the groundwater flow pattern for the study area, and estimating the amount of interaction between groundwater and surface water. This relationship is important for understanding how long it would take rain events to naturally drain into the ground, ultimately discharging into the ocean or any large body of water (Heath, 1994). Due to the presence of dunes and swales on Bogue Banks, the percolation rate is a major limiting factor for the recharge rate of precipitation (Heath, 1994). Other primary controls on recharge and water table elevations that will be investigated include infiltration rate, land cover, evapotranspiration, water-table depth, and soil type. This study will characterize how groundwater levels may influence storm-water generation, as well as how possible solutions to alternative storm-water management practices can be addressed.

1.3 Background

1.3.1 Previous work

There have been several studies conducted where hydrogeologic characteristics of barrier islands have been investigated. For example, Winner (1975) and Heath (1988) characterized the available ground-water resources, hydraulic properties, and salt-water encroachment on Hatteras Island for the Cape Hatteras Water Association. Working on the same island, Anderson (2000) calculated hydraulic properties of the island and investigated the relationship between progradational barrier island morphology and water-table elevations in the underlying stratigraphy. In particular, Anderson found that this progradation influences the soil properties in locations where lower-permeability swales have been covered up by dunes over time. Burkett (1996) estimated several hydrogeologic parameters within the Buxton Woods surficial aquifer at Cape Hatteras. The hydrogeologic parameters estimated in these studies, particularly hydraulic conductivity, were vital to the current study, and were used to verify slug tests results conducted on Bogue Banks. The hydraulic conductivity of the Surficial aquifer on Hatteras Island was very similar to those estimated within Bogue Banks.

Other regional studies have been conducted on the shallow groundwater system. Harden et al., (2003) studied the hydrogeology and groundwater quality of the Surficial aquifer in Brunswick County, NC, located southwest of the study area. A water budget conceptualized for Brunswick County estimated a similar ratio of precipitation to groundwater recharge to the surficial aquifer. Harden et al. (2003) also found no evidence of long-term trends in water level data. An absence of trends in regional water resources of the Surficial aquifer should implore further research to be conducted. This report, along with Anderson’s (2000) on Hatteras Island, reported on similar parameters measured in this study. These parameters helped justify values calculated in the study area. An analytical study conducted on strip-islands used the Dupuit-Ghyben-Herzberg analysis to estimate the position of the water table and salt-water interface on islands based on their geometry, distribution of hydraulic conductivity, and recharge variability (Vacher, 1988).

Moffat & Nichol (M&N) Engineers conducted a site study in Emerald Isle in 1996. The focus of this study was to identify alternative solutions to mitigate flooding problems under the current storm-water regulations. The solutions were then put through a cost/damage ratio analysis to determine which solutions would reduce the damages the most. However, the M&N report did not address two important issues: 1) the shallow groundwater system was not monitored over time, and 2) the alternatives did not include conservative non-structural and structural Best Management Practices (BMP's) that would benefit residential properties within the study area. The present study addresses these concerns in greater detail and in so doing, will improve our understanding of the role that shallow groundwater systems play in influencing storm-water runoff on barrier islands.

1.3.2 Hydrogeology

The hydrogeologic framework of eastern North Carolina is divided into nine aquifers. Nine confining units separate the aquifers, which range in age from Holocene to Cretaceous (Winner and Coble, 1996). The aquifers, which gradually increase in dip and thickness towards the east (Fig. 3), are part of a series of obliquely stacked marine terraces (Brown et al., 1972). A basement complex of Paleozoic age rocks lies beneath the terraces, which run parallel to the Atlantic Coast (Clark et al., 1912; Nelson, 1964; Lautier, 2009). An escarpment, the Suffolk scarp, bounds this hydrogeologic region to the west, which runs north to south from Washington County to the western edge of the study area (Brown, 1985; Mallinson et al., 2008).

The stratigraphic column of this region is subdivided into geologic formations based upon their depositional environment, with sediments, lithology, and faunal composition separating the varying members (Brown, et al., 1972). These deposits have been characterized into aquifers and their respective confining units by the delineation of non-permeable versus hydraulically connected permeable units, with some boundaries not always corresponding to certain geologic boundaries (Table 1) (Lautier, 2009). The names of the aquifers are (from youngest to oldest) the Surficial, the Yorktown, the Castle Hayne, the Beaufort, the Peedee, the Black Creek, the Upper Cape Fear, the Lower Cape Fear, and the Lower Cretaceous and/or Undifferentiated (Winner and Coble, 1996).

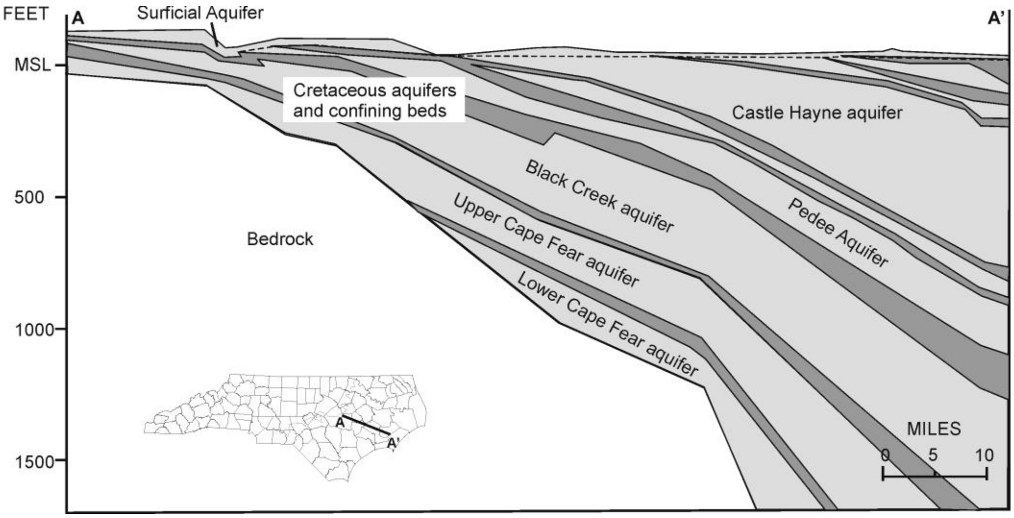

Figure 3: Hydrogeologic section showing the aquifer system of the North Carolina Coastal Plain (Adapted from Winner and Coble, 1996 and Heath and Spruill, 2003).

The Surficial aquifer is a water table aquifer, meaning that it is an unconfined aquifer that is in direct communication with the atmosphere (Fig. 3). The aquifer is the upper layer of sediments, which overlies much of the North Carolina Coastal Plain. The sediments, ranging in thickness from ~6 m to ~60 m, consist mostly of sand with some minor deposits of silt, clay, and peat beds (Ingram, 1987). The Surficial aquifer also consists of older sediments, which depend on the stratigraphic position of the underlying formation these sediments were deposited on (Wilder, et al., 1978).

Table 1: Geologic framework of the North Carolina Coastal Plain, and their respective hydrogeologic units (Adapted from Lautier, 2009).

North Carolina East Central Coastal Plain Geologic Units			**North Carolina East Central Coastal Plain Hydrogeologic Units**
System	Series	Formation (Fm.)	Aquifers, stratigraphically below their respective confining units (not shown)
Quaternary	Holocene	Undifferentiated	Surficial Aquifer
	Pleistocene		
Tertiary	Pliocene	Yorktown Fm.	Yorktown Aquifer
	Miocene	Pungo River Fm.	
	Eocene	Castle Hayne Fm.	Castle Hayne Aquifer
	Paleocene	Beaufort Fm.	Beaufort Aquifer
Upper Cretaceous		Peedee Fm.	Peedee Aquifer
		Black Creek Fm.	Black Creek Aquifer
		Cape Fear Fm.	Upper Cape Fear Aquifer
			Lower Cape Fear Aquifer/Lower Cretaceous Aquifer Undifferentiated
Lower Cretaceous			

Even though the Surficial aquifer is one of the thinnest of all the aquifers, it is an extremely important aquifer because it receives direct recharge from precipitation and in some places is the major source of water for underlying aquifers and baseflow to streams in the Coastal Plain (Giese et al., 1997). Since there are no streams within the study area, the Surficial aquifer groundwater would likely discharge to canals, ponds, estuaries, and the ocean. Along the coast and the Outer Banks, the Surficial aquifer is an important groundwater resource because saltwater intrusion affects the water quality in the deeper aquifers in these areas (Heath and Spruill, 2003). However, in Emerald Isle, the deeper Castle Hayne aquifer is the source of potable water. The water from the Castle Hayne aquifer may eventually recharge the Surficial aquifer via onsite wastewater treatment systems.

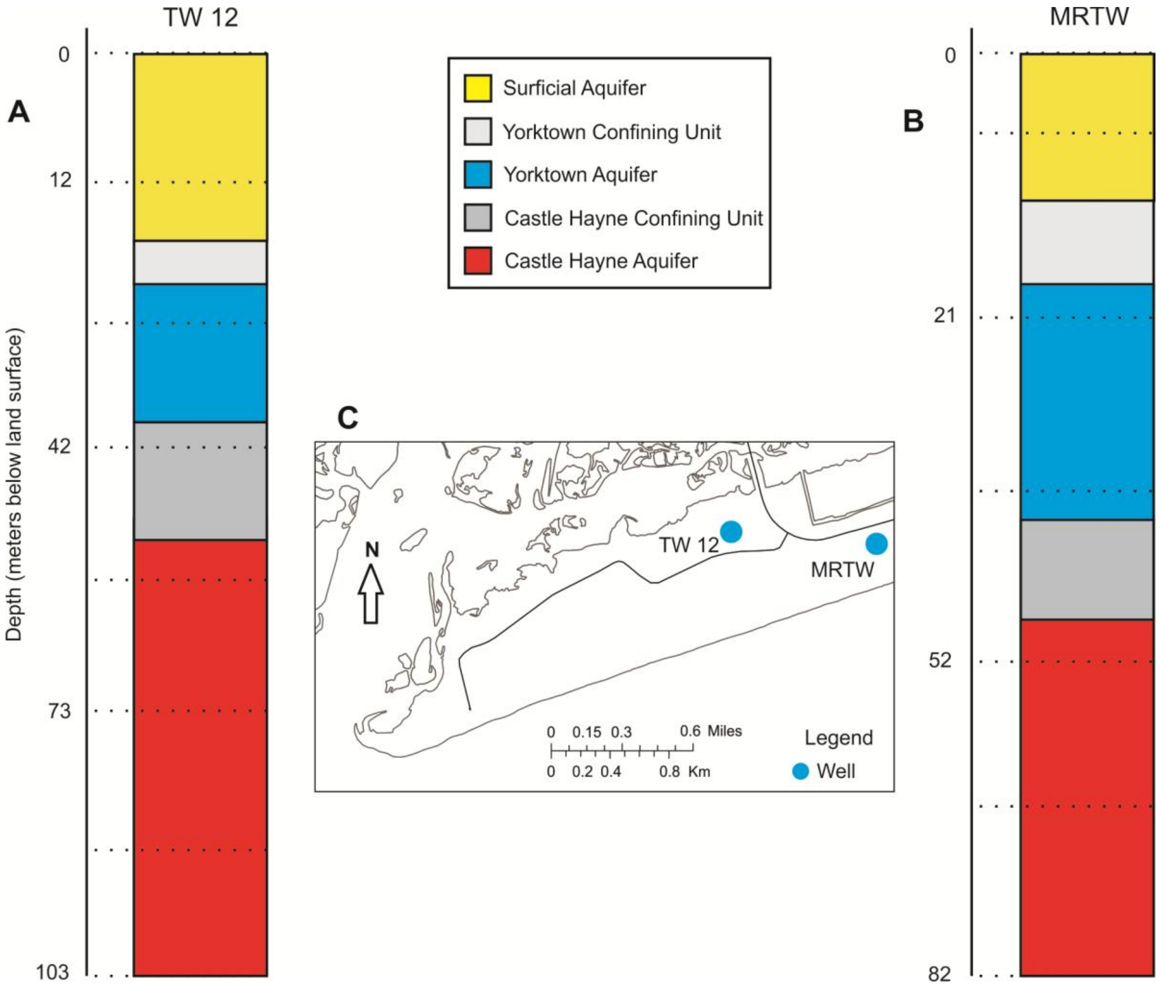

Figure 4: Hydrogeologic well logs of A) TW 12 (Test Well 12) and B) MRTW (Mallard Road Test Well). C) Shows the locations of the wells on Emerald Isle (Adapted from NC DWR, 2012).

Data from the North Carolina Department of Water Resources (NC DWR) reveal that the Bogue Banks Water Corporation (BBWC) has two wells on the western end of Bogue Banks.

These wells have hydrogeologic logs of the aquifers and confining units present in the subsurface, as well as their relative thicknesses (Fig. 4). The approximate thickness of the Surficial aquifer in the study area is 17.4 m (57 feet) (NC DWR, 2012). However, it appears the aquifer is thinner to the east with a thickness of 10.7 m (35 feet) at the Mallard Road Test Well (MRTW). At both sites, the Surficial aquifer is underlain by the Yorktown confining unit, which also increases in thickness to the east from 5-8 m (16-26 feet)

1.3.3 Soils

The United States Department of Agriculture's Soil Conservation Service classified soils within Carteret County in 1982 (NCSS, 1987). Within the study area, the soil series and soil complexes include: coastal beaches (Be), Carteret sand (CH), Carteret sand – low (CL), Corolla fine sand (Co), Corolla-Urban land complex (Cu), Duckston fine sand (Du), Fripp fine sand (Fr), Newhan-Corolla complex (Nc), Newhan-Urban land complex (Ne), and Newhan fine sand (Nh). Of the 10 soil series and complexes located on the western end of Bogue Banks, 6 of them encompass the majority of the study area.

The Duckston fine sand (Du) and beach sand (Be) are described as poorly drained sands that frequently flood. The Corolla fine sand (Co) and Newhan-Urban land complex (Nc) soils drain at moderate amounts leading to much lower flooding frequency. The Fripp fine sand (Fr) and Newhan fine sand (Nh) are described as being excessively drained and rarely flood. These last two soil types, Fripp fine sand (Fr) and Newhan fine sand (Nh), also represent the largest area of drainage class within the study area. Therefore, the majority of the study area is well-drained, according to the soil survey. The spatial distribution of these soils revealed a pattern of soil series that were generally oriented parallel with the long-axis of the island (Fig. 5).

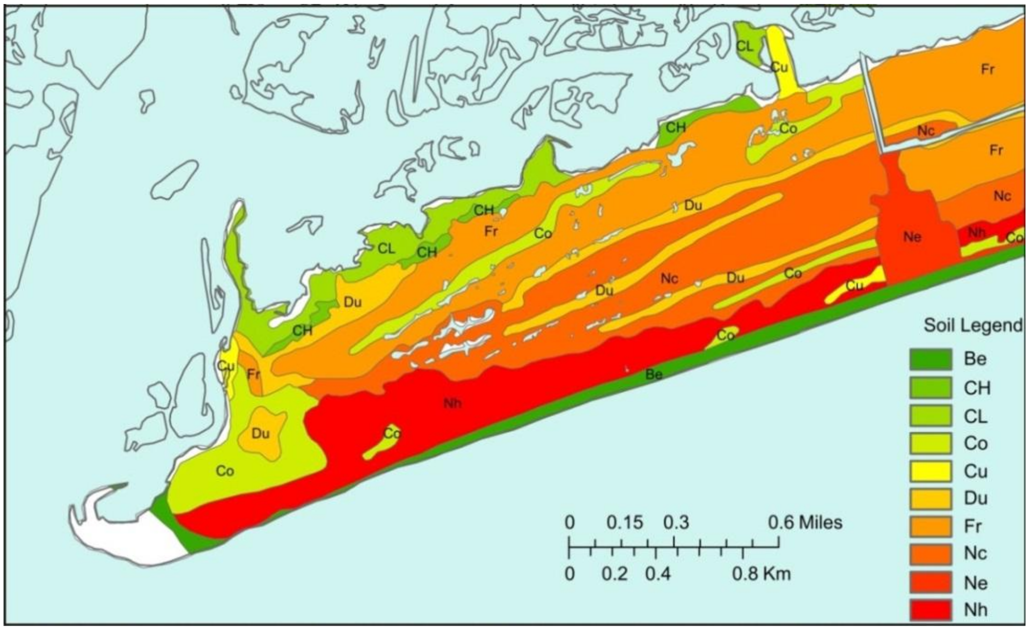

Figure 5: Soil distribution on the western side of Emerald Isle. Be = beach sand, CH = Carteret sand, CL = Carteret sand, low, Co = Corolla fine sand, Cu = Corolla-Urban land fine sand, Du = Duckston fine sand, Fr = Fripp fine sand, Nc = Newhan-Corolla fine sand, Ne = Newhan-Urban land fine sand, Nh = Newhan fine sand.

