**Source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks barrier island, North Carolina**

By:

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Saltwater intrusion is occurring in the confined Castle Hayne aquifer on the western part of the east-west trending barrier island of Bogue Banks, North Carolina. Of eleven municipal wells that are solely screened in the Castle Hayne aquifer on the central and western parts of the island, three wells withdraw water with elevated chloride levels that exceed the drinking water standards of the United States Environmental Protection Agency. The wells on the western side of the island have the highest chloride levels (>1,700 mg/L), whereas the levels progressively decrease in the wells to the east (<250 mg/L). Because the Castle Hayne aquifer is the sole source of potable water on the island, a reverse osmosis plant was built on the western part of the island to address elevated chloride concentrations in the potable water source. Despite this development, the underlying source of saltwater intrusion into the Castle Hayne aquifer is still not well known. Therefore, the goal of this study was to determine the source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks. Borehole logs, seismic profiles, vibracore, and ground penetrating radar data collected by other researchers were used to design a three dimensional multi-layered,

multi-density groundwater flow model using visual MODFLOW. The model was used in conjunction with chloride and long-term water level records to test the hypotheses that the source of saltwater intrusion into the Castle Hayne aquifer is from surface waters surrounding the island and/or a paleochannel underlying the island. Results from modeling suggest that saltwater emanating from surface waters surrounding the island is being drawn into municipal wells and not from the paleochannel underlying the island. The model suggests that brackish surface waters from Bogue Sound migrate downwards through overlying aquifers into the Castle Hayne aquifer. The major driver of the migration is groundwater withdrawal from the municipal wells on the western part of the island. Understanding how groundwater withdrawals impact the migration of saltwater in the Castle Hayne aquifer arms water managers with the knowledge to better safeguard the major source of potable water on the island for future generations.

**Source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks barrier island, North Carolina**

A Thesis

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East Carolina University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Geology

By:

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# CHAPTER 1: INTRODUCTION

## 1.1 Saltwater Intrusion

Saltwater intrusion, which is a major problem in coastal aquifers in many parts of the world (e.g., Cheng and Chen, 2001; Datta et al., 2009; Gossel et al., 2010; Sherif et al., 2012), is caused by landward migration of the saltwater wedge, groundwater withdrawal, or paleochannels that act like conduits from saltwater sources (Barlow, 2003; Hutchings and Tarbox, 2003; Masterson, 2004; Falls et al., 2005; Bray et al., 2007; Mulligan et al.,2007; Murgulet and Tick, 2008; Cobaner et al., 2012). Groundwater withdrawal can cause downward migration of saltwater and upconing from deeper aquifers. (Barlow, 2003; Masterson, 2004). A few examples in the United States where saltwater intrusion is a major concern include Florida, Massachusetts, South Carolina, California, Alabama, and North Carolina (Hutchings and Tarbox, 2003; Masterson, 2004; Falls et al., 2005; Bray et al., 2007; Murgulet and Tick, 2008). In North Carolina, saltwater intrusion in the Castle Hayne aquifer has impacted the communities of Carolina Beach, Wrightsville Beach, Topsail Island, Elizabeth City, and Bogue Banks (Foldesi et al., 2010; Spruill, R., personal communication, March, 2014). When saltwater intrusion occurs in aquifers, freshwater storage is reduced, leaving a major problem for coastal communities that rely on groundwater as their primary source of freshwater (Masterson, 2004).

### 1.2 Saltwater intrusion on Bogue Banks

Bogue Banks, located in the central Coastal Plain of North Carolina, is a thin barrier island that is approximately 40.4 km long with an area of about 29 $km^2$ (Steele, 1980; Grothe et al., 2012). The width of the island varies from 0.19 to 1.5 km with an average width of 0.62 km (Steele, 1980). Elevation on the island ranges from -1 m to 19 m above mean sea level (Grothe, et al., 2012). The island is composed of five main communities. Starting from the western part of the island, these communities are the town of Emerald Isle, Indian Beach, Salter Path, Pine Knoll Shores, and Atlantic Beach (Figure 1). There are three main water providers on the island. The Town of Atlantic Beach and Pine Knoll Shores provide water to their respective inhabitants, whereas BBWC serves the communities of Emerald Isle, Indian Beach, and Salter Path (Figure 2).

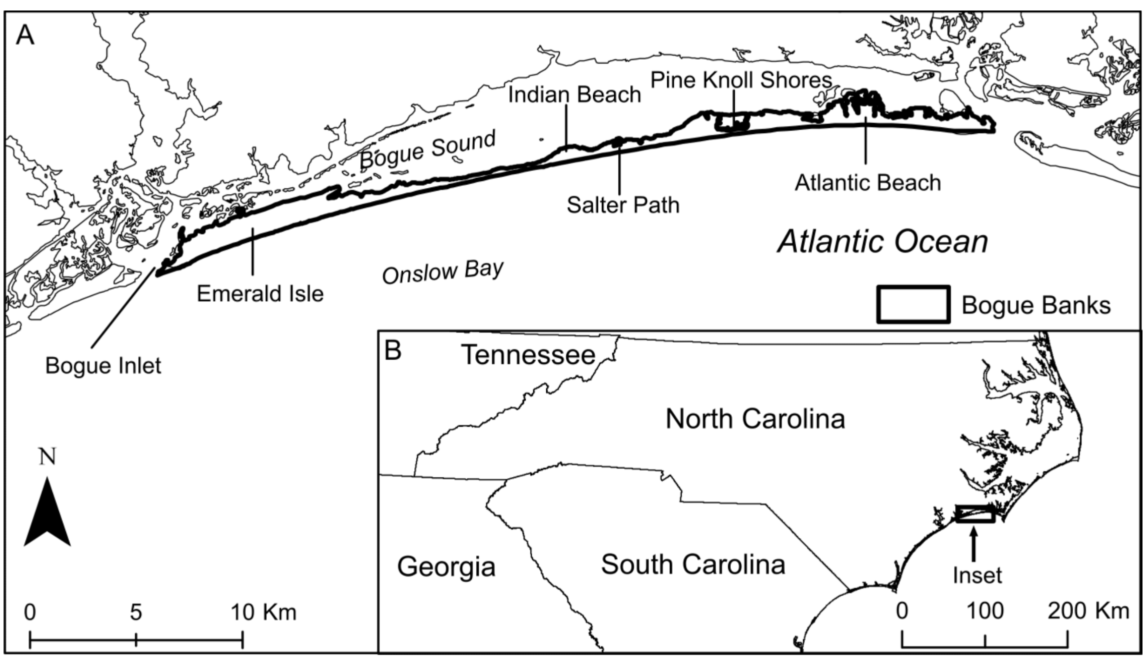


Figure 1. The five main communities located on Bogue Banks, North Carolina. (A) Bogue Banks, (B) Location of Bogue Banks with respect to North Carolina.

Bogue Banks has seen an increase in saltwater intrusion in recent years in the Castle Hayne aquifer on the western part of the island (Table 1). Saltwater intrusion in the aquifer has caused an increase in chloride concentrations in excess of 1,000 mg/L in three municipal wells (Table 1). These elevated chloride concentrations are higher than the United States Environmental Protection Agency's secondary drinking water standard of 250 mg/L (Environmental Protection Agency, 2013).

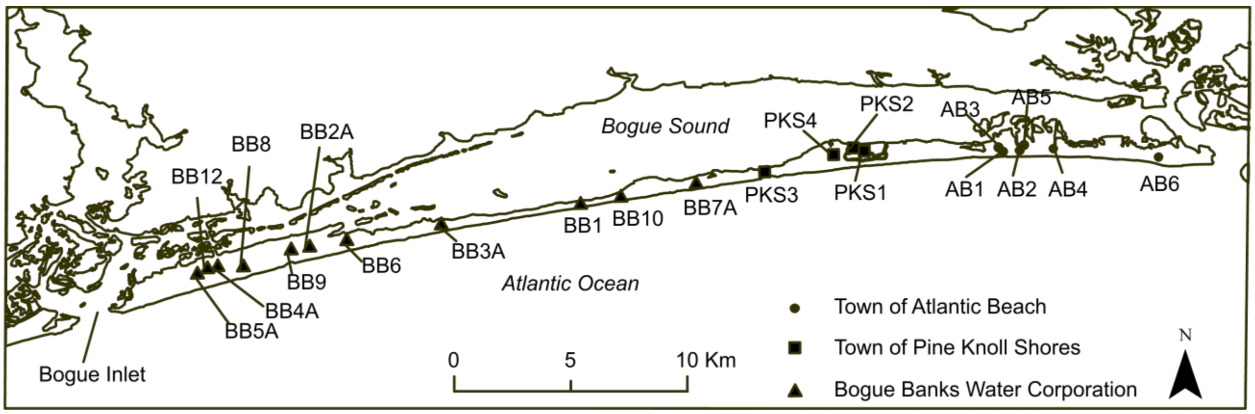


Figure 2. Location of municipal wells of the three main water providers on Bogue Banks.

Due to high demand for freshwater on the island, Bogue Banks Water Corporation (BBWC) completed a reverse osmosis plant (also known as a membrane plant) on 02/01/2013 in the town of Emerald Isle to combat saltwater intrusion occurring in the Castle Hayne aquifer (Hill, S., personal communication, August, 2013). Construction costs for the reverse osmosis plant amounted to ~$3,500,000, whereas the cost of the three replacement municipal wells totaled ~$1,500,000 (Hill, S., personal communication, August, 2013). In comparison, conventional water treatment plants that function at the same capacity (5,700 cubic meters per day) cost ~$1,000,000 (Hill, S., personal communication, August, 2013). Although it is clear that the western part of the island has higher chloride concentrations than the rest of the island, it is not entirely clear what is causing saltwater intrusion. This study utilized a numerical modeling approach to investigate the source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks barrier island.