1.3.4 Physiography

The physiography of Bogue Banks is characterized by a series of dunes and inter-dunal troughs (or swales), which run nearly parallel to the coastline (Fig. 6). The dune fields closest to the southern shoreline are present at some of the highest elevations on this part of Bogue Banks, whereas the smaller dunes are near the northern shoreline. Lower elevation swales, which are the primary areas of concern in this study, are located on the interior portions of the island.

It is evident from Figure 6 that regions with low elevations constitute a much larger surface area than the high elevation dunes. This would imply that the majority of the island has the potential for flooding in response to a shallow water table. The swales can also create discontinuous sections of the longitudinal dune fields, further complicating the drainage patterns within Emerald Isle. The topography to the south of the large dunes and north of the smaller dunes levels out to the Atlantic Ocean and Bogue Sound, respectively. The elevation within the study area ranges from 0 m along the shoreline to 13.7 m (45 feet) above sea level on the high southern dunes.

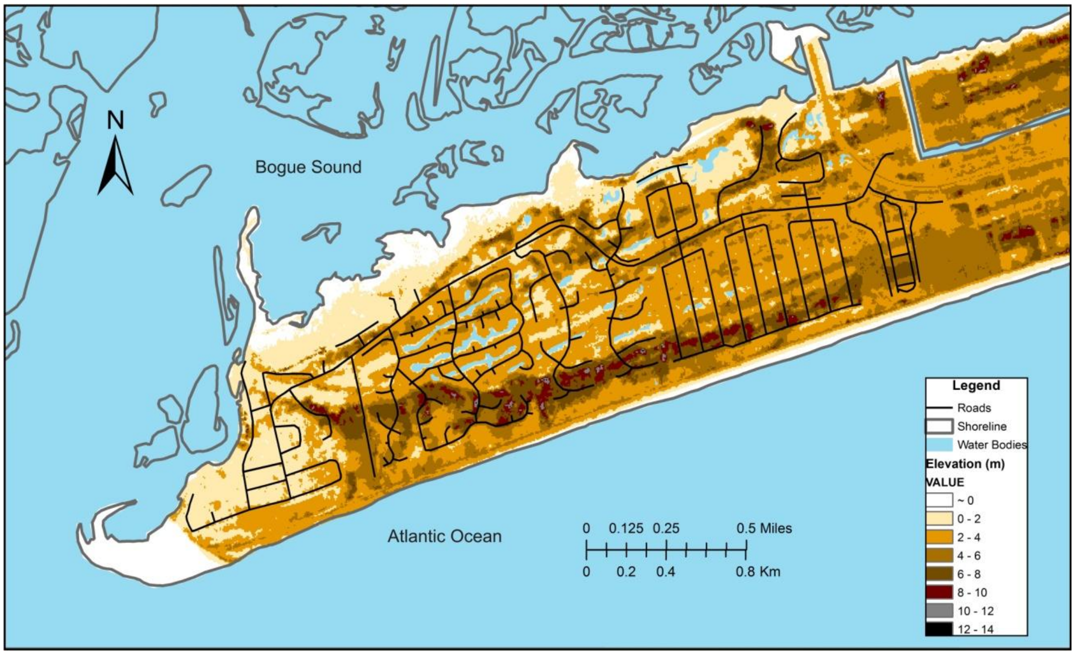

Figure 6: LiDAR map of the western side of Emerald Isle.

1.4 Climate

Precipitation and air temperature data for a 20 year period (1991-2011) leading up to the study window were collected from a weather station in Morehead City, North Carolina, approximately 32 km (20 miles) east of Emerald Isle (Table 2). The station was selected due to the availability of long term records and continuity of data, which were used to derive long-term averages for the region. Annual data were summarized from June to May of the following year. For the study period (2011-2012), weather data from the NCDWR station NC-ON-4 in Swansboro, North Carolina were used because the weather station in Morehead City did not record any data during Hurricane Irene. The Swansboro weather station is located 10 km (6.6 miles) north-northwest of the study area.

Table 2: Climate data for Morehead City over a 20 year period. Swansboro data are used in 2011. The year 2011 is not included in the 20 year average.

Year	Precipitation (mm)	Mean Temperature (°F)	Mean Temperature (°C)
1991	1621	65	18.3
1992	1440	63	17.2
1993	916	69	20.5
1994	473	65	18.3
1995	621	63	17.2
1996	349	63	17.2
1997	138	63	17.2
1998	182	65	18.3
1999	386	63	17.2
2000	921	61	16.1
2001	757	63	17.2
2002	1669	63	17.2
2003	1504	62	16.7
2004	1077	63	17.2
2005	1634	64	17.8
2006	1011	63	17.2
2007	1234	65	18.3
2008	1108	62	16.7
2009	1645	63	17.2
2010	1277	63	17.2
2011	987	66	18.9
Mean	998	63.5	17.5

The average temperature for the 20-year period was 17.5 ° C (63.7° F), with annual temperatures ranging from 16.1 ° C (61° F) to 20.5 ° F (69° F). Average precipitation for the 20-year period was 998 mm (39.30 inches), with annual amounts ranging from 138 mm (5.44 inches) to 1669 mm (65.7 inches). During the 2011-2012 study period, annual precipitation and temperature were 987 mm (38.88 inches) and 18.9° C (66° F), respectively. The mean temperature for 2011-2012 was the highest since 1993 (20.5° C). The precipitation during the study period was only 2% lower than the 20-year annual average (1991-2010), but was significantly lower than six of the previous nine years. During 2011, the months of August, September, and October combined to receive 45% of the yearly total. The high volume of sub-tropical and extra-tropical cyclones during these months yielded these elevated levels of rainfall.

CHAPTER 2: METHODS

2.1 Well Installation

A total of 15 polyvinyl chloride (PVC) water table wells were installed (Fig. 7) in the Surficial aquifer to monitor water levels over a 12 month period and conduct slug tests. The locations for the monitoring wells were chosen on the basis of accessibility, susceptibility to flooding, and areal coverage. This allowed for a diverse distribution of wells in both high dunes, shallow swales, and soil type. Taylor and Alley (2001) explained that the selection of observation wells should provide data representative of various topographic, geologic, climatic, and land-use environments.

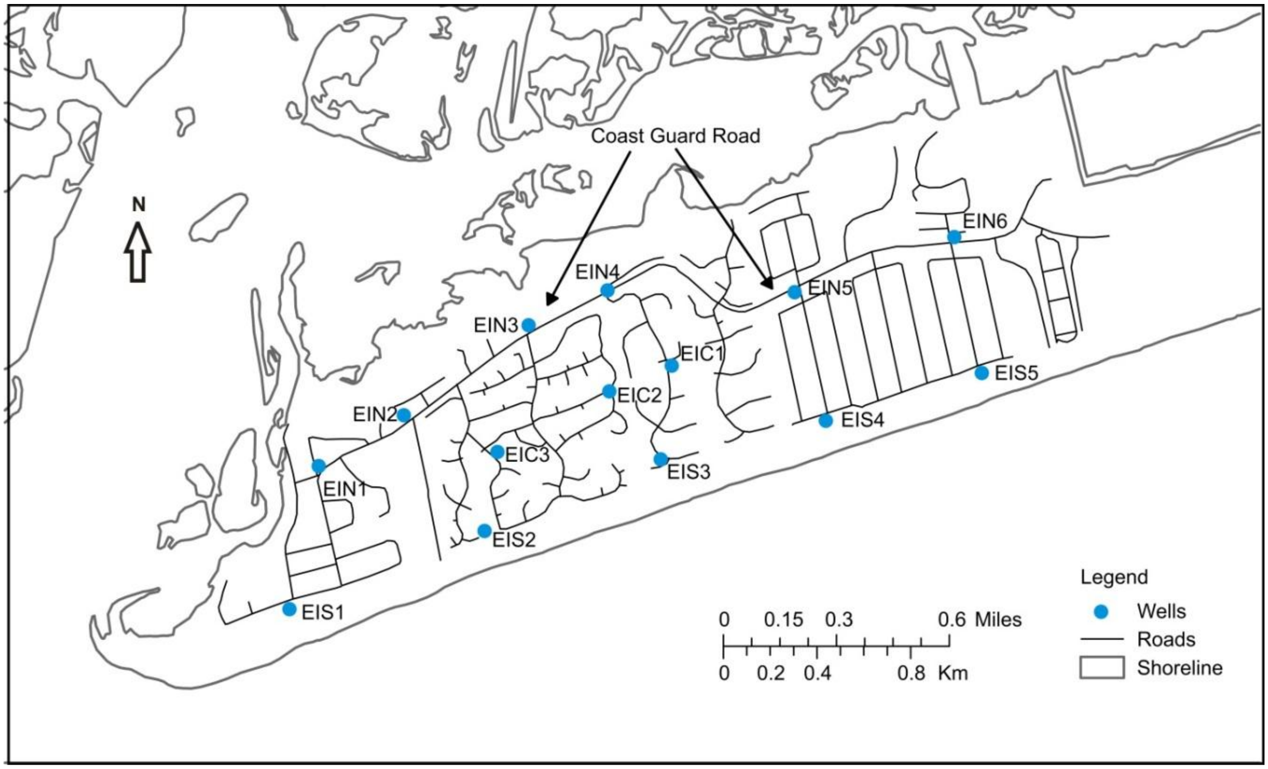

Figure 7: Map of the western part of Emerald Isle showing locations of water table monitoring wells within the study area.

A geoprobe (direct push coring machine) was used to install 12 of the 15 wells. The other three sites were shallow enough to use a hand auger. At each site, however, a hand auger was used to drill the first meter of soil. This allows for the 4-inch riser casing to fit in the subsurface, which helps to protect the screened PVC interval (Figure 8). Once installed, the wells were then sealed with bentonite at the surface.

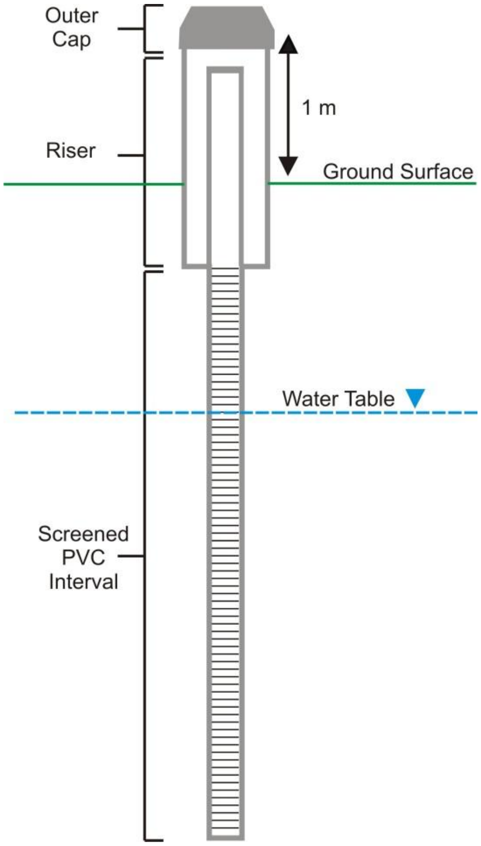

Figure 8: Observation well design utilized on Emerald Isle.

Each well in the network had a diameter of 0.254 m (1 inch). However, the lengths of the wells varied as a function of the topographic setting and depth to the water table. The depths of the monitoring wells ranged from ~1.9 m to ~8.6 m. Wells that were located on top of dunes were drilled to greater depths than those located in swales because the water table was typically deeper on top of the dunes than in the swales. Generally, the depth of the water table on dune ridges ranged from 1.6 m to 6 m, whereas the water table depths in swales ranged from 0.7 m to 1.6 m.

Groundwater elevation data that were provided by the town were used to derive the lowest water table elevations that were recorded in previous years. These measurements were then used to estimate the maximum depths to which monitoring wells were to be drilled such that the well screen would straddle the water table during the entire monitoring period. All the monitoring wells consisted of a slotted PVC pipe (i.e. the screen) that was connected to a PVC pipe (i.e. the riser). The top of the riser was set at 0.5 to 0.9 m above the ground surface whereas the bottom of the riser extended to ~0.3 m below the ground. The geoprobe was used to collect cores from the shallow sediment at 4-foot intervals. Descriptions of soil profiles were based on the recovered core sediment. In addition to monitoring wells, two nested piezometers were installed to determine a vertical hydraulic gradient in a swale (EIS2D and EIS2S). EIS2D represents the deep piezometer that was drilled to a depth of 3.67 m below the ground surface, whereas EIS2S represents the shallow piezometer that was drilled to a depth of 1.97 m below the ground surface. Thus, the vertical distance between the two wells was 1.70 m.

2.2 Groundwater Monitoring

In 12 of the 15 monitoring wells, water level measurements were collected continuously using water level loggers. The loggers used were Model 3001 Solinst Leveloggers, pressure transducers that are set to record absolute pressure (i.e., the water pressure and barometric pressure), which are accurate to ±0.05% of full scale. To derive actual water levels, the pressure readings from the loggers were therefore corrected for barometric pressure. At well site EIC3, a barologger was deployed to record atmospheric pressure, which was used to compensate the readings from the water level loggers.

The water levels were referenced to the North America Vertical Datum of 1988 (NAVD 88) using the National Geodetic Survey station markers located on the island. A Topcon Total Station was used to survey elevations of well sites via line-of sight from the geodetic markers. Once ground elevations were derived, elevations for the top of casings and water level loggers were calculated for each well. A Trimble Global Position System (GPS) unit was used to determine the geographic coordinates of the monitoring wells. The GPS unit has a horizontal accuracy of less than 5 meters. Data from the survey and additional well characteristics are listed in Table 3.

Table 3: Well characteristics derived from groundwater monitoring wells in Emerald Isle. TOC = Top of casing. Elevation is in reference to mean sea level.

Well ID	Latitude	Longitude	Elevation of TOC (m)	Elevation of ground (m)	Well depth (m)	Length of string and probe (m)	Elevation of probe (m)	Length of casing above ground (m)
EIC1	34.6548	-77.077	4.11	3.24	3.40	3.81	0.31	0.87
EIC2	34.6531	-77.079	2.88	2.26	1.82	2.20	0.69	0.62
EIC3	34.6515	-77.085	7.91	7.36	8.60	8.84	-0.93	0.55
EIN1	34.651	-77.093	3.53	2.96	3.11	3.28	0.26	0.57
EIN2	34.6528	-77.089	2.77	2.08	2.36	2.67	0.11	0.69
EIN3	34.6562	-77.083	2.54	1.99	3.53	2.85	-0.30	0.55
EIN4	34.6577	-77.079	2.46	1.55	3.05	-	-	0.91
EIN5	34.6576	-77.071	6.15	5.66	4.99	5.09	1.06	0.49
EIN6	34.6594	-77.063	4.14	3.53	4.88	5.08	-0.93	0.61
EIS1	34.6459	-77.094	3.86	3.29	3.19	-	-	0.57
EIS2D	34.6488	-77.085	2.25	1.37	3.67	3.59	-1.33	0.88
EIS2S	34.6488	-77.085	2.26	1.37	1.97	1.92	0.35	0.89
EIS3	34.6513	-77.077	7.54	6.67	6.24	6.81	0.74	0.87
EIS4	34.6526	-77.069	5.64	5.06	4.90	4.76	0.89	0.58
EIS5	34.6544	-77.062	3.43	2.86	1.87	-	-	0.57

Groundwater level, pressure, and precipitation data were collected from May 2011 to June 2012 so all seasons could be represented during the monitoring period. The water level loggers and barologger were set to take readings at 10-minute intervals. Periodic water level measurements were collected from all wells using a water level meter. These measurements were used to ensure the accuracy of the readings of the water level loggers. The software program, Surfer 8, was then used to create potentiometric surface maps of the Surficial aquifer.

2.3 Geospatial Analysis

Geospatial layers, representing physiography, hydrography, soil types, and man-made features were either created or acquired from the NC One-Map or NC Department of Transportation websites. Geospatial layers for the installed wells were created from the geographic coordinates taken from the Trimble GPS unit. A 2007 LiDAR digital elevation model was used to create a topographic map of the study area. The LiDAR data had a vertical accuracy of 0.25 m and a spatial resolution of 6.1 m. The shoreline, roads, and surface water bodies for Emerald Isle were created from existing geospatial layers acquired from NC One-Map.

Previous reports of storm-water runoff within the study area reveal that the areas prone to flooding are along Coast Guard Road (Moffat & Nichol Engineers, 1997). Using three different periods of water table elevation, flood potential maps were created to indicate where storm-water buildup would be observed on the western part of the island. The water table periods that were used to estimate flood potential maps include a pre-hurricane low, an intermediate rain event, and an extreme precipitation event (i.e., Hurricane Irene). A contour map representing each period was created using Geographic Information Systems (GIS) to show the position of the water table. The map calculator in ArcGIS was used to subtract water level data from elevation data to yield the flood potential maps. Areas with negative values would suggest that the water table was above the land surface and vice versa.