Table 1. Average chloride concentrations observed in municipal wells screened in the Castle Hayne aquifer (2009-2013). Data were acquired from Bogue Banks Water Corporation.

| Date | Chloride Concentrations (mg/L) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | BB1 | BB2A | BB3A | BB4A | BB5A | BB6 | BB7A | BB8 | BB9 | BB10 | BB12 |
| 2009 | - | - | - | 555 | - | - | - | - | - | - | 1170 |
| 2010 | 36 | 18 | - | - | 327 | 19 | - | 330 | 13 | 114 | - |
| 2011 | 21 | 17 | 146 | - | - | 16 | 21 | 344 | 15 | 123 | - |
| 2012 | 41 | 42 | 162 | - | - | 16 | 26 | 315 | - | 132 | - |
| 2013 | 130 | 15 | 175 | 1940 | 1730 | 16 | 22 | 245 | 14 | 157 | 2700 |

### 1.3 Water source and significance of study

The population on Bogue Banks has increased in the past several decades. Communities like Emerald Isle have seen an increase in permanent population from 122 in 1970 to 3,655 in 2010 (http://www.census.gov/) (Figure 3). Indian Beach and Salter Path had no reported permanent residents in 1970, however, by 2010 the permanent populations were112 and 316, respectively (http://www.census.gov/). As part of the Outer Banks, Bogue Banks attracts thousands of tourists each year. The tourist population in the summer months is about eleven times higher than the permanent population on the island (Allenby, 2011). In 2003, it was estimated that 36,000 tourists visited Emerald Isle, with other communities on the island showing a similar tourism impact (Town of Emerald Isle, 2006).

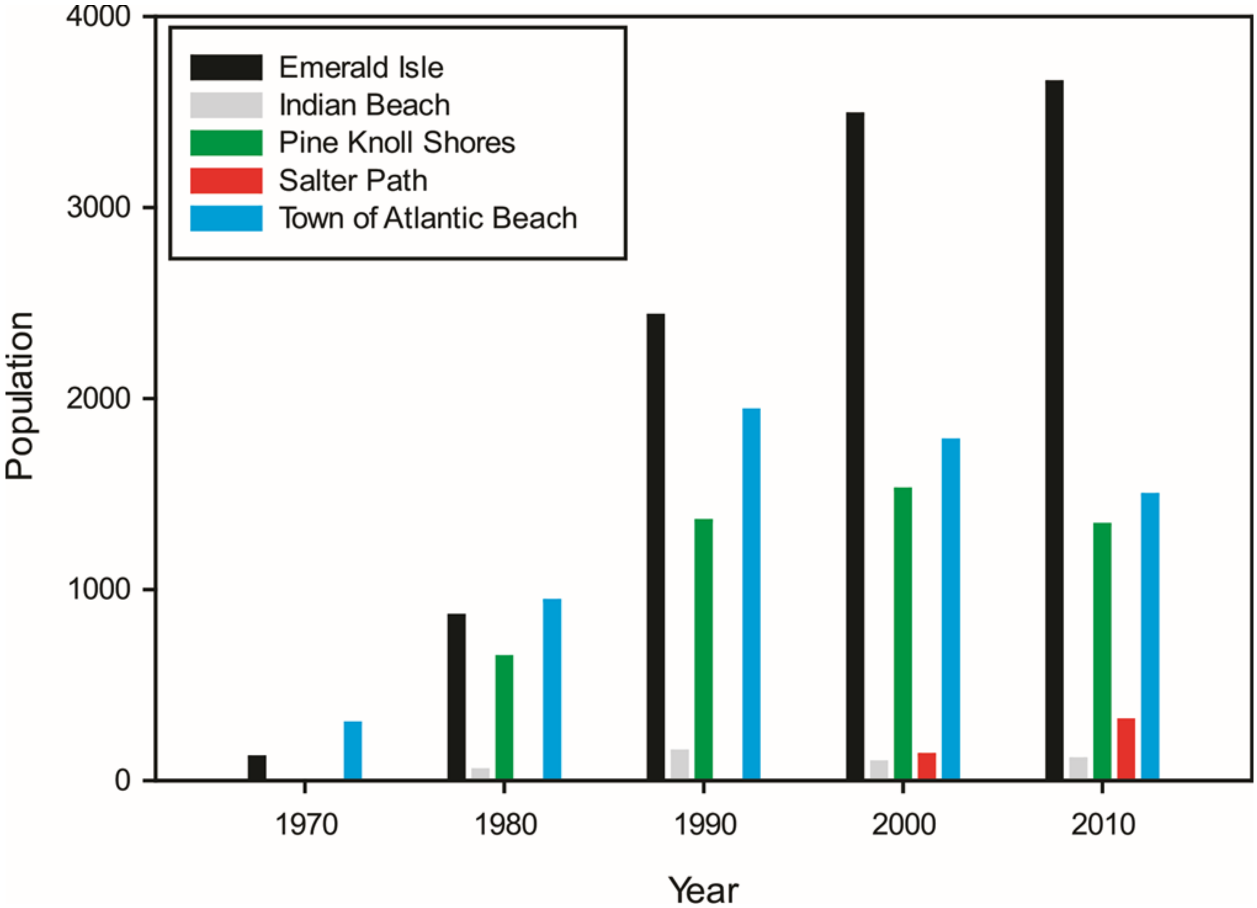


Figure 3. Permanent population of Emerald Isle, Indian Beach, Pine Knoll Shores, Salter Path, and Town of Atlantic Beach from 1970-2010.

All three water providers on the island withdraw water from the Castle Hayne aquifer through a series of 21 wells, the majority of which are no deeper than 100 m below the land surface (Table 2). According to the Division of Water Resources of the North Carolina Department of Environment and Natural Resources (NC DENR) (NC DENR, 2014a,b,c), BBWC withdraws water from the Castle Hayne aquifer through eleven municipal wells, whereas the towns of Atlantic Beach and Pine Knoll Shores withdraw water from six and four municipal wells, respectively (Figure 2).

Since 1989, when water providers began keeping groundwater withdrawal records, the total amount of groundwater withdrawn from the Castle Hayne aquifer by BBWC has increased from ~1.4 million cubic meters to ~1.5 million cubic meters in 2010 (Hill, S., personal communication, August, 2013; NC DENR, 2014a). The records indicate that the total amount of groundwater withdrawn by the town of Atlantic Beach has decreased from ~1 million cubic meters to ~946 thousand cubic meters over the period 2001-2010 (NC DENR, 2014b). The town of Pine Knoll Shores has experienced an increase in the amount of groundwater withdrawal from ~75 thousand cubic meters in 2000 to ~534 thousand cubic meters in 2010 (NC DENR, 2014c).

Table 2. Well characteristics derived from groundwater municipal wells on Bogue Banks (Figure 2). BB = Bogue Banks Water Corporation, AB = Town of Atlantic Beach, PK = Town of Pine Knoll Shores.

| Well ID | Land surface elevation (m) | Well diameter (cm) | Pump capacity ($m^3$/min) | Depth of top of well screen (m) | Well Depth (m) |
|---|---|---|---|---|---|
| BB5A | 4 | 25 | 4.2 | 47 | 61 |
| BB12 | 5 | 25 | 4.5 | 51 | 63 |
| BB4A | 4 | 25 | 2.6 | 51 | 67 |
| BB8 | 4 | 43 | 1.5 | 49 | 59 |
| BB9 | 4 | 51 | 1.2 | 55 | 61 |
| BB2A | 4 | 25 | 1.2 | 53 | 69 |
| BB6 | 3 | 25 | 1.2 | 59 | 68 |
| BB3A | 5 | 25 | 3.7 | 55 | 73 |
| BB1 | 6 | 10 | 0.6 | 73 | 86 |
| BB10 | 7 | 30 | 2.5 | 65 | 88 |
| BB7A | 3 | 25 | 3.2 | 74 | 86 |
| PK3 | 4 | 15 | 1.1 | 43 | 52 |
| PK4 | 2 | 20 | 1.5 | 39 | 48 |
| PK2 | 3 | 15 | 1.4 | 49 | 64 |
| PK1 | 4 | 15 | 1.1 | 48 | 57 |
| AB3 | 5 | 25 | 1.5 | 65 | 74 |
| AB1 | 5 | 25 | 1.1 | 60 | 69 |
| AB2 | 4 | 25 | 1.0 | 74 | 83 |
| AB5 | 2 | 25 | 1.5 | 74 | 94 |
| AB4 | 2 | 25 | 1.0 | 61 | 79 |
| AB6 | 3 | 25 | 1.5 | 78 | 134 |

With the source of saltwater intrusion still undermined on the island, additional corrosion resistant municipal wells and reverse osmosis plants could be built on the island if more wells and potable water become susceptible to saltwater intrusion. This study aimed to determine the source of saltwater intrusion in the aquifer. Ultimately, the results can improve our understanding of water resources on the island and provide water managers with the tools needed to account for future reduction of freshwater storage.

## 1.4 Objective

The objective of this study was to determine the source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks barrier island. Using borehole logs, seismic profiles, vibracore, and ground penetrating radar data collected by other researchers, a three dimensional multi-layered, multi-density groundwater flow model was created. The model was then used in conjunction with chloride records and twenty five years of water level data to test the hypotheses that the source of saltwater intrusion is from (a) surface water surrounding the island and/or (b) a paleochannel underlying Bogue Banks.

## 1.5 Rationale

The hypotheses were developed by first assessing all the possible sources of high chloride concentrations in the Castle Hayne aquifer on the western part of Bogue Banks (i.e., groundwater withdrawal, landward migration of the saltwater wedge, downward migration of surface waters, upconing from deeper aquifers, or paleochannels). From the possible sources, landward migration of the saltwater wedge and upconing from deeper aquifers were discarded as options because based on information and data from NC DENR, the saltwater wedge was determined to be much farther east of the study area (NC DENR, 2014d).

The options that were therefore shortlisted as potential sources are the downward migration of surface waters, and the possibility that saline water may be channeled to groundwater wells via a paleochannel underlying the island. Surface water bodies surrounding Bogue Banks include the Atlantic Ocean, Bogue Inlet, and Bogue

Sound. Surface water bodies have been shown to be sources of saltwater intrusion by other researchers working in other sites that have similar hydrogeology (Barlow, 2003; Foldesi et al., 2010).

Research conducted at other sites within the region has also revealed that paleochannels may be sources of high chloride concentrations in confined aquifers (Barlow, 2003; Falls et al., 2005; Mulligan et al., 2007). For example, Barlow (2003) found that saltwater migrated downward into confined aquifers at Cherry Point (~22 km inland from Bogue Banks) owing to the presence of paleochannels that breached confining units of the aquifers. For the options shortlisted above, it was assumed that groundwater withdrawal from the municipal wells on Bogue Banks was driving saltwater intrusion (Giese et al., 1997; Barlow, 2003).

## CHAPTER 2: HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the central Coastal Plain of North Carolina consists of eight aquifers and seven confining units (Giese et al., 1997). Aquifers and confining units ranging in age from recent through Cretaceous are eastward dipping, eastward thickening wedges of sediment and sedimentary rock lying on top of Paleozoic age basement rocks (Lautier, 2001). Aquifers include the Surficial, Yorktown, Castle Hayne, Beaufort, Peedee, Black Creek, and the Upper and Lower Cape Fear (Winner and Coble, 1989). Confining units are located between each aquifer and are named after the aquifer located directly below the confining unit. Since the purpose of this study is to identify the possible sources causing saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks Island, only the Castle Hayne aquifer and the overlying hydrogeologic units are considered in this study (Figure 4).

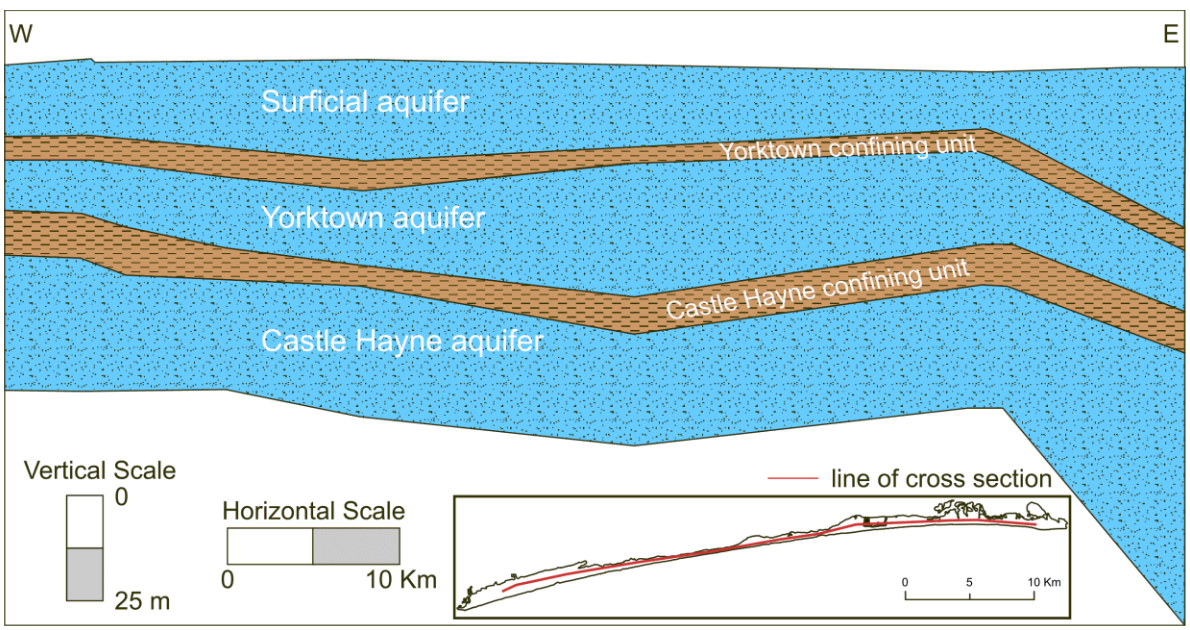


Figure 4. Hydrogeologic cross section across Bogue Banks showing the three aquifers and two confining units identified for this study. The cross section was created using borehole data available from municipal wells located on the island.

### 2.1 Surficial aquifer

The Surficial aquifer, also known as the water table aquifer, underlies all of the North Carolina Coastal Plain (Lautier, 2001). The aquifer is Pleistocene to Holocene in age and is composed of fine sand, silt, clay, shell, soil, residuum, and peat beds (Giese et al., 1997). The aquifer ranges in thickness from 1.0 m to 9.1 m in the west and central portions of the Coastal Plain, but can get as thick as 61 m in the Outer Banks (Giese et al., 1997). The aquifer receives direct recharge from precipitation and runoff, and is the source of water for underlying confined aquifers and base flow to streams (Lautier, 2001). Recharge rates from precipitation vary from 30.5 cm/year to 50.8 cm/year, depending on clay content of the aquifer (Winner and Coble, 1989, 1996). Horizontal hydraulic conductivity ranges from 3.0 to 15.2 m/day, with an average of 8.8 m/day (Winner and Coble, 1989, 1996).

### 2.2 Yorktown confining unit

The Yorktown confining unit is Pliocene in age, and consists of beds of clay and silt (Lautier, 2001, 2006). The thickness of the confining unit increases from west to east and from less than 3.0 m, to as thick as 21.3 m, with an average thickness of 7.6 m (Winner and Coble, 1989; Giese et al., 1997). In most of the central Coastal Plain, the confining unit is directly below the Surficial aquifer (Winner and Coble, 1989).

### 2.3 Yorktown aquifer

The Yorktown aquifer is Pliocene in age, and consists of fine sand, silty and clayey sand, sands with shells and shell beds, and some limestone and coarse sand beds (Giese et al., 1997). The thickness of the aquifer increases from west to east at 1.3 m/km and gets as thick as 91.4 m (Winner and Coble, 1989). Recharge in the aquifer comes from the overlying Surficial aquifer at a rate of 2.5 cm/year (Winner and Coble, 1989; Giese et al., 1997). Average horizontal hydraulic conductivity of the aquifer is 6.7 m/day, with a range of 5.8 to 10.1 m/day (Giese et al., 1997).

### 2.4 Castle Hayne confining unit

The Castle Hayne confining unit is Eocene in age, and consists of beds of clay, and sandy clay, and has an average thickness of 3.0 m (Giese et al., 1997). Most of the confining unit is thin and comprises enough sand to allow significant leakage between the Surficial and Castle Hayne aquifer (Winner and Coble, 1989). The Surficial and Castle Hayne aquifers have similar responses to seasonal recharge variations, indicating that the Castle Hayne confining unit is not completely impermeable, and that the Castle Hayne aquifer is not well confined (Lautier, 2001). Horizontal hydraulic conductivity in the confining unit was measured by Winner and Coble (1989) to be $2.8 \times 10^{-5}$ m/day with a vertical hydraulic conductivity of $9.17 \times 10^{-6}$ m/day.

### 2.5 Castle Hayne aquifer

The Castle Hayne aquifer is the most productive aquifer in North Carolina with an average of 80 to 90 percent sand and carbonate rock (Giese et al., 1997; Winner and Coble, 1996). The aquifer is composed of Eocene age limestone, sand, and marginal amounts of clay which were deposited under marine conditions (Winner and Coble, 1989). The thickness of the aquifer ranges from a few meters to 291 m (Lautier, 2001). Overlying aquifers provide a recharge of 2.5 cm/year to the Castle Hayne aquifer (Giese et al., 1997). Horizontal hydraulic conductivity in the aquifer ranges from 8 to 61 m/day, with an average horizontal hydraulic conductivity of 20 m/day (Winner and Coble, 1996; Groundwater Management Associates, Inc., 2013).

### 2.6 Paleochannel Characteristics

Previous research on Bogue Banks conducted by other researchers using seismic, vibracore and ground penetrating radar (GPR) reveal multiple paleochannels located off the coast running through the island (Hines and Snyder, 1985; Timmons et al., 2010). Prior to the last sea-level rise during the late Pleistocene-Holocene epochs, one of these channels flowed across the study area and cut into underlying confining units and confined aquifers (Hines and Snyder, 1985; Mulligan et al., 2007; Timmons et al., 2010). During sea-level rise, the channel was infilled with mud, and minor amounts of sands and shells (Hines and Snyder, 1985). The shells which infilled the channel have been dated via amino acid racemization technique to be Pleistocene in age (Belknap, 1982; Snyder et al., 1982a, b, c).

Although multiple paleochannels are present off the coast and cut through Bogue Banks, only one paleochannel in particular was included in this study. The paleochannel included in this study is located on the western part of the island (Figure 5). This paleochannel seemed to be the most probable channel to influence the three municipal wells experiencing high chloride concentrations owing to (a) its close proximity to the wells and (b) its dip to underlying hydrogeologic units.

## 2.7 Bogue Inlet

Bogue Inlet is located between the western side of Bogue Banks and Bear Island (Figure 5). The inlet is 2.4 km wide and provides a path for marine waters to enter the admitted areas behind Bogue Banks (Goff, 1977). The inlet has many channels with the deepest channel having a depth of 6.0 m (Goff, 1977). The exact age of the inlet is unknown but best records indicate a pre-1585 opening date (Fisher, 1962). The position of the inlet has not moved since the earliest map of the island was created in 1681 (Goff, 1997). According to Goff (1977), the sediment composition in the inlet ranges from silt/very fine sand to medium sand/coarse sand.