2.4 Aquifer Properties

To estimate the hydraulic conductivity (K) of the Surficial aquifer, falling-head slug tests were conducted in all wells in the study area. Falling-head slug tests involve quickly inserting a large displacement object into a well and then recording the rate at which the water levels return to equilibrium (Bouwer and Rice, 1976). A long steel rod of known volume (slug) was added to the well, while a pressure transducer measured the rate at which the water level recovered to the starting value.

The slug test data collected in the field were imported into Aquifer Test Solve (AQTESOLV) software program to derive the hydraulic conductivity of the Surficial aquifer. Multiple slug test solutions are available in the program; however, two were chosen to best represent the data. The Hvorslev (1951) and Bouwer and Rice (1976) method are ideal for unconfined, water table aquifers. Both methods account for a variety of well geometries and aquifer conditions (Campbell et al., 1990). These methods match a straight-line solution to displacement data derived from quickly inserting the slug. Well characteristics from Table 3 were also required for the derivation of hydraulic conductivity. The results from the slug tests were compared to values calculated in previous studies that were conducted on nearby barrier-islands to determine whether the hydraulic conductivity measurements from the Surficial aquifer were within acceptable ranges.

Since specific yield was not directly measured, grain size and core analyses were used to derive estimates for this parameter (Healy and Cook, 2002). Johnson (1966) and Healy and Cook

(2002) characterized average specific yield values based on sediment type, which have been assigned based on the grain-sizes in a given location. Averages for coarse, medium, and fine-grained sand are 0.27, 0.26, and 0.21, respectively. The value used for specific yield was 0.20. This is due to the predominant grain size being fine-grained sand with portions of silt and clay. The Water-Table Fluctuation (WTF) method was then used to derive an estimate of annual groundwater recharge by using the following equation:

$$R = Sy\ (\Delta h\ /\ \Delta t) \qquad \text{Eq. (1)}$$

where R is recharge, S_y is specific yield, **Δ**h is the change in water-table height, and **Δ**t is the change in time (Healy and Cook, 2002). This method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Scanlon, et al, 2002). The WTF method is best applied to relatively short periods (≤1 year) in locations where there is a shallow water table that experiences sharp rises and declines in water levels (Healy and Cook, 2002). The equation requires the total amount of head change in each well during the time period.

A double ring infiltrometer was also used to determine the infiltration rates of the different soils at the site of each monitoring well (Fig. 5). The infiltration rate was derived by measuring the amount of water that was drained in dry soil during a 20-minute period. During single storm events, as the soil becomes more saturated, it is assumed the infiltration rates will become lower as the soil moisture content increases (Akan, 1993). All of the soil classes were represented at the various well sites, so none of the soil types described above were excluded in the analysis. Infiltration capacities were also looked at using the Carteret County Soil Survey (NCSS, 1987). The saturated hydraulic conductivity of the soils is likely very similar to the infiltration capacity, thus the permeability of the soils were used as the maximum rate of water absorption.

2.5 Water Budget

A water budget for Emerald Isle was derived using parameters acquired from field data, modeling programs, and a literature review. The water balance for the study area is derived using the following (Thornthwaite, 1948; Thornthwaite and Mather, 1955):

$$\mathrm{ET} = (\mathrm{P} + \mathrm{I}) - \mathrm{G} - \mathrm{RO} \pm \Delta S \qquad \text{Eq. (2)}$$

where G is natural groundwater recharge, P is precipitation, I is artificial recharge, RO is direct runoff, ET is estimated actual evapotranspiration, and ΔS is the change in groundwater storage. Since the basis for the water budget is the shallow groundwater system, natural groundwater recharge is considered an outflow (Shade, 1995). Artificial recharge in this area is predominantly from onsite wastewater treatment systems and other domestic water uses (e.g., irrigation). This value is derived from the volume of water extracted from the Castle Hayne aquifer system, assuming that this water eventually recharges to the Surficial aquifer via artificial inflows. Groundwater withdrawals from the Castle Hayne aquifer were obtained from Bogue Banks Water Corporation. The water budget equation has been arranged to solve for ET, since this value was not directly measured or calculated during the study period. Estimating for ET algebraically would assume a range of values from the parameters required in the calculation.

Using the time-series data from each well, the difference in water level between June 1, 2011 and May 31, 2012 was used to calculate change in storage for the period of record. This was achieved by multiplying the difference between initial water level (June 1, 2011) and the final water level (May 31, 2012) by specific yield (Eq. 1). Change in storage, or net recharge, takes into account the specific yield of the material, owing to the fact that only a percentage of the recharge is capable of being stored in the pore spaces of a material (Healy and Cook, 2002). Precipitation values were taken from a nearby weather station (Swansboro, NC), while recharge was calculated using the WTF method. The 'Simple Method' to calculate urban storm-water loads was used to estimate direct runoff (Schueler, 1987). Using the Simple Method, direct runoff is computed as follows:

$$\mathrm{R} = \mathrm{P} \times \mathrm{Pj} \times \mathrm{Rv} \qquad \text{Eq. (3a)}$$

$$\mathrm{Rv} = 0.05 + 0.9(\mathrm{IA}) \qquad \text{Eq. (3b)}$$

where R is the annual runoff, P is the annual rainfall, Pj is the fraction of annual rainfall events that produce runoff, Rv is the runoff coefficient, and IA is the proportion of land cover that is impervious area. Impervious area was estimated to be 0.30 based on the predominant residential land use of the island (Cappiella and Brown, 2001), whereas Pj was estimated to be 90% (Schueler, 1987). The direct runoff within the study area is likely within a range of values that the island experiences in a given year.

2.6 Groundwater Modeling

The software program Visual MODFLOW was used to simulate groundwater flow in the Surficial aquifer on the western side of Emerald Isle under steady state conditions. Groundwater flow was simulated in a 3-dimensional model using a finite-difference method that numerically solves the groundwater flow equation (Harbaugh et al., 2000). The one layer model that was created was discretized into 499 columns by 250 rows representing a volume consisting of 50 m x 50 m x 17 m cells (L x W x H). Cells that were not superimposed over the island were made inactive for computational efficiency.

A geospatial layer was input into the modeling program to represent the shoreline of Bogue Banks. The layer served as a constant head boundary, set to sea level (i.e., head = 0 m). A digital elevation model of the island was imported to simulate the topography during the modeling process. Observation wells monitored during the study period were included in the model. Recharge to the model was applied via a United States Geological Survey (USGS) geospatial shape file. Hydrogeologic characteristics acquired from other aspects of this study were used as input parameters in the groundwater model. These parameters include hydraulic conductivity (x, y and z directions), specific yield, effective porosity, total porosity, recharge, evapotranspiration, and extinction depth. The extinction depth is the point in the subsurface at which evapotranspiration from the water table ceases. This is directly related to the depth of the roots of plants, which were assumed to be at a maximum of 3 m.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Hydrogeological Analysis

Analysis of geologic maps and drill cores reveal that the sediments studied in the upper 18 meters of the subsurface comprise the Surficial aquifer (Fig. 4, Table 1). Sediments logged from the geoprobe cores are primarily fine to medium sands, but there were lenses of rich organic materials and clay in some locales (Figs. 9). The sediments derived from the northern wells consisted of gray, well-sorted sands, with occasional low permeability sediments near the surface (e.g., at EIN2 and EIN4). The sediments derived from the central wells were also composed of mostly fine to-medium sand, but had small amounts of shell fragments near the bottom of each section. Low percentages of silt were also mixed into the finer-grained sand. The southern transect of wells, located mostly in the dune fields near the shoreline, were slightly more coarse-grained than the other transects. Aside from thin organic layers near the top of the sediments derived from EIS3 and EIS5, the rest of the cores revealed the presence of medium-grained sand in these areas.

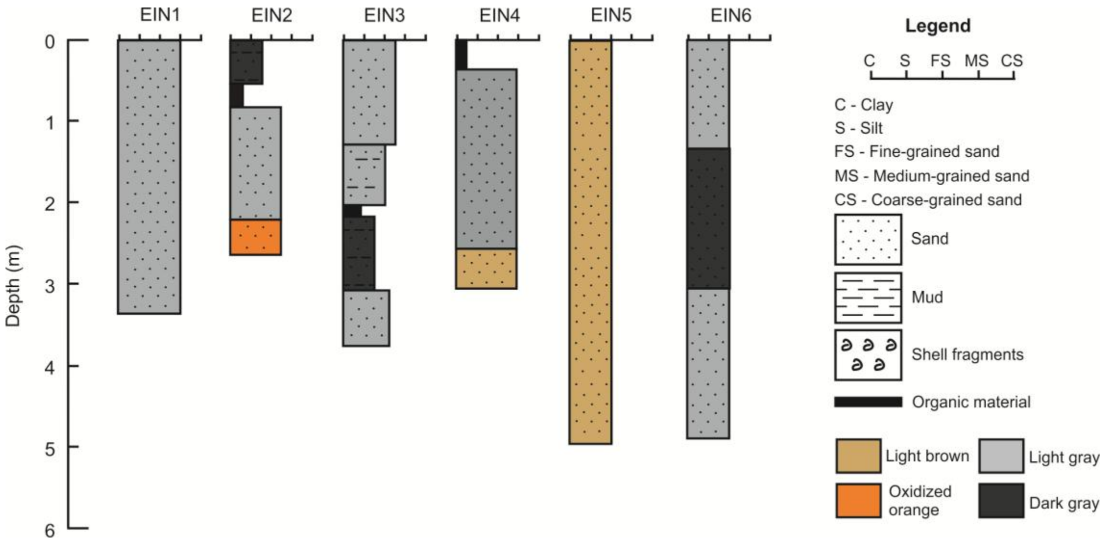

Figure 9: Core logs from the northern transect of wells.

Cores taken indicate that the clay and organic rich units are not very thick, ranging from 0.15 to 0.3 meters (0.5 to 1.0 feet). The presence of these clay lenses in the lower lying swales are likely to reduce the infiltration rates of surface water into the shallow groundwater system. This is particularly a problem during storm events, which may lead to flooding due to the perching of the water table (e.g., sites EIN2, EIN3 and EIN4) (Moffat & Nichol Engineers, 1997). Observations made in the field reveal that these sites were inundated with water during storm events during the monitoring period. Flooding from perching typically occurs when a thin layer of soil close to the surface gets saturated and prevents water from seeping into the ground to the water table below. Several sites in the study area have been identified where low infiltration rates of the soil may cause perching of the water table. These sites, represented by red in Figure 10, are areas that should be targeted for managing storm-water runoff.

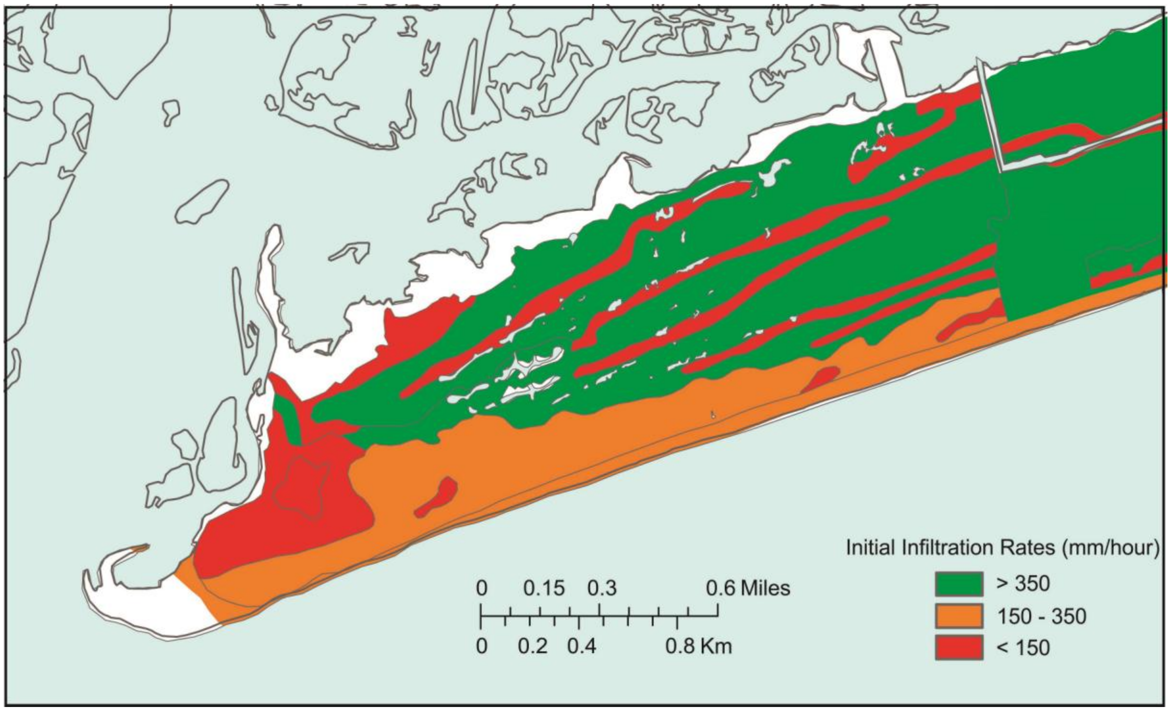

Figure 10: Infiltration rates for the study area.

The results of the infiltrometer tests show that the lowest infiltration rates occur in the elongated soil sections, which overlap with some of the swales on the western part of the island (Fig. 10). These data suggest that the second hypothesis is partially supported; low infiltration rates are impeding groundwater recharge in these swales during storm events, but not to the entire extent which was postulated. The ranges where intermediate and high infiltration rates are observed are associated with the dunes and dune slopes identified on the LiDAR map (Fig. 6).

Table 4: Horizontal hydraulic conductivity results from slug tests data.

	Hydraulic Conductivity (x 10^{-5} m/s)	
Well ID	Hvorslev method	Bouwer and Rice method
EIC1	1.4	1.5
EIC2	2.9	3.2
EIC3	1.3	1.5
EIN1	3.2	3.8
EIN2	3.0	3.4
EIN3	0.9	0.9
EIN4	1.1	1.2
EIN5	5.1	6.0
EIN6	2.5	3.8
EIS1	3.4	4.5
EIS2	0.6	0.7
EIS3	3.0	3.4
EIS4	3.5	3.9
EIS5	1.0	1.1

Slug tests in the monitoring wells revealed that the horizontal hydraulic conductivity in the Surficial aquifer ranged from 8.6 x 10^{-6} to 6.0 x 10^{-5} m/s (Table 4). Smith and Chapman (2005) used constant-rate pumping tests at three locations within the Little Contentnea Creek Basin, North Carolina to estimate hydraulic properties of the Surficial aquifer. Their results show that the hydraulic conductivity ranges from 1.2 x 10^{-5} to 7.4 x 10^{-5} m/s. Anderson (2000) estimated that the Buxton Woods aquifer on Hatteras Island, NC also had a horizontal hydraulic conductivity (6.5 x 10^{-5} m/s) similar to those estimated in this study.

Table 5: Calculated recharge rates of the monitoring wells using the Water Table Fluctuation method (WTF). Healy and Cook's (2002) specific yield values for similar grain-size were used in this table.

Well ID	Mean specific yield S_y	Total head change (mm/year)	Recharge (mm/year)
EIC1	0.20	3,050	610
EIC2	0.19	4,480	851
EIC3	0.20	2,120	424
EIN1	0.20	3,110	622
EIN2	0.16	5,600	896
EIN3	0.20	4,310	862
EIN5	0.19	2,320	441
EIN6	0.19	3,820	726
EIS3	0.20	2,350	470
EIS4	0.19	3,240	616
Mean	0.20	3,440	688

From Healy and Cook's (2002) estimations, specific yields were likely to be higher in wells that had continuous sections of coarse-grained material, and lower in drill cores where sections of mud and organic material were present. Due to the predominant grain size being fine-grained sand, the average specific yield was estimated to be 0.20. Thus, recharge rates computed using the WTF method ranged from 424 mm/year to 896 mm/year with an average groundwater recharge of 688 mm/year (Table 5). Giese et al. (1997) estimated recharge to the Surficial aquifer to vary between 300 and 550 mm/year. The variance is due to the difference in infiltration rates, depths to the water table, and vegetative cover contributing to evapotranspiration.

3.2 Changes in Water Levels

Low barometric pressures and high precipitation rates that occurred in August 2011 and May 2012 were a result of Hurricane Irene and Tropical Storm Beryl, respectively. Hurricane Irene was a significant storm event that occurred in the study region, and provided further insight about how the shallow groundwater system responded to extreme flooding events. Groundwater levels in the monitoring wells responded quickly to such precipitation events. However, the rate of response was not the same in each well. This variance is most likely a function of the infiltration rate of the soil, soil moisture, and depth to the water table prior to precipitation events. The depth of the water table controls the amount of storage between the land surface and water table. The monitoring wells located in areas where the water table was shallow (swales) responded quicker than those wells where the water table was deeper (ridges and dunes).

The magnitude of the response of the water table to precipitation input was large in the shallow wells, which produced sharp peaks in the time series plots (Fig. 11). In the wells with deeper water tables, the magnitude was much smaller and the time series plots showed smoother peaks (Fig. 12 and 13). To test the hypothesis that a shallow water table may breach the land surface and cause flooding, the water levels were monitored in relation to the ground surface. The time-series of groundwater levels reveal that the water table did not rise above the land surface in the monitoring wells at any point during the monitoring period. With the exception of EIC2 and EIN2, the water table did not come to within 0.5 m of the ground surface.

Although the groundwater monitoring wells showed no evidence that the water table breached the land surface, the data that were used are point measurements that are limited to specific locations where the entire water table could not be fully characterized. Flood potential maps, however, capture the water table over large spatial areas and thus are able to better indicate regions that would be prone to flooding. This approach is beneficial on an island such as Bogue Banks where the topography is characterized by ridges and swales. While there is some error inherent in the interpolation of data for contouring, this approach is nonetheless beneficial because large areas are captured in the flood potential maps created.

Flood potential maps (Fig. 14-16) have the ability to illustrate where the water table may be the source for storm-water buildup. As expected, the flood potential maps show that the low-lying elevations are the primary areas where flooding would be prevalent. Areas identified to flood in the pre-hurricane period coincide with existing ponds and natural wetland areas. This time period was used to validate the flood potential maps during increased precipitation. The biggest problem area, where residential properties are built in the troughs of the island, is located in the southeastern part of the study area. Even at times of little precipitation, this area is in close contact with the groundwater system. Storm events bringing at least 25 mm of rainfall (the amount received from the storm event in Fig. 15) should produce storm-water runoff caused by an elevated water table.

Problem areas predicted by the flood potential maps have some overlap with locations where the infiltration rates were found to be low (Fig. 10). The infiltration rates of these soils may be retarding water from rain events to recharge the Surficial aquifer. The close proximity of the water table to the land surface in areas identified by the flood potential maps would mean a high incidence of saturation-excess in the soils. The association between the generation of storm-water runoff and an elevated water table is strongly related to the frequency of precipitation events, which have been found in previous studies to control water table levels (Evans, et al., 1999). Since the study area received less rainfall than previous years, the frequencies of runoff events may have also differed from the long-term average.

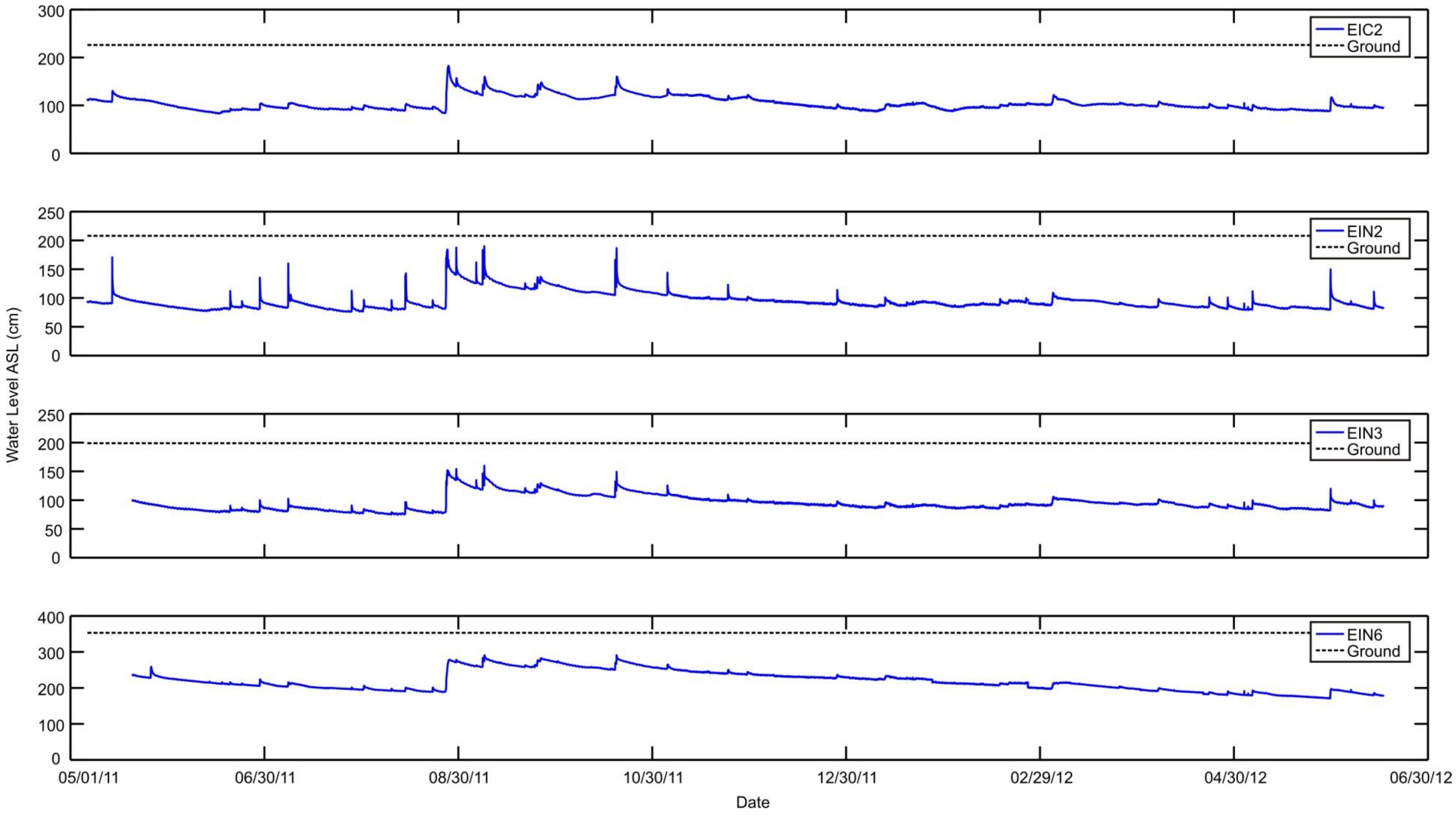

Figure 11: Groundwater levels in monitoring wells where the water table is shallow. The dashed black line represents the ground surface.

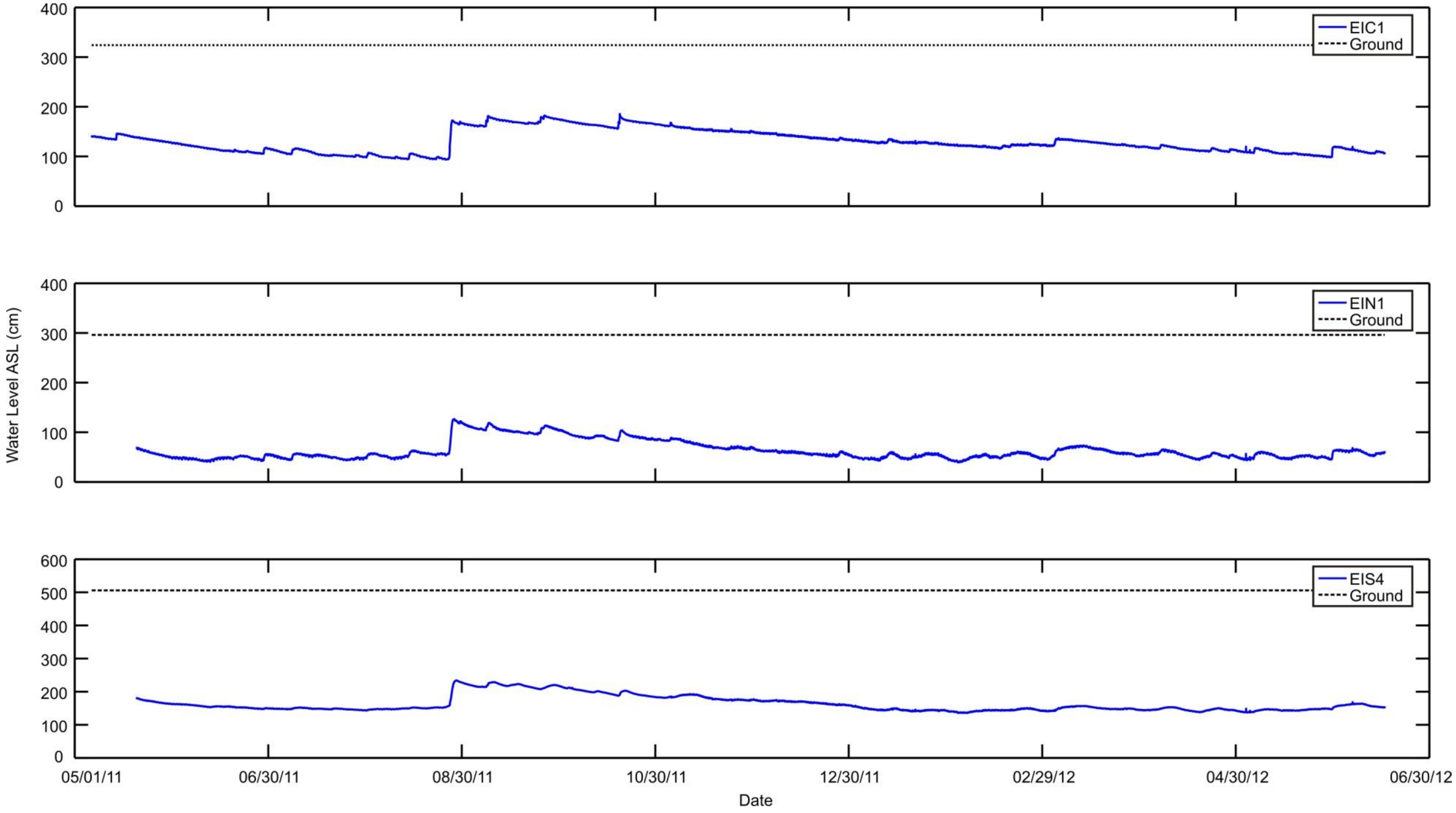

Figure 12: Groundwater levels in monitoring wells where the water table is moderately deep. The dashed black line represents the ground surface.

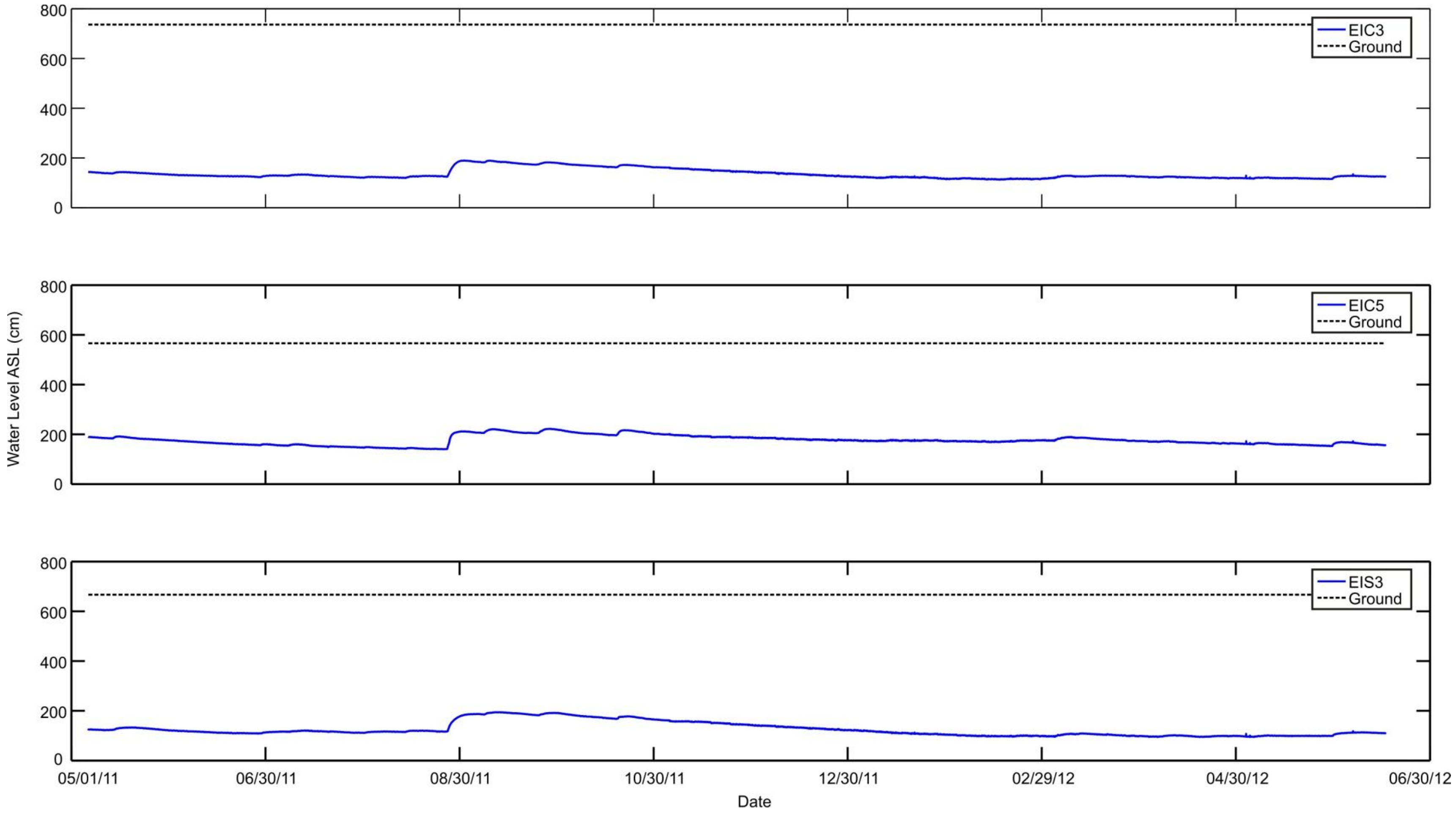

Figure 13: Groundwater levels in monitoring wells where the water table is deep. The dashed black line represents the ground surface.

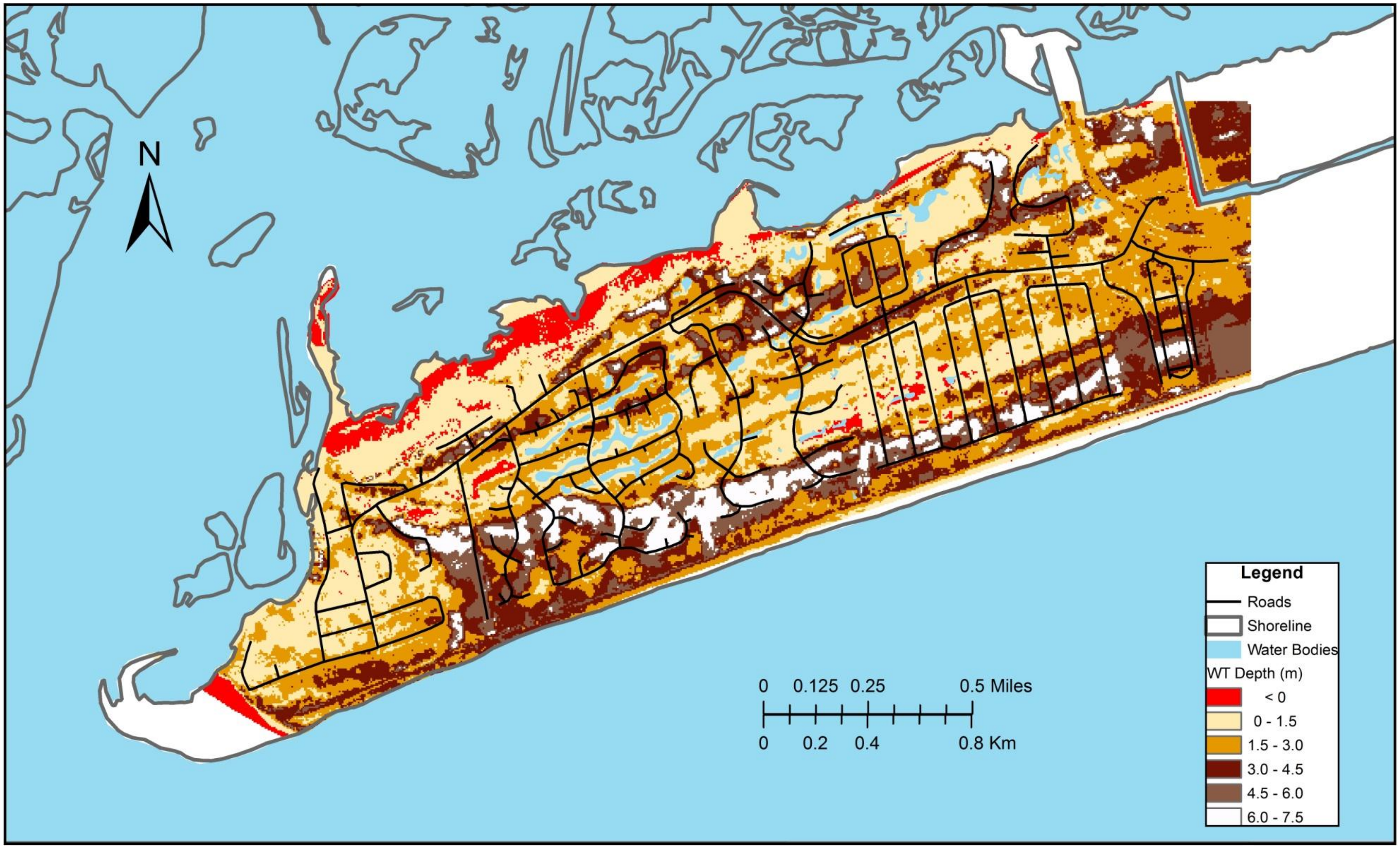

Figure 14: Depth to the water table prior to Hurricane Irene. Red areas are where the water table breaches the land surface.