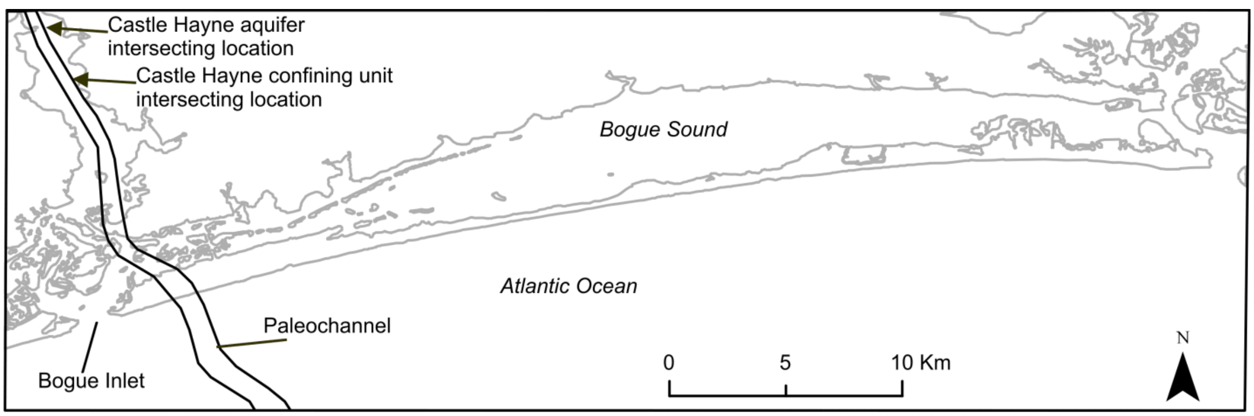


Figure 5. Map of model area showing the locations at which the paleochannel breaches the Castle Hayne confining unit and the Castle Hayne aquifer.

# CHAPTER 3: METHODOLOGY

## 3.1 Groundwater Flow Modeling

Following the protocol for simulating groundwater flow suggested by Anderson and Woessner (2002) (Figure 6), a conceptual model of the groundwater system on Bogue Banks was first developed (Figure 7). Then, the commercially available groundwater flow modeling software, Visual MODFLOW (v. 2011.1) was used to calibrate and verify the model. Visual MODFLOW utilizes the three-dimensional modular finite-difference groundwater flow code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh, 2005) to simulate flow in steady or transient state. The model was calibrated using static heads from both the Surficial and Castle Hayne aquifers. Verification of the model was done using groundwater withdrawal data and potentiometric heads of the Castle Hayne aquifer. After the model was verified, four scenarios were simulated in the numeric engine SEAWAT to identify the source of saltwater intrusion. A predictive model was then created with the best identified source to determine the future impact of saltwater intrusion on Bogue Banks.

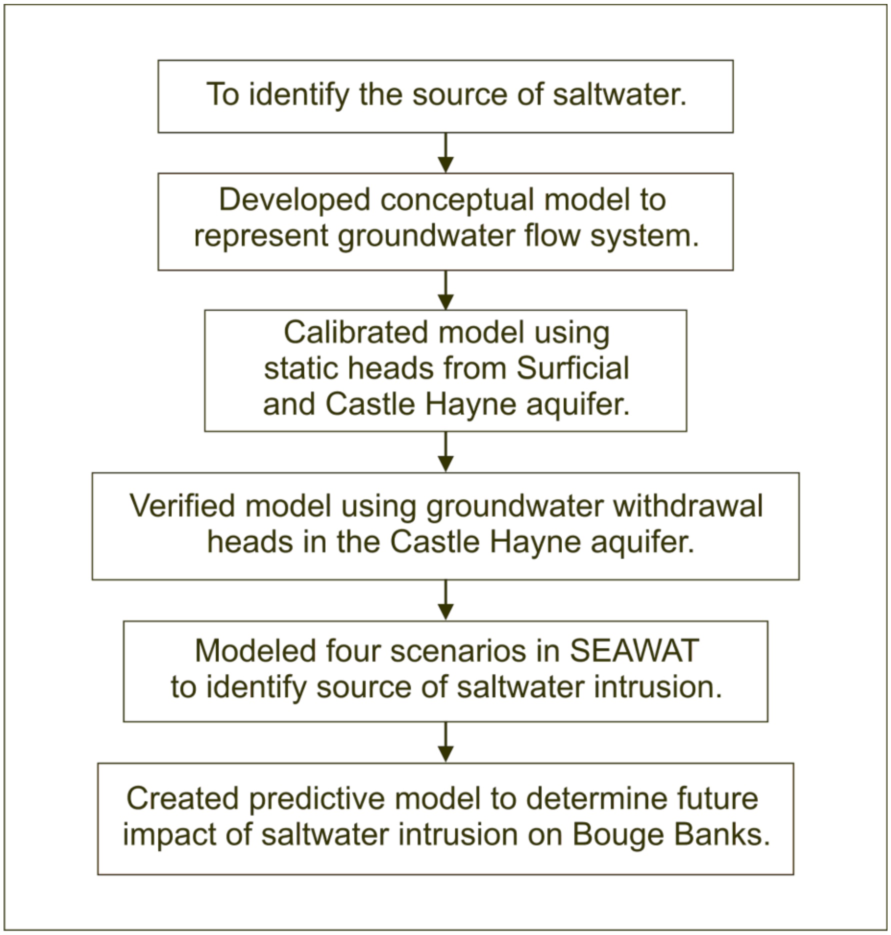


Figure 6. Flow chart showing process from defining purpose to making predictions with groundwater model (Adapted from Anderson and Woessner, 2002).

The SEAWAT engine has been used in MODFLOW to better understand groundwater flow in unconfined and confined aquifers in many coastal regions (e.g., Jackson, 2007; Mulligan et al., 2007; Langevin, 2003; Rozell and Wong, 2010; Cobaner, 2012; Sherif et al., 2012; Fine and Kuniansky, 2013). For example, Rozell and Wong (2010) used SEAWAT to model the saltwater wedge underlying Shelter Island, New York. Rozell and Wong (2010) ran two scenarios to identify the impact of climate change on the location of the saltwater wedge underlying the island by changing precipitation and sea-level from their current levels. Results from the study show a seaward migration of freshwater when precipitation and sea-level were increased. When precipitation decreased and sea-level increased, a landward migration of saltwater occurred. Although Rozell and Wong's (2010) focus was on how precipitation and sea-level impact the islands freshwater availability, a greater understanding of the boundary conditions needed for island modeling were gathered.

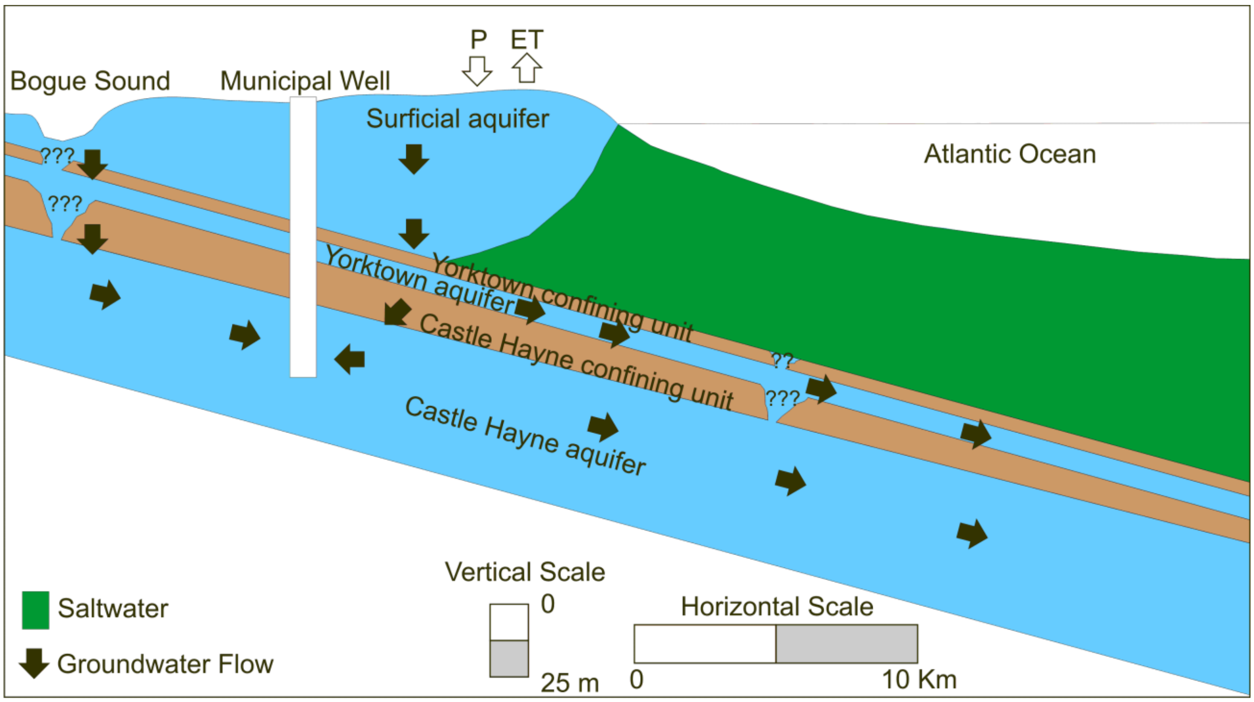


Figure 7. Conceptual model representing the hydrogeologic units and boundary conditions of the model. P=Precipitation, ET=Evapotranspiration.