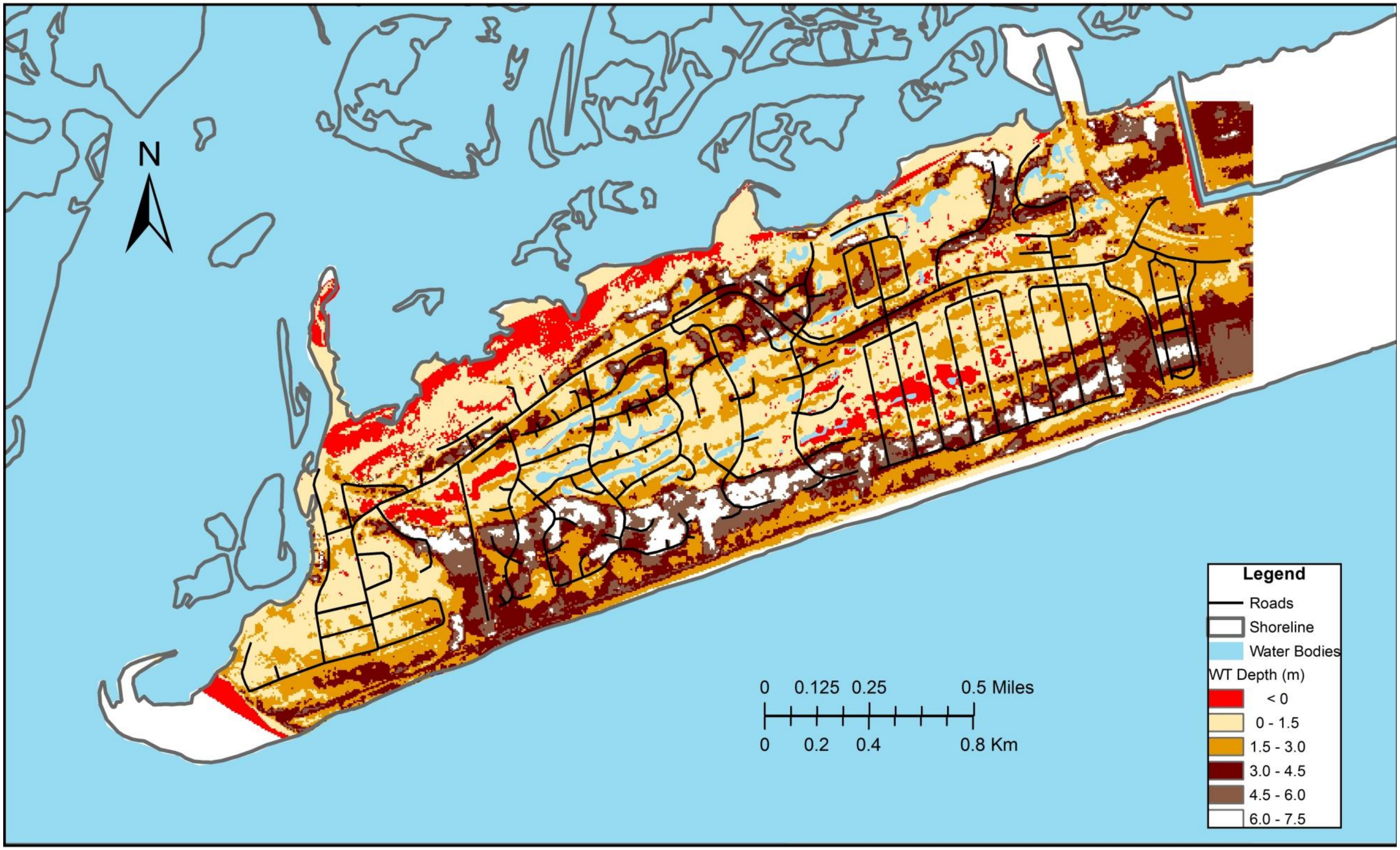

Figure 15: Depth to the water table for an intermediate storm event on March 5, 2012. Red areas are where flooding is modeled to have occurred.

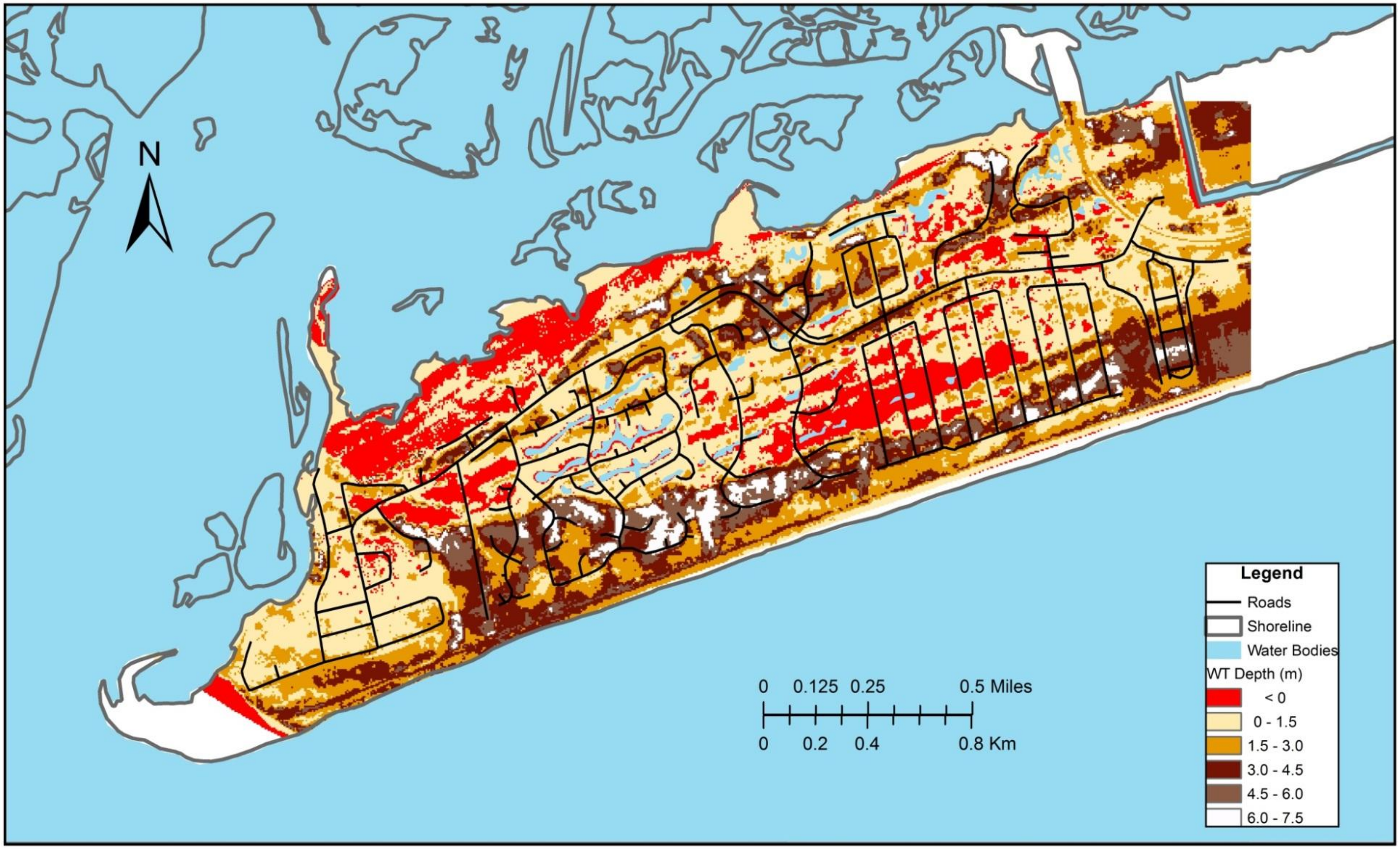

Figure 16: Depth to the water table following Hurricane Irene. Red areas are where flooding is modeled to have occurred.

The NCSCS Soil Survey (1986) for Carteret County estimated infiltration capacities of the soils within the study area to range from 150 to 500 mm/hour (6 to 20 in/hour). Even during Hurricane Irene, rainfall intensity would not have exceeded this capacity. The soil survey likely generalizes soils across a large area. As evidenced by the soil logs, the spatial variability of similar soils may include layers of clay and organic material. These layers tend to lower the infiltration capacities in certain areas. Infiltration capacities estimated by the soil survey have not accounted for soil compaction and vegetation removal over time, which are a result of residential and urban development. Emerald Isle and Bogue Banks as a whole have experienced development over the years that could have the potential to lower the infiltration capacity of the soil. Soil compaction has the potential to reduce infiltration properties by up to 70% (Gregory et al., 2006).

It is likely that in some areas not identified to flood in Figs. 14-16, the low infiltration excess of the soil from development (i.e., impervious surfaces, compaction, etc.) is the main concern for storm-water generation. These areas are not able to be identified in the flood potential maps, because they are not associated with the shallow groundwater system. If the compacted surface soils and the road network are unable to soak up precipitation, then those soils and impervious areas will cause the storm-water to runoff towards lower-lying soils. Thus, it is in these areas of storm-water convergence that the soil properties and water table (infiltration capacity and saturation excess) are creating a flooding problem. Future efforts of soil classification should include a much more detailed look at the spatial variability of infiltration capacities within the same soil series, as well as how this has changed as the island has developed over time. These data can further link the groundwater system characterized in this paper to storm-water generation from soil properties in other areas of the island. In addition, flood potential maps can be verified during rainfall events and the areas of major storm-water generation can be mapped and overlain on the flood potential maps.

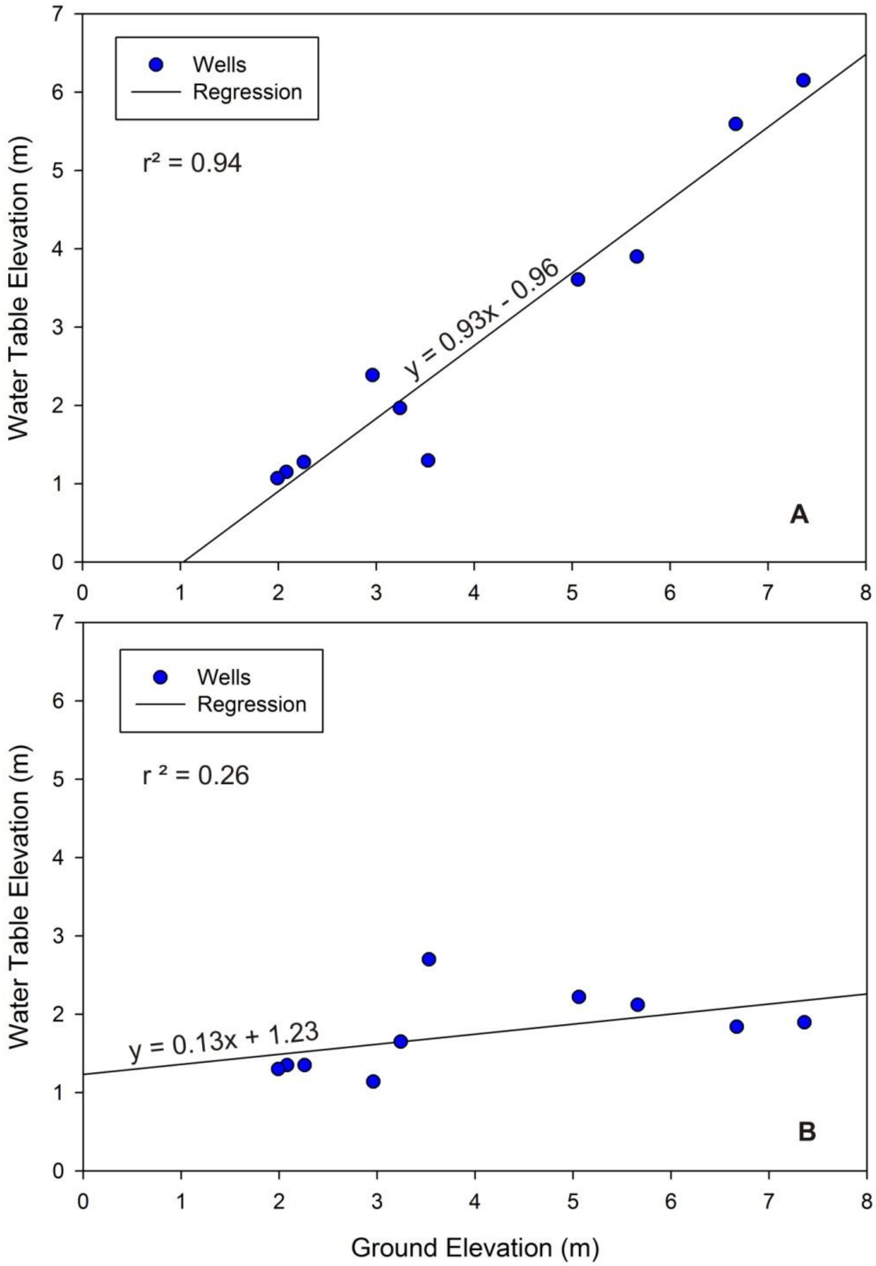

Figure 17: Plot of ground elevation versus water level during a period of no recharge (A) and recharge (B).

The data also reveal that during periods of low recharge, there is a positive association between the elevation of the ground surface at the location of a well and the depth to the water table at that site (Fig. 17). This association means that a deeper groundwater table should be observed on ridges than in the swales. During periods of higher recharge, this association is not as strong, due to the water table being much closer to the land surface in all of the observation wells.

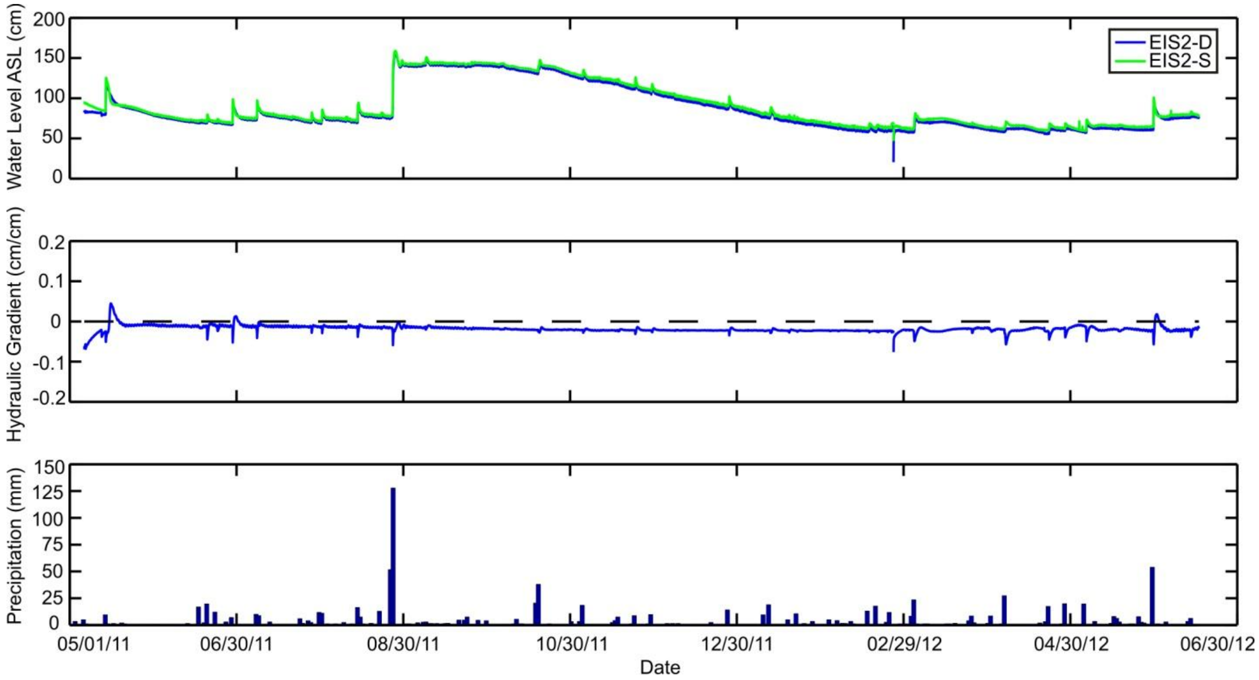

Figure 18: Plots showing water level, hydraulic gradient variation in wells EIS2-D and EIS2-S, and precipitation recorded in the study area. Positive hydraulic gradient values represent upward flow (discharge), whereas negative values represent downward flow (recharge).

Time-series data of groundwater levels from the nested piezometers indicate that the shallow piezometer (EIS2-S) predominantly has a higher hydraulic head than the deep piezometer (EIS2-D) (Fig. 18). This reveals that the vertical groundwater flow direction at this location is downwards. During most precipitation events over the study period, the magnitude of the downward flow increases. This is represented by sharp troughs evident in the hydraulic gradient plot (Fig. 18). The hydraulic gradient derived from these piezometers also indicates that the flow of groundwater may on occasion reverse, by flowing upwards instead of downwards. The month of May, in both 2011 and 2012, experiences a substantial directional change in vertical movement compared to other months. These results suggest that although the low lying areas on Emerald Isle may act as recharge zones for the majority of the year, certain hydrologic conditions can periodically vary such that the areas begin to act as a discharge zones. Flood potential is therefore at its highest during periods when discharge is likely.

Water level data from Tropical Storm Beryl were used to show how long it takes for the groundwater system to respond to a rainfall event (Fig. 19). The time-series plots show the response time between initial rainfall and peak water levels. Shallower wells within the study area, such as well EIN2 (Fig. 19a), have sharper peaks of groundwater levels. Following storm events, shallow wells return to background water levels much faster than the deeper wells. Well EIC2 (Fig. 19b), which is a moderately shallow well, exhibits a sharp rising limb, but a much more gradual falling limb once the storm passes. The deepest wells have a much more gradual water level rise and decline, such as well EIS3 (Fig. 19c). The primary control on these magnitudes of response is the depth to water table and infiltration rate of the soil.

Table 6 lists the lag times for each well in the study area. Response time in Table 6 is defined as the time elapsed from initial rainfall (red-dashed line) to initial head rise in the well (above pre-storm conditions), whereas the lag time is the elapsed time from initial rainfall to peak water level. Due to one weather station being used for rainfall amounts over the entire town, the actual initial time of rainfall and total rainfall amounts may be different from well to well. Shallower wells (EIC1, EIC2, EIN1, EIN2 and EIN6) experience an exceedingly short lag time during their period of recharge.

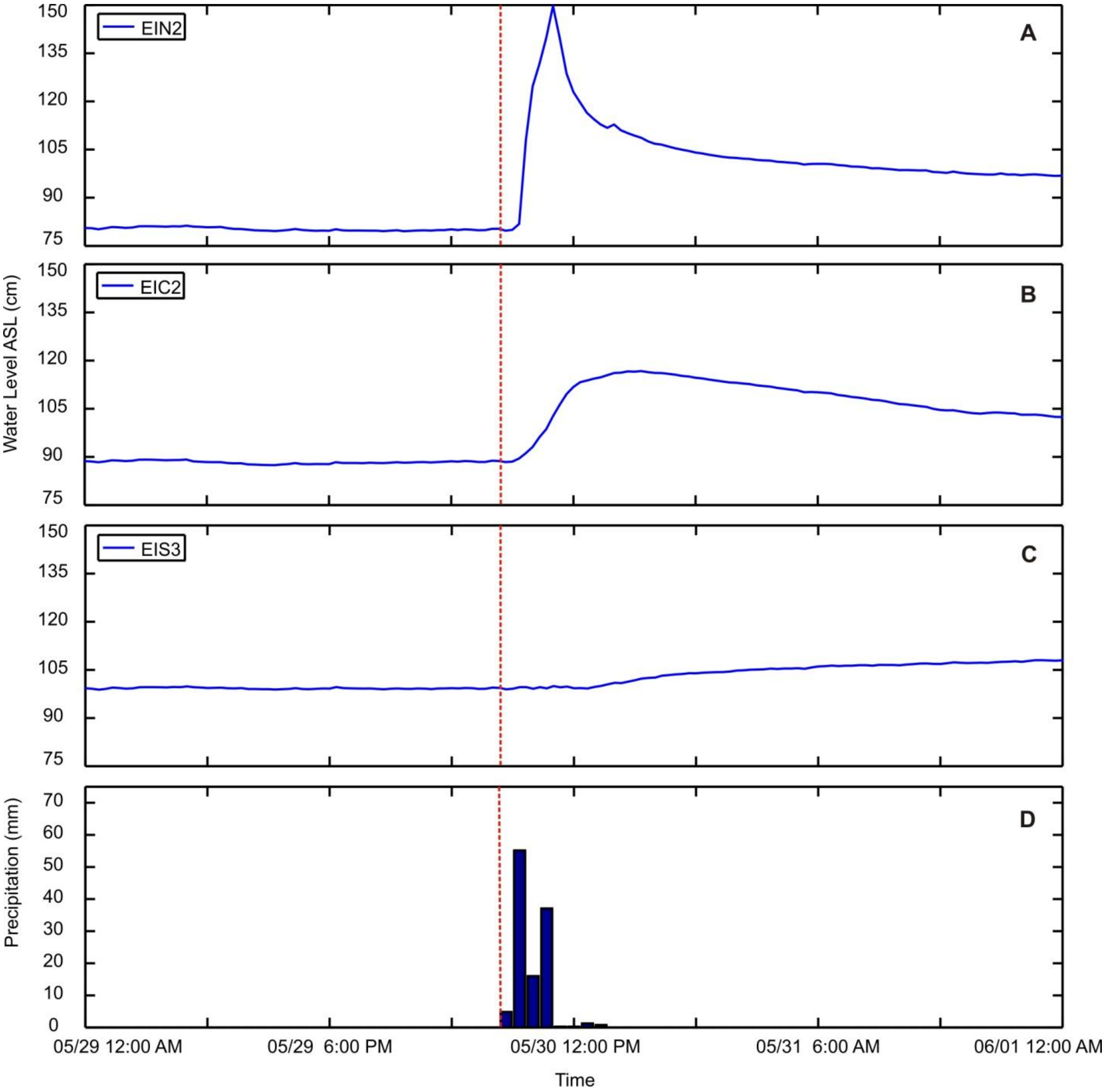

Figure 16: Groundwater hydrographs for wells EIN2 (A), EIS3 (B), EIC3 (C), and bar graph of precipitation (D). The red dashed line represents time of initial rainfall.

The deeper wells experience the opposite: a delayed lag time and much steadier rates of recharge over longer periods of time. Longer lag times are due to low infiltration rates and hydraulic conductivity, which increase the time required for the water to reach the water table. The topography may also play a role in regards to anomalous response times, as runoff from impervious surfaces and dunes may affect the timing of infiltration. Trends can be identified with respect to the location of each well site (Fig. 7). Wells located along the southern dune field had the lowest rates of recharge, whereas the wells located adjacent to the dunes experienced significantly higher recharge rates.

Table 6: Examples of response and lag times for monitoring wells in the study area during Tropical Storm Beryl.

Well ID	Response time	Water level rise (mm)	Lag time
EIC1	0.9 hours	210	6.5 hours
EIC2	1.0 hour	270	9.5 hours
EIC3	2.3 hours	100	39.3 hours
EIN1	2.5 hours	170	23.5 hours
EIN2	1.0 hour	700	4.2 hours
EIN3	0.9 hours	380	3.8 hours
EIN5	2.3 hours	140	35.4 hours
EIN6	0.9 hours	260	10.9 hours
EIS3	6.3 hours	90	36.3 hours
EIS4	3.6 hours	100	39.6 hours

3.3 Groundwater Flow

Time-series data show how water levels vary at specific locations, whereas contour maps of the water table show groundwater levels on selected dates across the study region (Fig. 20). The dates used here were selected to encompass a diverse representation of the water table fluctuations. The selected dates include a minimum water level, which preceded Hurricane Irene, a common rain event in March, 2012, and a maximum water level directly following Hurricane Irene. Within the study area, there are two to three groundwater mounds where the water table is at its highest within the Surficial aquifer. One mound is generally to the west towards the center of the study area, while the other two are located to the east, adjacent to each other near Coast Guard Road.

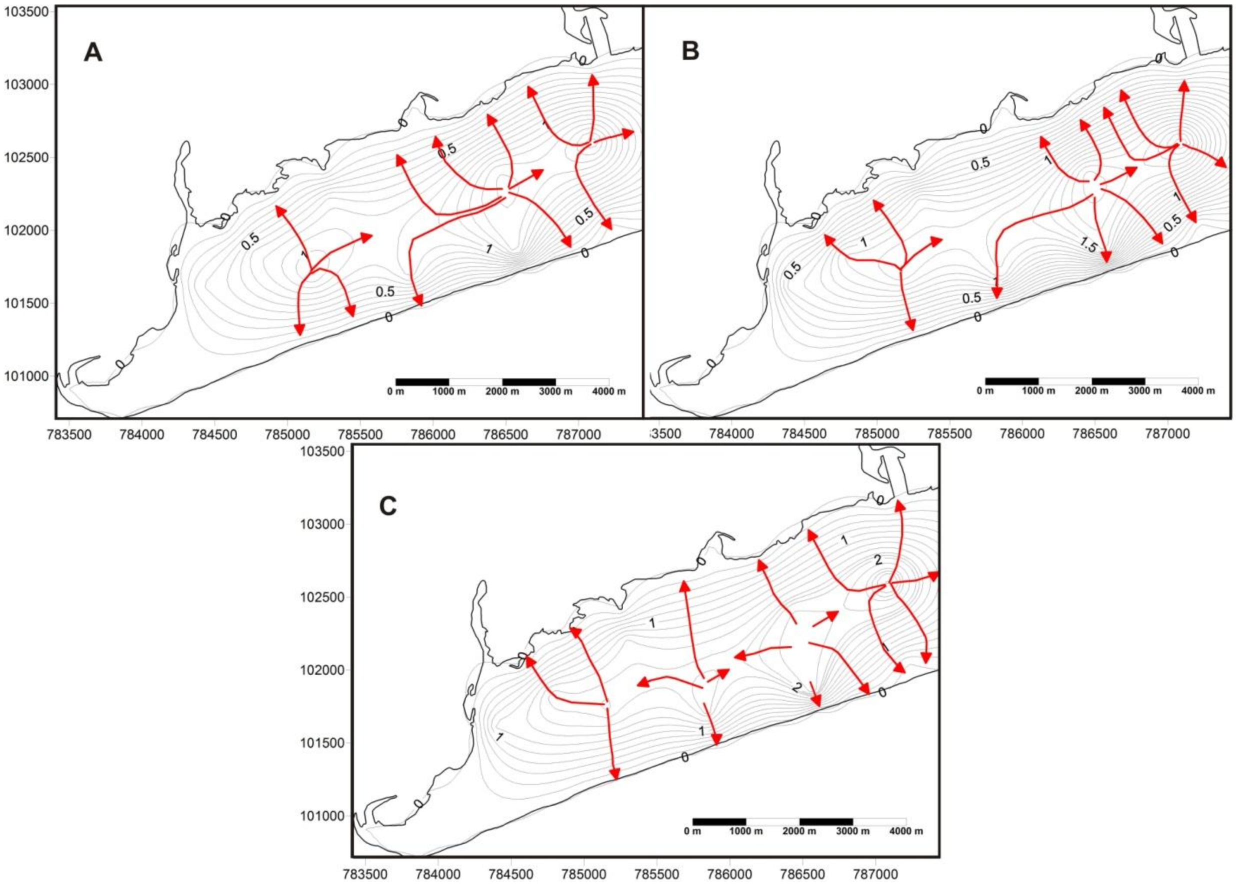

Figure 20: Groundwater flow patterns for the study area during pre-hurricane conditions (A), an intermediate storm event (B), and post-hurricane conditions (C). Red lines represent groundwater flow.

Flow lines on each of the contour maps divulge two patterns. First, the groundwater mounds create radial flow patterns away from the mounds. During periods of high precipitation (e.g., during Hurricane Irene), this radial flow increases as the mounds grow in size. This is evidenced by the compressed water table contours seen in the contour map representing the conditions after the hurricane (Fig. 20c). Second, the lateral flow patterns show convergence of flow lines in several locations. These patterns indicate that the groundwater may perhaps collect in areas of low-lying elevation. The presence of the groundwater mounds suggests that these mounds are the primary recharge zones for the Surficial aquifer. The mounds also appear to shift position during periods of increased precipitation. The mounds shift towards the southeast along the high elevation dune ridge that was identified in the ground surface elevation map. These results support Hubbert's (1940) principle that a topography driven water table will create groundwater divides and divergent flow.

3.4 Hydrologic Components

Recharge data indicate that the summer months received the most recharge, whereas the winter months received considerably less recharge (Appendix A). This difference for this particular year can be attributed to increased precipitation from Hurricane Irene. The small average change in groundwater storage for the wells (-0.8 cm), indicates that the shallow groundwater system can be considered to be in a steady-state condition over the monitoring period (Table 7). In general, steady-state conditions mean that water levels do not change through time. This has implications on the groundwater flow model constructed to simulate flow in the Surficial aquifer, and was the justification behind running the model under steady-state conditions.

Table 7: Water level data for the beginning and end of the study period. Change in storage = ΔWL x Sy. WL = water level.

Well ID	6/1/2011 WL (cm)	5/31/2012 WL (cm)	ΔWL (cm/year)	ΔS (cm/year)
EIC1	126.95	118.97	-7.97	-1.67
EIC2	100.47	102.44	1.97	0.45
EIC3	133.25	125.72	-7.53	-1.58
EIN1	49.89	63.92	14.03	3.65
EIN2	85.1	96.85	11.75	2.46
EIN3	87.49	96.65	9.15	2.10
EIN5	175.92	166.88	-9.04	-1.89
EIN6	225.95	194.19	-31.1	-7.15
EIS3	121.1	108	-13.1	-3.01
EIS4	162.71	156.52	-6.19	-1.43
Mean	-	-	-3.22	-0.81

Using the Simple Method (Eq. 3), the annual runoff in the study area was estimated to be 284 mm/year. Due to the shallow nature of the water table, septic systems and other man-made pipes/inflows are likely contributing to the hydrologic system. Data from the BBWC wells estimates artificial recharge to the Surficial aquifer to be 216 mm/year. This may vary due to evaporative losses of irigation water. The summer months, when tourism significantly boosts the population, is likely when the majority of this volume plays a role in raising the water table elevation. BBWC estimates usage of onsite wastewater systems increase nearly tenfold during this period, as large amounts of tourists occupy the island and use water for a wide variety of reasons (pools, lawns, septic systems, etc.). Using Eq. (2) the estimated actual evapotranspiration was calculated to be 223 mm/year (Fig. 21). Frank and Inouye (1994) estimated evapotranspiration in the coastal plain of North and South Carolina to be between 821 mm/year and 1363 mm/year. This variance between the estimated actual evapotranspiration and coastal plain values is likely due to the limited availability of input (precipitation and artificial recharge) during the study year, which experienced drought-like conditions compared to previous years.

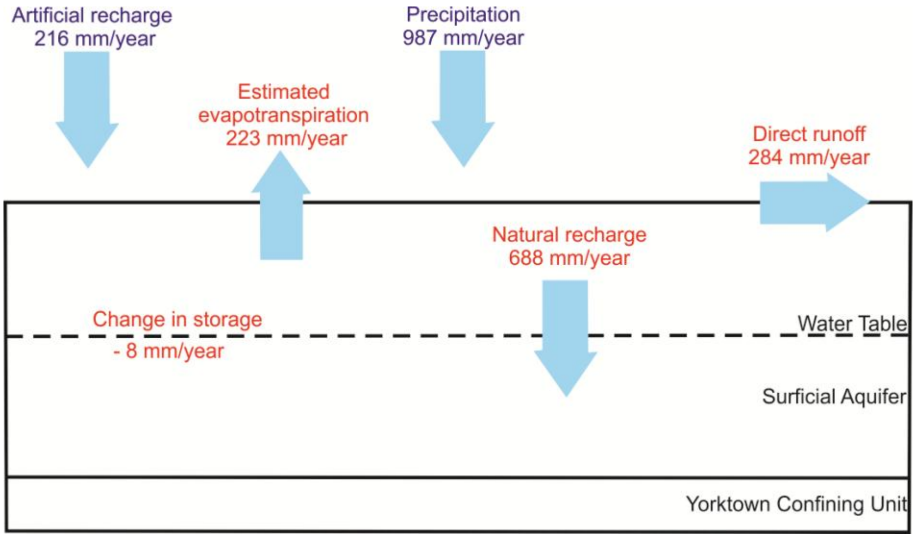

Figure 21: Components of the water budget within the study area. Blue text represents inflows, while red text represents outflows.

Long term records (20 years) of climatic data near Emerald Isle reveal two important factors that may have implications on long-term trends of the water budget:

1) Based on a mean temperature of 17.5 °C (63.5 °) and mean precipitation of 998 mm (39.3 inches), the town can be characterized as a humid subtropical climate (Peel et al., 2007).
2) The previous decade brought greater (~20%) rainfall than in 2011. These years may have had higher instances of flooding than the study year.