### 3.2 Model Design

A grid consisting of 17 layers, with 124 rows and 363 columns was created for the study area (Figure 8). Thus, each layer of the model had 45,012 cells, for a total of 765,204 cells for the 17 layers. Cell size throughout the model varied. Cells not around municipal wells had dimensions of 121 x 144 m. Telescopic mesh refinement was used to make the cell sizes finer (77 x 71 m) around wells where groundwater withdrawal was simulated. The layers in the model represent the following units: Layers 1 to 6 - Surficial aquifer, layer 7 -Yorktown confining unit, layers 8 to 11 - Yorktown aquifer, layers 12 to 15 - Castle Hayne confining unit, and layers 16 to 17 - Castle Hayne aquifer. (Figures 9 and 10). The area of interest for the model covers 522.9 km$^2$ of water, 183 km$^2$ of the mainland of southern Carteret County, 18.7 km$^2$ of eastern Onslow County, and all 28.7 km$^2$ of Bogue Banks. The total area covered by the model is 753.3 km$^2$.


Figure 8. Grid of model area showing the location of row 62 and column 181. The row and column are located at the midpoint of the grid along each axis.

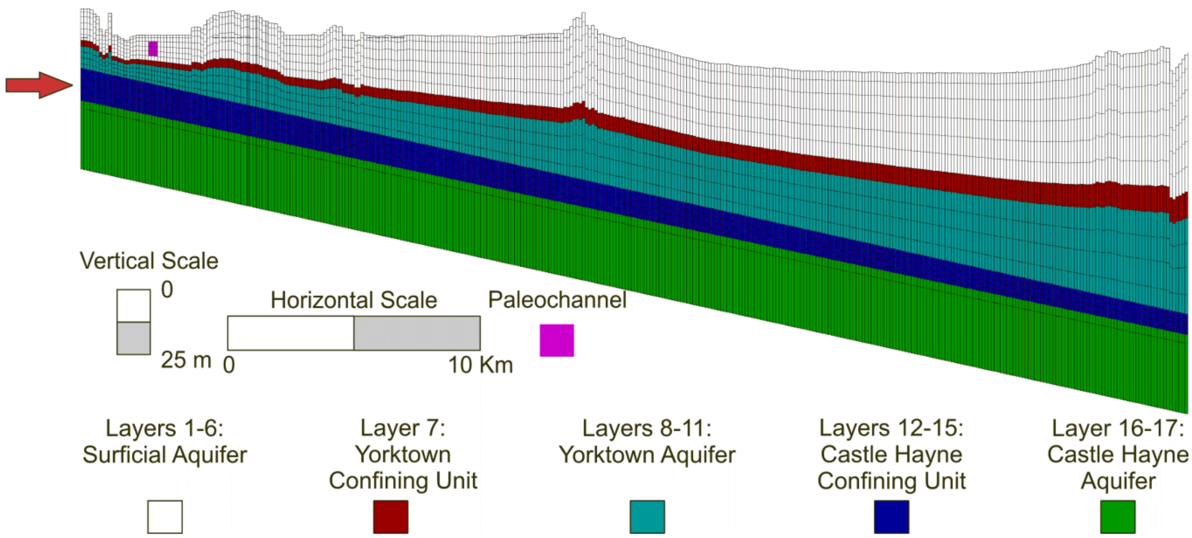


Figure 9. Cross section along Row 62 of the model area.

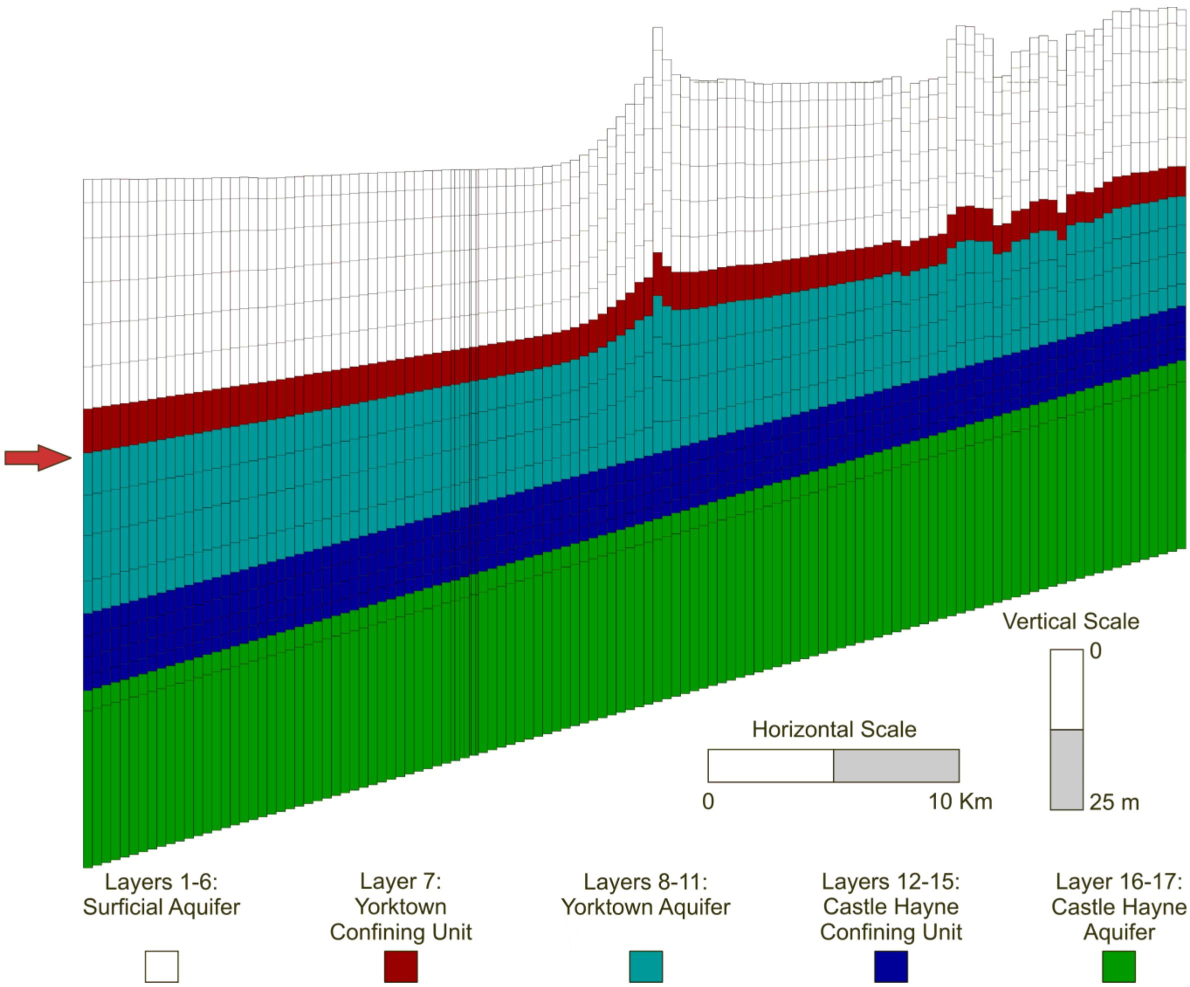


Figure 10. Cross section along Column 181 of the model area.

### 3.3 Layer Elevations

Elevations of the land surface and seafloor, along with confining units and aquifers, were needed to create the groundwater model. For the land surface and seafloor elevations, a Digital Elevation Model (DEM) of the land surface with integrated bathymetric elevations of Bogue Sound, Bogue and Beaufort Inlets, White Oak River, and the surrounding Atlantic Ocean was used (Grothe et al., 2012). Hydrostratigraphic data acquired from the hydrogeologic framework database of the NC DENR (NC DENR, 2014e) and Groundwater Management and Associates Inc., were used to determine the elevations of the confining units and aquifers. Interpolated surfaces created from the elevation data were used to characterize the general dip of each hydrogeologic unit in the model. Underlying the Castle Hayne aquifer on the island is the Beaufort confining unit. No data from the hydrostratigraphic framework portal were available for the top of the Beaufort confining unit in the study area, so the bottom of the deepest municipal well on the island (i.e., AB6) was used to establish the bottom of the model. The bottom of the model was assigned the same dip as the top of the Castle Hayne aquifer.

### 3.4 Model Properties

To model groundwater flow and saltwater intrusion in the study area, hydrogeologic properties acquired from various sources were assigned to the appropriate hydrogeologic units in the model. Hydrogeologic properties include recharge, evapotranspiration, hydraulic conductivity, storage, and porosity (Table 3). During calibration, parameters for the hydrogeologic properties were adjusted between the minimum and maximum values observed for each property to allow for optimization.

Hydrogeologic properties used in the model were either derived from the island or from similar hydrogeological settings close to the island.

### 3.4.1 Recharge and Evapotranspiration

Recharge and evapotranspiration were only assigned to the Surficial aquifer. The Surficial aquifer was assigned recharge rates ranging from 0.0 to 121.2 cm/year in order to account for various types of soil (Haven, 2003). Evapotranspiration used in the model was determined by Sisco (2013) using the water balance equation by Thornthwaite (1948) and Thornthwaite and Mather (1955) to be 22.3 cm/year. At Maysville climate station (in Onslow County North Carolina) located ~ 39 km away, the long-term average evapotranspiration rate is 86 cm/year (Maysville 2014). The large difference found between evapotranspiration rates in Onslow County and Bogue Banks could be contributed to drought like conditions on Bogue Banks the year evapotranspiration rate was estimated on Bogue Banks (Sisco, 2013). Recharge from septic tanks to the Surficial aquifer was not accounted for in the model since the primary focus of this study was the deeper Castle Hayne aquifer. An extinction depth of 3.0 m was used (Sisco, 2013).

### 3.4.2 Hydraulic Conductivity

A horizontal hydraulic conductivity of 3.9 m/day was assigned to the layers representing the Surficial aquifer (Sisco, 2013). Horizontal hydraulic conductivity for the Surficial aquifer was derived from falling-head slug tests in monitoring wells on the western part of the island by Sisco (2013). For the Yorktown and Castle Hayne confining units, a horizontal hydraulic conductivity of $2.8 \times 10^{-5}$ m/day was assigned to the layers (Giese et al., 1991). The Yorktown aquifer was assigned a horizontal hydraulic conductivity of 5.8 m/day (Heath, 1983), whereas a horizontal hydraulic conductivity of 6.1 m/day was assigned to the Castle Hayne aquifer. Horizontal hydraulic conductivity for the Yorktown and Castle Hayne confining units, and the Castle Hayne aquifer were derived from groundwater withdrawal tests on the island using wells screened in the Castle Hayne aquifer by Groundwater Management Associates, Inc.. The paleochannel was assigned a horizontal hydraulic conductivity value of $1.0 \times 10^{-3}$ m/day (Heath, 1983). The horizontal hydraulic conductivity for the Yorktown aquifer and paleochannel were estimated using descriptions of sediments derived from the literature (Heath, 1983). Vertical hydraulic conductivity test were not conducted on the island therefore a 1:10 ratio for vertical to horizontal hydraulic conductivity was assumed for all hydrogeologic units (Hudak, 1999).

### 3.4.3 Storage

A specific yield value of 0.23 was assigned to the Surficial aquifer (Healy and Cook, 2002; Johnson, 1996). Specific yield for the Surficial aquifer was estimated from grain size and sediment core collected by Sisco (2013) from sites located on the western part of Bogue Banks. For the confining units, a storage coefficient of $1.0 \times 10^{-10}$ determined by Groundwater Management Associates, Inc. was used to represent storage. Groundwater pumping tests in wells screened in the Castle Hayne aquifer were used to estimate storage in the Castle Hayne confining unit. The Yorktown confining unit was assumed to have the same storage as the Castle Hayne confining unit due to similar compositions. In the Yorktown and Castle Hayne aquifers, a storage coefficient of $1.0 \times 10^{-4}$ was used (Giese et al., 1997) to represent storage. Results of aquifer tests conducted in the North Carolina Coastal Plain were used to determine the storage coefficients of the Yorktown and Castle Hayne aquifers (Giese et al., 1997). Hines and Snyder (1985) did not measure storage of the paleochannel located in the study area. However, since the paleochannel in the study area comprises the same composition as the confining units in the model area as indicated by vibracore results, a storage value of $1.0 \times 10^{-10}$ was assumed for the feature.

### 3.4.4 Porosity

Porosity values for each unit were estimated using values from McWorter and Sunada (1977). A total porosity of 0.25 was ascribed to the sands of the Surficial aquifer. In the Yorktown and Castle Hayne confining units, a total porosity value of 0.34 was used to represent the clay. For the Yorktown aquifer, which is composed of sands, silts and clays, a total porosity value of 0.46 was used. In the predominately limestone Castle Hayne aquifer, a total porosity value of 0.56 was used. The paleochannel was assigned a total porosity value of 0.34 to represent the mud in the unit.

Table 3. Hydrogeologic properties assigned to the calibrated model. $K_x$ or $K_y$ = horizontal hydraulic conductivity, $K_z$= vertical hydraulic conductivity. The storage for the Surficial aquifer is given as specific yield.

| Hydrogeologic Unit | $K_x$ or $K_y$ (m/day) | $K_z$ (m/day) | Storage Coefficient | Total Porosity |
|---|---|---|---|---|
| Surficial Aquifer | 3.9 | 0.39 | 0.23 | 0.25 |
| Yorktown Confining Unit | $2.8 \times 10^{-5}$ | $2.8 \times 10^{-6}$ | $1.0 \times 10^{-10}$ | 0.34 |
| Yorktown Aquifer | 5.8 | .58 | $1.0 \times 10^{-4}$ | 0.46 |
| Castle Hayne Confining Unit | $2.8 \times 10^{-5}$ | $2.8 \times 10^{-6}$ | $1.0 \times 10^{-10}$ | 0.34 |
| Castle Hayne Aquifer | 6.1 | .61 | $1.0 \times 10^{-4}$ | 0.56 |
| Paleochannel | $1.0 \times 10^{-3}$ | $1.0 \times 10^{-4}$ | $1.0 \times 10^{-10}$ | 0.34 |

### 3.5 Model Boundaries

The model area for this study was selected to incorporate the whole island of Bogue Banks, along with the point of intersection of the paleochannel with the Castle Hayne aquifer north of the island. In the Surficial aquifer (layers 1-6), a constant head of 0.0 m was applied to all areas in the model where water was present. Tidal fluctuations recorded in Beaufort, NC by the National Oceanic Atmospheric Administration (NOAA) show average monthly ranges of 0.456 m and 0.706 m between low and high tide. With the focus of the study on the Castle Hayne aquifer, setting constant head at 0.0 m and not between 0.456 m and 0.706 was deemed acceptable. Constant head remained at 0.0 m and did not account for the 0.25 m range in tides. Extending the model in the northern direction until the intersection point of the paleochannel with the Castle Hayne aquifer occurred allowed for testing the second hypothesis. The boundaries for the Yorktown and Castle Hayne confining units (layers 7, and 12-15) were designated no-flow boundaries because groundwater flow was assumed to flow vertically in these hydrogeologic units (Giese et al., 1997). Vertical groundwater flow between confining units and aquifers was implemented by adjusting the hydraulic conductivity in the vertical direction to one tenth that of horizontal hydraulic conductivity (Hudak, 1999). In the Castle Hayne aquifer (layers 16-17), groundwater flowed west to east, and therefore no-flow boundaries were assigned to the northern and southern boundaries. Head-dependent flow boundaries were assigned to the western and eastern boundaries of the Castle Hayne aquifer using the General Head package in order to simulate the west to east groundwater flow pattern (Figure 7). The study area did not contain any wells that were screened in the Yorktown aquifer, so the heads in the Yorktown aquifer were assumed to be equal to the static heads found in the Castle Hayne aquifer (Spruill, R., personal communication, April, 2014; Lautier, J., personal communication, April, 2014). Head dependent flow boundaries were also assigned to the Yorktown aquifer (layers 12-15) using the same head values as those used in the Castle Hayne aquifer. The bottom of the Castle Hayne aquifer was treated as a no-flow boundary. Any recharge due to runoff and septic tank recharge was assumed to have no impact on the Castle Hayne aquifer.

### 3.6 Model Calibration

Calibration of the model involved a trial and error adjustment procedure where model inputs were varied in all three aquifers and observed heads were compared to simulated heads in steady state conditions (Anderson and Woessner, 2002). Observed heads from the Surficial and Castle Hayne aquifers were acquired from observation and municipal wells during a period when there was no groundwater withdrawal from the wells. The root mean square (RMS) error between observed and simulated heads, and the coefficient of determination ($r^2$) were used to assess how the field derived data (i.e., observed heads) compared to the model derived data (i.e., simulated heads).

The groundwater model was calibrated by independently adjusting hydraulic heads in the Surficial and Castle Hayne aquifers. Hydraulic head values from the Surficial aquifer were acquired from observation wells that were installed in the aquifer during a prior study done on the western part of the island by Sisco (2013). An average head value from each observation well was calculated from the time series of head values collected from 05/06/2011 to 06/15/2012. Over the period of record, the Surficial aquifer was considered to have been at steady state since the change in storage was minimal, and the groundwater withdrawal from the aquifer was negligible.

Both qualitative and quantitative approaches were used to assess how well the model was calibrated. Qualitative and quantitative assessments focused on the western part of the island where observation wells were present. Qualitative assessment compared the observed versus simulated head values (Figure 11). Statistical results from observed versus simulated head values on the western part of the island show an RMS error of 0.45 m and an $r^2$ value of 0.61 m. The Surficial aquifer was considered calibrated when observed versus simulated head values were similar qualitatively and when an RMS error of < 0.50 m and an $r^2$ value > 0.60 m occurred. No observation wells existed in the Yorktown aquifer in the model area, therefore the Yorktown aquifer was not calibrated.

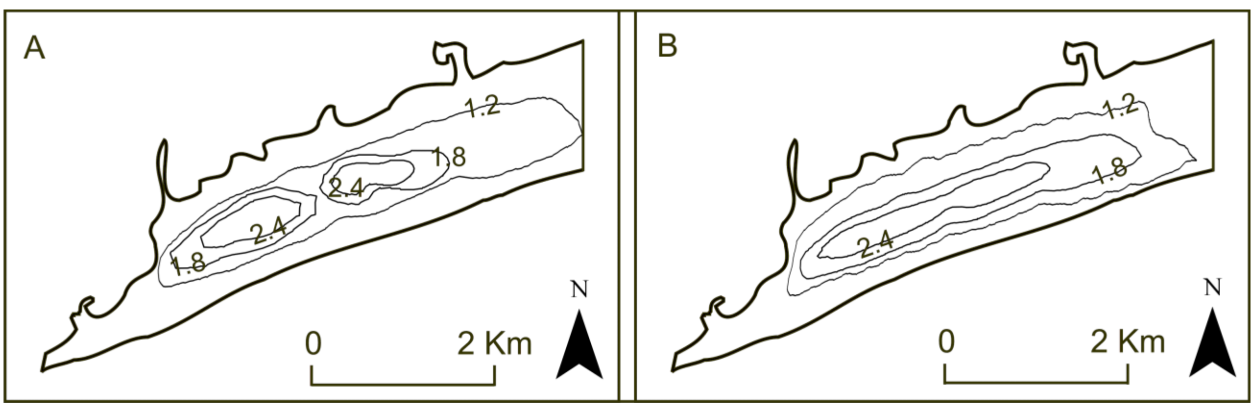


Figure 11. Modeled equipotential maps of observed (A) and simulated (B) heads (in meters) in the Surficial aquifer. Datum is sea-level.