The significant differences in both precipitation and temperature for the past decade play a large role in regards to the water table influencing future flooding. If there is less recharge coming into the shallow groundwater system, then the water table may see a diminished elevation and reduce the flood potential for certain areas on the island. Conversely, if there is more recharge, then the storm-water problem could potentially be worse during those periods.

3.5 Groundwater Flow Model

3.5.1 Conceptual model

The Surficial aquifer of the North Carolina Coastal Plain is a shallow, unconfined, ground-water system which overlies the Yorktown confining unit in the study area (Winner and Coble, 1996). The Surficial aquifer receives most of the recharge from precipitation, due to direct areal exposure. No water is received as recharge from the underlying system, which is impeded by the Yorktown confining unit. The conceptual model describes a water table that is controlled by the overlying topography and soil properties (Fig. 22). In the groundwater model, we expect to see a deep water table on the dunes and a shallow water table in the troughs. In certain low-lying areas, the water table is expected to come very close to intersecting or exceeding the land surface. The flow regime is such that groundwater flows from the dunes towards the troughs and surface water bodies (i.e., the Atlantic Ocean and Bogue Sound). Runoff from the dunes would exacerbate the high water table in the low-lying troughs.

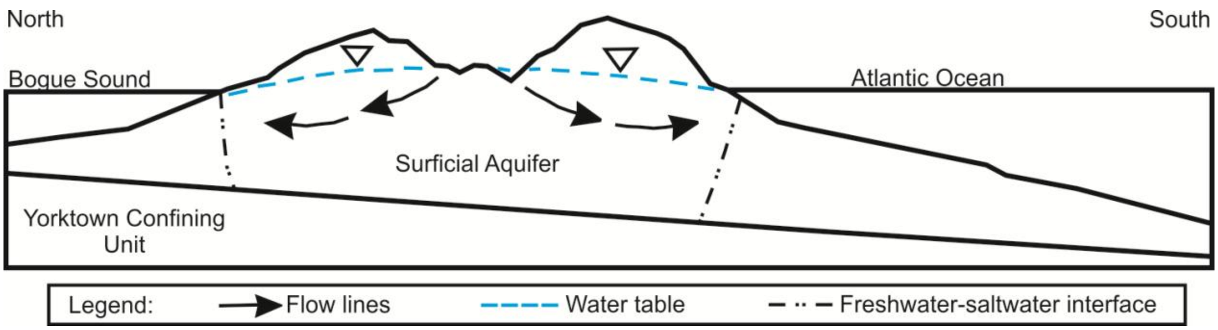

Figure 22: Conceptual flow model of groundwater in the Surficial aquifer of Emerald Isle.

Tide data were assessed to determine whether the ranges of tidal fluctuations would affect the model results. National Oceanic and Atmospheric Administration (NOAA) tidal records from Beaufort, NC were the closest to the field site that were found. The average monthly ranges of low and high tide were between 0.456 m and 0.706 m. Martin (2008) found that tidal fluctuations influencing Cape Cod Bay were up to 3.505 m. This range is five times as high as that found near Emerald Isle. These data suggest that the study area (Atlantic Ocean and Bogue Sound) is not heavily influenced by normal tides. Observed water levels near the shoreline verify that a high mean tide would not reverse groundwater flow on Emerald Isle, and that the surrounding water bodies act as discharge zones for the Surficial aquifer.

3.5.2 Model calibration

Simulated heads were calibrated against average observed head values in the model. These values take into account typical storms the groundwater system experiences throughout the year, so flooding will still be evident during model simulation. Ranges of hydraulic parameters (Table 8), based on field calculations and literature review, were used in the model to minimize the difference between simulated and observed head values. All hydraulic conductivities were based on slug test results in the monitoring wells and nested piezometer. Vertical hydraulic conductivity (K_z) was estimated to be about one order of magnitude less than horizontal conductivity (K_x/K_y). Eight runs were simulated during calibration of the model. The parameters that gave the best calibration are Run #8 (Table 8).

During the calibration process, each cell was designated a value for every hydraulic parameter the model required. These parameters were uniform throughout the entire model. The only input that had any variance was recharge. A recharge layer, which designates 32 recharge zones based on groundcover, was applied to the model to account for the variability of recharge in the study area. This variability is a result of land-cover, soil data, and vegetation classes.

Table 8: Hydrologic parameters used for each Visual MODFLOW run during calibration of the model. K_x/K_y = horizontal hydraulic conductivity, K_z = vertical hydraulic conductivity, S_y = specific yield, ET = evapotranspiration.

Run #	K_x/K_y (m/s)	K_z (m/s)	Sy (%)	Effective Porosity (%)	Total Porosity (%)	ET (m/d)	Extinction Depth (m)
1	1.1×10^{-5}	1.1×10^{-6}	0.20	0.22	0.25	0.00232	3
2	1.5×10^{-5}	1.5×10^{-6}	0.21	0.22	0.25	0.00239	3
3	2.0×10^{-5}	2.0×10^{-6}	0.21	0.22	0.25	0.00246	3
4	2.5×10^{-5}	2.5×10^{-6}	0.21	0.22	0.25	0.00246	3
5	3.0×10^{-5}	3.0×10^{-6}	0.22	0.22	0.25	0.00253	3
6	3.5×10^{-5}	3.5×10^{-6}	0.23	0.22	0.25	0.00253	3
7	4.0×10^{-5}	4.0×10^{-6}	0.23	0.22	0.25	0.00256	3
8	4.5×10^{-5}	4.5×10^{-6}	0.23	0.22	0.25	0.00256	3

Table 9 lists the statistical results during each simulation. The residual statistics are the maximum, minimum, and average distance of the calculated data from the observed data. This can further be quantified as an absolute value (distance from zero) to yield the absolute residual mean. The standard error of estimate is the standard deviation of all the wells in the calibration.

Root mean squared (RMS) error measures the accuracy of the calculated head values against the observed head values. The normalized RMS error, which is the RMS error divided by the range of values found in the calibration, was used to ensure the model was as accurate as possible. Lower percentages of the normalized RMS error mean that there is less residual variance in each model run. The model was considered calibrated when the statistical analysis revealed there was little measurable variance in the errors. Ideally, the residuals and errors for a calibrated model should be a small percentage of the actual head values, in this case below 0.25

m. The coefficient of determination (r^2) should be as close to 1 as possible to be deemed plausible. The target threshold for the RMS error was < 10%.

Table 9: Errors for each run that was conducted to calibrate the numerical model.

Run #	Maximum Residual (m)	Minimum Residual (m)	Residual Mean (m)	Absolute Residual Mean (m)	Standard Error (m)	RMS (m)	Normalized RMS (%)	r^2
1	3.240	0.431	1.997	1.997	0.290	2.178	134.425	0.883
2	2.498	0.289	1.135	1.395	0.226	1.551	95.768	0.867
3	1.952	0.165	1.001	1.001	0.190	1.152	71.098	0.855
4	1.631	0.088	0.795	0.795	0.168	0.941	58.111	0.860
5	1.326	0.010	0.583	0.583	0.149	0.734	45.317	0.861
6	1.117	-0.043	0.453	0.461	0.135	0.607	37.474	0.867
7	0.920	0.005	0.325	0.344	0.123	0.492	30.345	0.871
8	0.755	-0.003	0.224	0.273	0.113	0.407	25.131	0.876

During the calibration, wells EIC1, EIC2, and EIC3 consistently had calculated head values higher than observed head values. This was most likely a result of the hydrologic parameters being overly sensitive in those areas. Although the normalized RMS error was 25%, which is 15% higher than ideal, the model was still calibrated enough with these wells included in the model. During the next phase of calibration, wells EIC1, EIC2, and EIC3 were turned off to determine the statistical influence the wells had on the model (Table 10). Each run maintained identical hydrologic parameters simulated during the last calibration that included the three wells. The statistics of the calibration without the three wells were significantly better, with most values improving by up to 75%. The normalized RMS error was computed to 6.2%, which is below acceptable thresholds for groundwater models (< 10%) (Lutz et al., 2009).

Table 10: Errors for each run that was conducted to calibrate the numerical model. Wells EIC1, EIC2, and EIC3 are not included.

Run #	Maximum Residual (m)	Minimum Residual (m)	Residual Mean (m)	Absolute Residual Mean (m)	Standard Error (m)	RMS (m)	Normalized RMS (%)	r^2
1	2.372	0.431	1.554	1.554	0.262	1.681	103.778	0.968
2	1.772	0.289	1.037	1.037	0.187	1.133	69.960	0.955
3	1.310	0.165	0.683	0.683	0.139	0.763	47.088	0.952
4	1.005	0.088	0.501	0.501	0.107	0.566	34.944	0.963
5	0.732	0.010	0.316	0.316	0.083	0.376	23.197	0.969
6	0.528	-0.043	0.203	0.215	0.065	0.258	15.913	0.977
7	0.345	0.005	0.094	0.121	0.051	0.156	9.617	0.982
8	0.192	-0.003	0.009	0.079	0.041	0.101	6.229	0.986

3.5.3 Simulation of groundwater pumping

During the study period, the highest observed head rise for a single storm event was 1 meter for Hurricane Irene. This is considered to be the maximum height of water in the model that would need to be removed to diminish a flood event. This conservative estimate is used in deducing where pumping wells should be placed, and how much should be pumped to achieve the ideal drawdown. Using the calibrated steady state model, five scenarios were envisioned to test the effects of pumping on the water table at various locations. These locations were identified from the flood potential maps as areas that are prone to flooding (Fig. 23).

To successfully reduce the water table back to normal values, a pumping well was simulated at each location, and would run for the entire duration of the steady-state simulation. The wells were designed to have a fully penetrating well screen for the model’s single layer. Pumping well diameters were set at 0.51 meters (20 inches), which are used in industry production wells for similar pumping rates (Amsbaugh, 1996). The groundwater contour maps acquired from Visual MODFLOW representing extreme events were used to determine the drawdown required to lower the water table such that flooding potential would be reduced in the problem area. Thus, no more than this amount is needed to lower the water table to reduce the flooding potential from a shallow water table (Table 11).

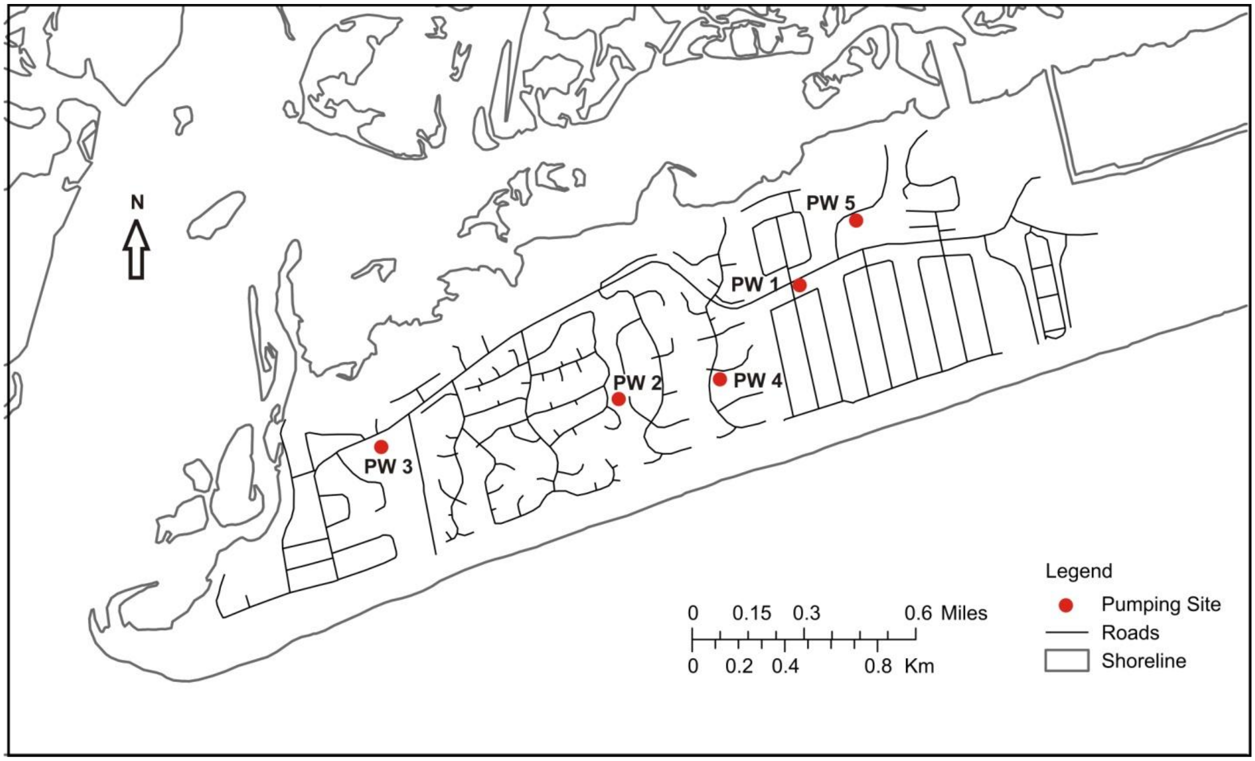

Figure 23: Locations of sites chosen to simulate groundwater pumping at to lower the water table.

The results for each pumping scenario are shown in Appendix B. In each of the figures, the water level contours associated with the non-pumping, steady-state simulation are compared to the stressed water level conditions after pumping. The first four pumping scenarios simulated a relatively low pumping rate of 500 m^3/day (92 gpm), while the last was doubled to assess the effects pumping would have on drawdown. This volume was deemed suitable to reduce a high water table during a storm event, while not extracting unnecessary volumes of water from the aquifer. The cone of the depression was also monitored closely, so that the cone did not reach any major surface water body such as Bogue Sound or the Atlantic Ocean. Interaction of the cone of depression with the major water bodies would not be desirable as this would induce saltwater intrusion in to the shallow aquifer. Although scenario 5 would create a larger area of influence to reduce an elevated water table, the results suggest that the potential for drawing in saltwater from Bogue Sound to the north would be considerably high.

Table 11: Results of simulating groundwater pumping in the numerical model.

Scenario	Subdivision	Pumping rate (m^3/day)	1 m drawdown radius (m)	Cone of depression diameter (m)
1	Ocean Oaks	500	115	750
2	Eastern Lands End	500	175	975
3	Point Emerald Villas	500	170	775
4	Dolphin Ridge	500	150	875
5	Emerald Isle Woods Park	1000	250	1150

3.5.4 Analytical solution to test feasibility of numerical model

An analytical solution was used to assess whether the results of the numerical model were practical. Using Neuman's (1972) equation for unconfined aquifers:

$$\mathrm{ho} - \mathrm{h} = [\frac{\mathrm{Q}}{4\pi \mathrm{T}}]\mathrm{W}(\mathrm{uA}, \mathrm{uB}, \Gamma) \qquad \text{Eq. (4)}$$

where h is the drawdown, Q is the pumping rate, T is transmissivity, and $W(u_A, u_B, \Gamma)$ is the well function for the water-table aquifer. Variables used in the numerical model were input to solve for the drawdown. Results from the analytical solution show that a well pumping at 500 m^3/day for the entire day will produce a drawdown of less than the 1 meter requirement (Table 12). At a distance of 50 m, which is the cell size of the numerical model, the drawdown estimated using the analytical solution would be 0.43 m. This reduced drawdown in relation to those estimated by the numerical model is due to the assumptions inherent when pumping from an unconfined aquifer. The Neuman equation assumes that water pumped from an unconfined aquifer will behave in two manners. First, that the early stage of water withdrawal will be a result of the decline in pressure because of the elastic storage of the aquifer storativity (u_B), and second, the later stage of withdrawal will be a result of the water draining under the gravity of the sediments, or specific yield (u_A) (Fetter, 2000). This lower estimate of water withdrawal may be more accurate due to the assumptions in Neuman's equation. However, the pumping of the Surficial aquifer may be impracticable for two reasons: cost benefit, and an excess volume of water the town will have to safely discharge of elsewhere.

Pumping scenarios proposed in this chapter were meant to show the possibility of withdrawing water during storm conditions to reduce flooding. Although the likely cost for the installation and running of these shallow pumps would be practicable, the pumps would not solve the infiltration problems that the soil analysis revealed. To better address the storm-water issue, broader, more conservative measures must be taken to ensure current and future development minimizes flooding potential. Urban storm-water can best be controlled in this manner by various Best Management Practices (BMPs) (Wossink and Hunt, 2003, Wahl, 2009). These methods can not only be considered for future alterations to the island, but can be applied to existing areas to enhance the natural infiltration of water in to the subsurface.

CHAPTER 4: STORM-WATER BEST MANAGEMENT PRACTICES

4.1 Overview

As discussed in previous sections, the urban development of Emerald Isle has increased the relative percentage of impervious cover over the last few decades. This development, along with the natural dune and swale topography, has created flooding problems in several locations within the study area. When this storm-water is not properly managed, the surrounding environment may be adversely affected in two ways. First, the changes in volume, timing, and location of discharge will be altered. Second, the movement of pollutants from the site to nearby water bodies and the underlying groundwater system will be a threat to the water quality (Wossink and Hunt, 2003). Although the water quality effects will not be detailed in this discussion, the suggestions will lead to safer management of possible pollutants on the island.

Storm-water Best Management Practices (BMPs) can be broken down into two categories: non-structural and structural. Typically, the state of North Carolina prefers non-structural methods of reducing runoff (NCDENR, 2007). However, structural methods may have greater benefits on Emerald Isle since much of the study area is already developed. The North Carolina Division of Environment and Natural Resources (NCDENR, 2007) cite the following as preferred, non-structural methods for storm-water management:

- Public education and participation
- Land-use planning and management (vegetative controls, reduced and/or disconnected impervious areas)
- Material use controls (housekeeping practices, pesticide and fertilizer use)
- Spill prevention and cleanup (vehicle spill control, aboveground tank spill control

- Connection controls (illicit connection detection, removal, and prevention, leaking sanitary sewer control)
- Street and storm drain maintenance (roadway cleaning, catch basin cleaning, vegetation controls, storm drain flushing, roadway/bridge maintenance)

Many of these non-structural methods target source pollutants. As mentioned before, water quality was not looked at, only flood potential of storm-water. However, the structural methods looked at in this study do have strengths in the reduction/removal of suspended solids, particulates, metals, bacteria, and excess nutrients. The methods which outline land-use planning are important for future development proposals, particularly to consider storm-water runoff in early stages of implementation.

4.2 Structural Examples for Reducing Storm-water Runoff

Although the primary concerns of this study have been focused on the shallow groundwater system, low infiltration rates and increased rainfall leading to surface runoff can be a contributing factor to excess storm-water runoff. Infiltration rates can be controlled with the addition of structural BMP’s. Structural BMPs include physical structures that reduce downstream erosion, provide significant flood control from storm-water runoff, and help runoff naturally recharge into the subsurface (NCDENR, 2007). Some structural BMPs perform better under certain conditions. These factors include the size of the watershed or catchment, the impervious cover of the area, and the amount of available land (Wossink and Hunt, 2003). The structural BMPs detailed in this chapter are bioretention areas (rain gardens), level spreaders, and infiltration basins/trenches. These BMPs are some of the simplest and most feasible within the study area to implement, based on current land-use and goals of the study. Other methods may include sand filters, filter strips, grassed swales, infiltration aids/devices, enhanced riparian buffers, permeable pavements, rainwater harvesting, and storm-water wetlands (NCDENR, 2007).

4.2.1 Bioretention

The use of bioretention areas as a structural BMP is accomplished by creating a shallow basin for plants and soils to aid in natural infiltration. The layout of the bioretention cell (Fig. 24) consists of a layer of mulch to aid in protection from weeds, mechanical erosion, and desiccation, located on top of the sandy, native soil (Wossink and Hunt, 2003). Some bioretention cells designed for less permeable soils have an underdrain which moves water to the storm drain system rather than the subsurface. The high permeability of soils on Emerald Isle (mostly fine to-medium grained sand) would potentially be able to drain runoff at appreciable amounts without the need for an underdrain, unless the bioretention area was sited in an area with low permeability soils (e.g., clay lenses). Surface runoff is removed from the bioretention area via downward movement into the native soil, and evapotranspiration to the water-tolerant vegetation (Wahl, 2009).

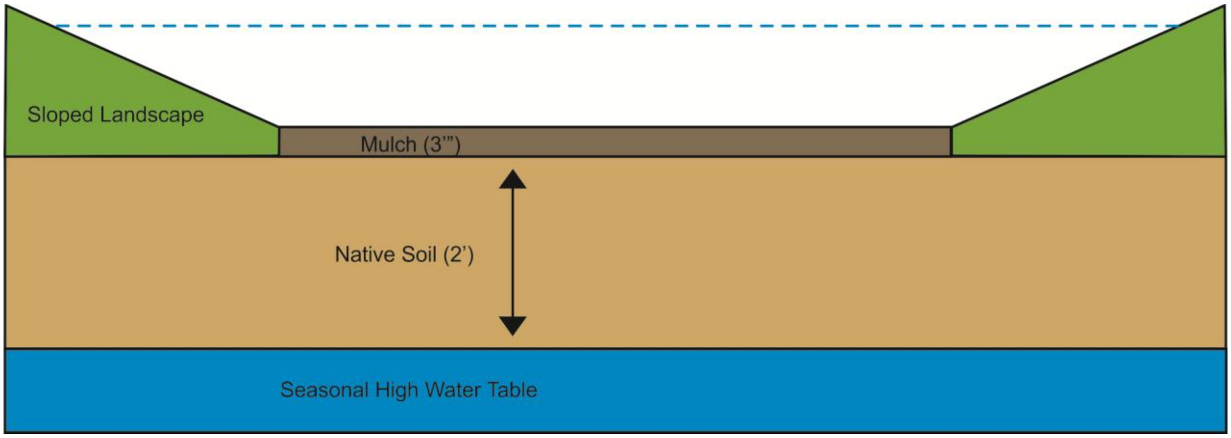

Figure 24: Design of a bioretention cell (adapted from NCDENR, 2007).

Bioretention cells are intended in areas where the seasonal high water table is at least 0.6 m (2 feet) below the land surface, and which receive runoff from a nearby impervious surface (i.e., lawns next to roads, adjacent to sidewalks, parking lots) (Fig.25). The main reason these locations are ideal is to prevent the concentration of flow so the entry velocity is reduced (NCDENR, 2007). The two greatest disadvantages of the bioretention method are that the area drained by the cell can be small, and the cells require constant mulch and vegetation for upkeep (Schueler, 1992). There are three primary factors that make bioretention areas an ideal choice for the study area. First, due to the high volume of residential properties on the western end of Emerald Isle, the small land requirement for bioretention areas could be utilized in most areas. Second, the sandy soil that dominates beneath the subsurface is ideal for drainage in designated problem areas. Last, the landscaping value inherent in these bioretention cells will greatly increase property values and beautification of properties. Bioretention cells are also characterized as a low impact development (LID) (Hunt et al., 2010).

Figure 25: Bioretention garden built in a residential property (from AWPA, 2008)

4.2.2 Level spreader – vegetative filter strip system

A level spreader – vegetative filter strip (LS-VFS) is designed to disperse concentrated storm-water flows, maintain non-erosive flow, and promote higher infiltration/evapotranspiration rates (NCDENR, 2007). The LS-VFS is another example of a structural, low impact development method to remediate runoff problems. However, as bioretention requires a mandatory water table depth, LS-VFS's are able to be constructed in a much wider variety of locations due to no water table constraints. Although some LS-VFS systems encompass fairly large areas of land, the size of them is dependent on the typical flow rate that is directed nearby (Hunt et al., 2010).

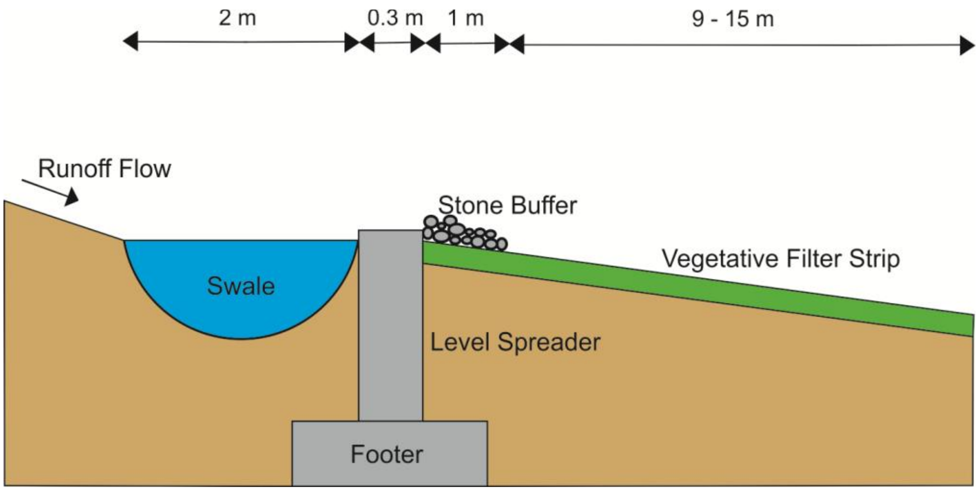

Figure 26: Design of a level spreader - vegetative filter strip (adapted from NCDENR, 2007)

The design of the LS-VFS is separated in into two parts, the level spreader, and the vegetative filter strip (Fig. 26). The level spreader is a concrete structure that acts as a temporary stopper for high volumes of flow. The water is held in the swale until either 1) the water is dispersed and diffused onto the VFS at a manageable rate or 2) the water infiltrates in the swale itself. The size of both the level spreader and vegetative filter strip is determined based on the estimated overland flow the area receives. The higher the volume of runoff, the longer the level spreader length and bigger the vegetative filter strip are.

The application of the LS-VFS as a structural BMP is meant primarily as a component in a larger storm-water management system, not a stand-alone solution (NCDENR, 2007). Case studies in the Charlotte area have shown that these structures can reduce the runoff volume by up to 85% (Hunt et al., 2009). Due to the simple design, low cost of construction, minimal upkeep required, and high community acceptance (NCDENR, 2007), LS-VFS can have a large impact in problem areas within the study area.

4.2.3 Infiltration basins/trenches

Areas along the Coast Guard Road corridor and low-lying swales in residential neighborhoods were found to be the most problematic for storm-water runoff during the study. Infiltration basins and trenches can be used in these areas due to their variability in size, but may be of limited effectiveness in areas with a shallow water table. Both systems are designed to capture runoff from nearby impervious surfaces and channel the water into their respective catchment. The primary difference in application between infiltration basins and trenches is the availability of space.

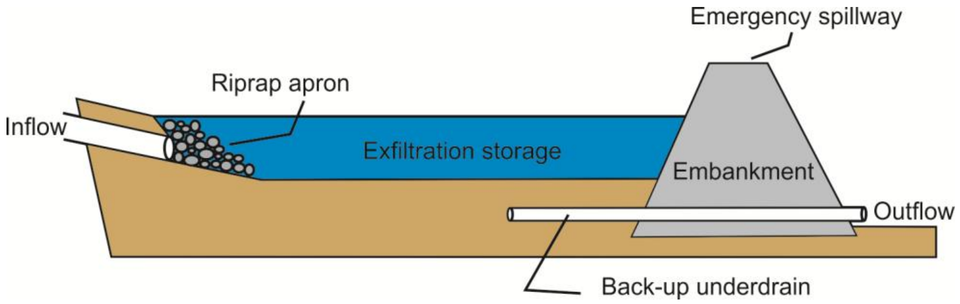

Figure 27: Design of an infiltration basin (adapted from NCDENR, 2007).

Infiltration basins are designed as a shallow depression that captures and stores storm-water until it can infiltrate into the subsurface (Fig. 27) (NJDEP, 2004). They typically provide runoff management for drainage basins 5 to 50 acres in area (Schueler, 1992). Inflow is received from a pipe which collects runoff from nearby impervious surfaces. Once stored for exfiltration, water is discharged via infiltration into the underlying soil, spilled over the embankment, or out of the system during severe events using an underdrain. Infiltration basins are applicable in locations where the soil permeability is high enough and there is sufficient land to construct one. In cases where an infiltration basin would be ideal, but required space is not available, infiltration trenches work well in their place.

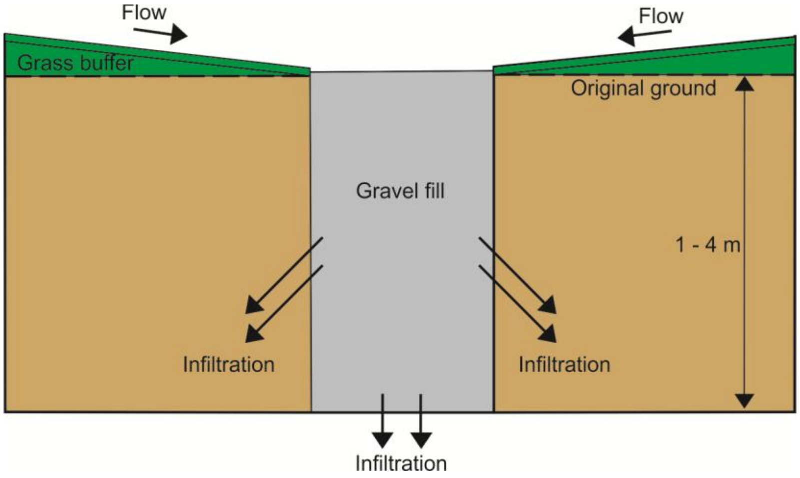

Figure 28: Design of an infiltration trench (adapted from NCDENR, 2007).

Similar to infiltration basins, infiltration trenches are shallow excavated areas designed to create a storm-water reservoir from runoff (APWA, 2008). They are typically filled in with coarse, granular material which creates a highly permeable conduit for infiltration (Fig. 28). Since they are much smaller than basins, their lower storage volumes in smaller catchments are designed to easily capture the first wave of runoff during storm events. Areas where infiltration trenches would be the most effective on Emerald Isle would be in residential lots where flooding is a frequent occurrence. When infiltration trenches are used in combination with other structural BMP’s, the negative side effects of storm-water runoff can be minimized by allowing for increased infiltration potential (Schueler, 1987).

CHAPTER 5: CONCLUSIONS

The results of this study show that the shallow groundwater system may play a significant role in generating storm-water runoff in Emerald Isle on Bogue Banks. Through the creation and analysis of potentiometric maps, the water table did appear to rise to levels at or above the ground surface during storm events. These potentiometric maps reveal that even during times of little precipitation, the water table may have breached the land surface in several locations within the study area. These data confirmed the first of the two hypotheses proposed, that an elevated water table was contributing to storm-water ponding.

The second hypothesis, that infiltration capacities impede natural recharge in low-lying areas, was partially confirmed by analyzing sediment properties of the Surficial aquifer. Low infiltration capacities likely contribute to storm-water runoff in small, elongated soil sections (Fig. 10). Due to the close proximity of the water table to the ground surface (as shown in the flood potential maps), storm-water generation in these areas is likely a result of saturation excess throughout the majority of the year. Therefore, if more areas of the island observe a rise in water levels, storm-water runoff should be more widespread than found during the study year. High water tables and storm-water generation are influenced by the frequency and duration of rain events, which directly control water table levels in the Surficial aquifer. Other conclusions drawn from this study are as follows:

1) Geological analyses of core samples show that the island is composed predominantly of fine to-medium-grained sand. Some horizons of silt, clay and organic material, similar to those found by Anderson (2000) on Hatteras Island, are present close to the surface, suggesting that the infiltration rates may be retarded in these horizons. These reduced infiltration rates should not be ruled out as a major factor contributing

to the storm-water runoff problem. Slug tests performed indicate that the sediment is moderately permeable; with horizontal hydraulic conductivities ranging from 8.6 x 10^{-6} to 6.0 x 10^{-5} m/s. Vertical hydraulic conductivity was estimated to be on the order of one magnitude less than the average horizontal conductivity.

2) Contour maps of the water table divulge a flow regime that is dominated by several mounds on the western part of the island. Groundwater flow is radial from these mounds, and is moving water from the dunes to the low-lying swales which were identified to have a water table near the surface and low infiltration rates impeding recharge.
3) The components of the water budget were estimated to be 223 mm/year for evapotranspiration, 987 mm/year for precipitation, 284 mm/year for surface runoff, 688 mm/year for natural groundwater recharge, -8 mm/year for the change in groundwater storage, and 216 mm/year for artificial recharge. Although the natural recharge is approximately 70% of the precipitation, the permeability of the sediments within the study area would recharge water at appreciable amounts. The change in storage was low enough (-8 mm/year) to assume that the Surficial aquifer can be considered in steady-state conditions.

Pumping was simulated both numerically and analytically to assess storm-water mitigation during extreme rain events. The effects of Hurricane Irene, which brought a maximum water level increase of 1 meter in the observation wells, were used as the baseline data. An analytical solution (Neuman, 1972), which takes into account the behavior of the unconfined aquifer when pumped, showed that the numerical model may be overestimating the drawdown.

This could be a potential short term solution to alleviate flooding, but is likely impracticable and broader, long-term remedies for the town should be considered.

Storm-water Best Management Practices (BMP's) provide a much more conservative approach to reducing runoff. These include structural methods such as bioretention, level spreader-vegetated filter strips, and infiltration basins and trenches. Current and future development should consider the addition of structural BMP's as a sustainable way to mitigate problematic flooding. Not only are most BMP's cost effective, but they can also add aesthetically pleasing landscapes to the area.

This study highlights the need for more studies to be conducted on barrier islands to improve our understanding of the Surficial aquifer. For example, because drainage patterns continue to be altered with the addition of impervious surfaces such as roads and buildings, changes in groundcover can in turn alter the locations and volumes of recharge to the Surficial aquifer, as well as the intensity of runoff. As the island continues to develop, further studies should look into quantifying how this impervious cover changes over time, and how this development has affected infiltration capacities of the soils.

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