Model calibration with respect to the Castle Hayne aquifer was also accomplished by comparing observed head to simulated head values, qualitatively and quantitatively. Hydraulic heads collected during non-pumping conditions on 12/02/2003 were used to create a potentiometric surface for the Castle Hayne aquifer. A potentiometric surface map indicates that groundwater generally flows from west to east across the island (Figures 12A, 13). The potentiometric surface map of observed hydraulic heads was then qualitatively compared to the potentiometric surface of simulated head values (Figure 12B). Statistics indicate an RMS error of 0.64 m, whereas the $r^2$ was equal to 0.76 between observed and simulated heads. The Castle Hayne aquifer was considered calibrated when observed versus simulated head values were similar qualitatively and when a RMS error of $< 0.65$ m and an $r^2$ value $> 0.75$ m occurred.

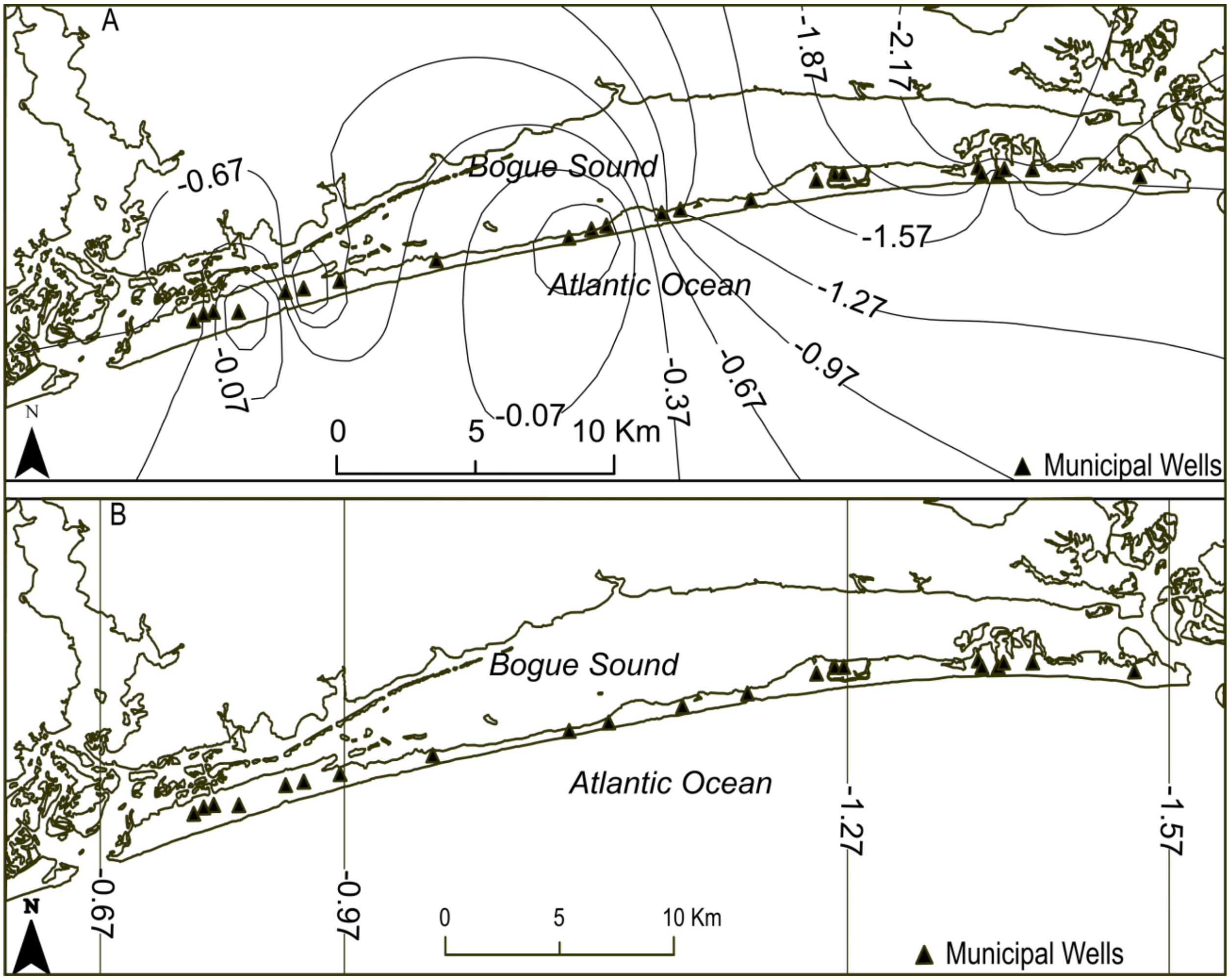


Figure 12. (A) Contour map of the potentiometric surface (in meters) of the Castle Hayne aquifer during non-pumping conditions on 12/02/2003. (B) Modeled potentiometric map of simulated heads in the Castle Hayne aquifer for 12/02/2003. Datum is sea-level.

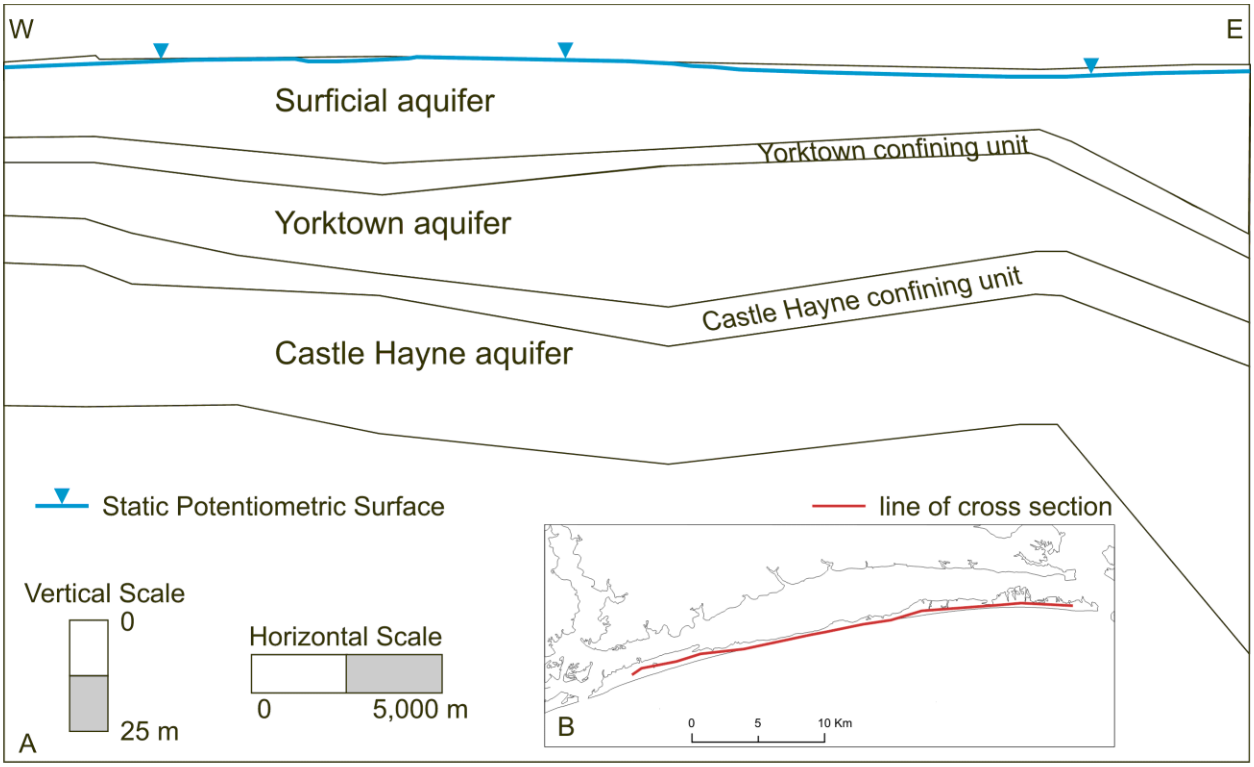


Figure 13. (A) Cross section showing stratigraphic layers and the potentiometric surface of the Castle Hayne aquifer. (B) Location of cross section line on Bogue Banks.

### 3.7 Model Verification

The model was verified under a transient simulation using observed heads collected over the period 01/01/2004 to 12/31/2004. Initial conditions were derived from the steady state simulations. Each day represented one stress period for a total of 366 stress periods. At the end of the simulation, observed heads were compared to simulated heads, qualitatively and quantitatively. To qualitatively compare the observed heads to simulated heads during groundwater withdrawal, time series plots for the year 2004 were used (Figure 14). RMS errors ranged from 4.1 to 30.1 m in municipal wells located across the island (Table 4). Large differences between observed and simulated heads could be attributed to water level measurements that were taken during pumping but not likely at maximum drawdowns. The differences could also be attributed to the failure to adequately capture the heterogeneous character of the complex aquifer system on the island.

Table 4. Root Mean Square errors for observed and simulated heads derived from municipal wells screened in the Castle Hayne aquifer.

| Well | RMS error |
|---|---|
| BB4A | 4.1 |
| BB8 | 6.4 |
| BB9 | 8.7 |
| BB2A | 30.1 |
| BB6 | 26.0 |
| BB3A | 4.1 |
| BB1 | 5.3 |
| BB7A | 18.5 |
| AB3 | 5.2 |
| AB1 | 5.7 |
| AB2 | 23.9 |
| AB5 | 16.7 |
| AB4 | 8.1 |
| AB6 | 13.2 |

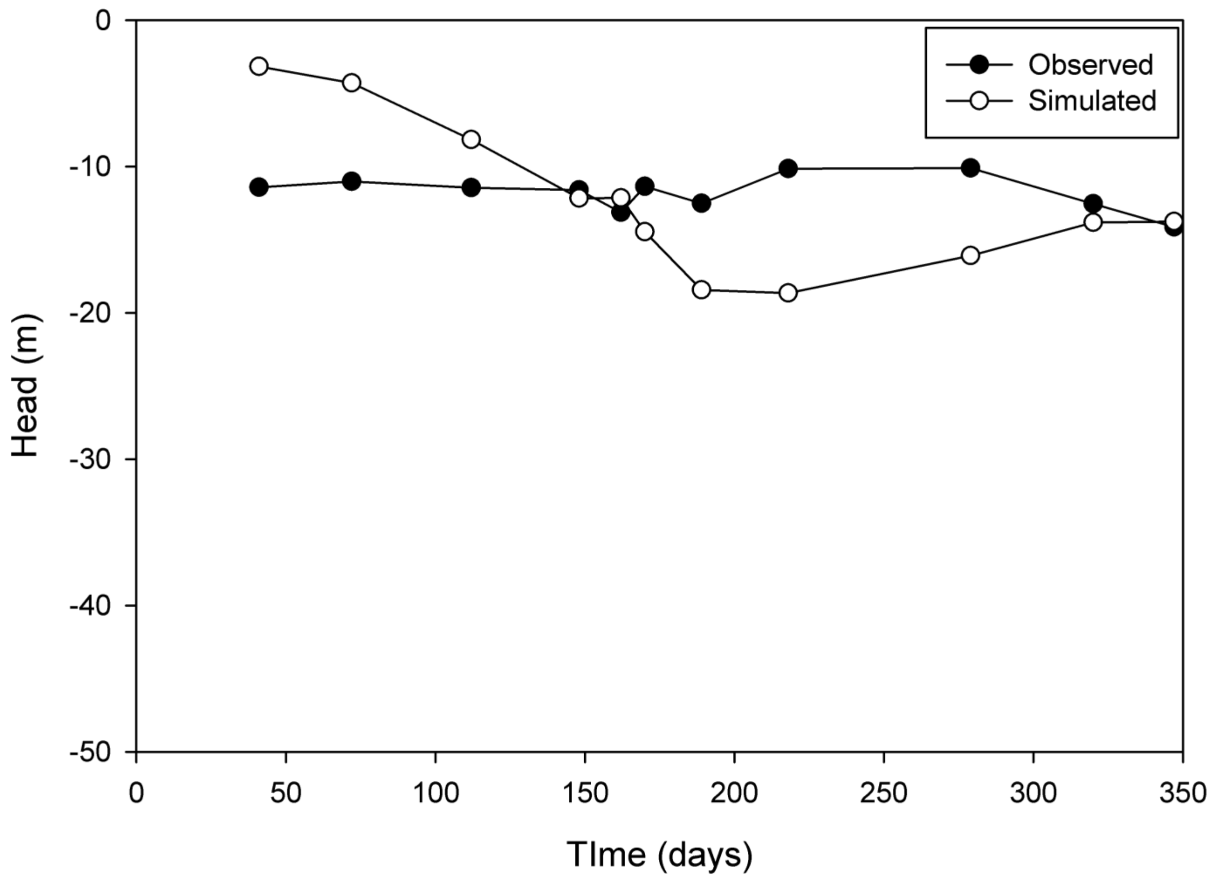


Figure 14. An example of a time series plot showing observed and simulated heads in the Castle Hayne aquifer for municipal well BB4A.

### 3.8 Model Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the effects of hydraulic conductivity and storage properties of the Castle Hayne aquifer on the model. Each hydraulic property was changed by +/-90%, and +/-50%. To quantify the change that the hydraulic properties had on model outputs, the average head change of the municipal wells in the Castle Hayne aquifer was used (Giese et al, 1997). A sensitivity analysis was not conducted to evaluate the effects of hydraulic properties in the Surficial aquifer as the Castle Hayne aquifer is the focus of the study.

The sensitivity analysis revealed that hydraulic conductivity had the most significant impact on head change (Table 5). Decreasing hydraulic conductivity by 90% resulted in lowering average heads by 22.5 m. The rest of the changes in hydraulic conductivity did not yield average head changes greater than 2.3 m. Decreasing storage by 90% and 50% resulted in average head changes of 0.2 m, whereas increasing storage by 90% and 50% decreased average heads by a maximum of -1.0 m (Table 5).

Table 5. Results from sensitivity analysis of the Castle Hayne aquifer. Average head change (in meters) as a result of adjusting hydraulic conductivity and storage.

| | Change in Property by Percent | | | |
|---|---|---|---|---|
| Property | -90% | -50% | +90% | +50% |
| Hydraulic Conductivity | -22.5 | +0.4 | -2.3 | -1.5 |
| Storage | +0.2 | +0.2 | -1.0 | -0.7 |

### 3.9 Estimation of Groundwater Withdrawals for Bogue Banks Water Corporation

Although BBWC began pumping groundwater from the Castle Hayne aquifer in 1969, record keeping of groundwater withdrawal data did not begin until 1989. Thus, to simulate groundwater withdrawals before 1989, withdrawal rates were estimated from population data. First, the volume of water used per person per year was derived by dividing the total volume of water withdrawn by BBWC (2.02 x $10^6$ $m^3$) by the total population (3,717 permanent + 43,233 seasonal) in the communities served by BBWC in 2000 (Allenby, 2011; NC DENR, 2014a, c). The volume of water used per person per year (43 $m^3$) was then multiplied by the permanent population (122 from 1969 to 1979, 918 from 1980-1989) on the island to find the total volume of water withdrawn from the aquifer (Table 6). The total volume of water withdrawn was then divided by the number of municipal wells (six) to determine the volume of water withdrawn per well per year.

The estimated amount of groundwater withdrawn between 1969 and 1989 is assumed to be lower than the actual withdrawal because the seasonal population during that period was unknown and thus not accounted for in the computations.

Table 6. Estimate of volume of water withdrawn per well per year from 1969-1989 for BBWC in the Castle Hayne aquifer.

| Year | Permanent Population | Total volume withdrawn ($m^3$) | Volume of water per well per year ($m^3$) |
|---|---|---|---|
| 1969-1979 | 122 | $5.3 \times 10^3$ | $8.7 \times 10^2$ |
| 1980-1989 | 918 | $4.0 \times 10^4$ | $6.6 \times 10^3$ |

### 3.10 Simulating Scenarios for Saltwater Intrusion

The numerical engine SEAWAT was used in Visual MODFLOW to determine the source of saltwater intrusion on the western part of Bogue Banks. SEAWAT is designed to simulate groundwater flow in three dimensions with variable-density, multi-species solute, and heat transport (Guvanasen, 2000; Guo and Langevin, 2002). The ability to produce multi-density groundwater flow makes it ideal for modeling saltwater movement in a freshwater aquifer (Guo and Langevin, 2002). The MODFLOW package Preconditioned Conjugate Gradient (PCG) was used to solve the variable-density groundwater flow equation while the Generalized Conjugate Gradient (GCG) package was used to solve the transport equation (Hill, 1990; Zheng and Wang, 1999). A courant number was assigned designate the maximum number of nodes in the model where water can move by the process of advection in all directions during one time step (Anderson and Woessner, 2002).

Each scenario that was envisioned was run from the year 1585 to 2014. The simulation began in 1585 as it is the earliest known date that Bogue Inlet existed (Fisher, 1962). The 429 year simulation has a total of 582 stress periods (Figure 15). The first four stress periods are in one year increments, whereas stress periods 5-42 represented ten year increments from 1589 until 1969 representing the period when there was no groundwater withdrawal from the Castel Hayne aquifer. Starting in 1969, stress periods represented monthly periods for the remainder of the simulation (stress periods 43-582). For stress periods 43-283, estimates of monthly average groundwater withdrawals from 1969 to 1989 (as described above) were assigned to withdrawal wells in the model (BB1-BB6), whereas for stress periods 284-582, the observed monthly average groundwater withdrawals from BBWC were assigned to the wells.

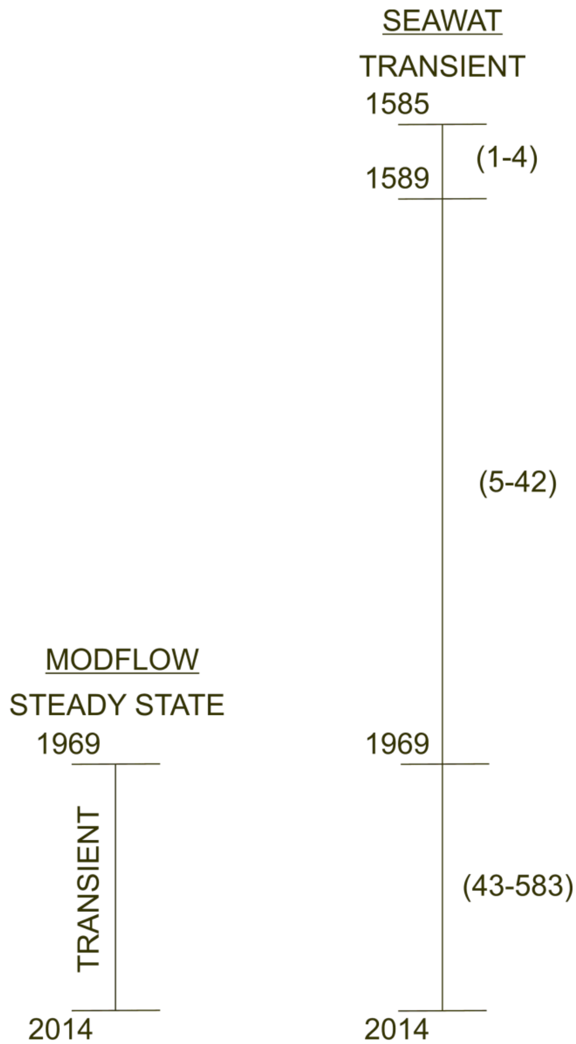


Figure 15. Timeline indicating the simulation type and stress periods used in MODFLOW and SEAWAT. Values in parentheses represent stress periods.

For each simulation, a constant chloride concentration of 35,000 mg/L (representing saline conditions) was assigned to the areas of the model where seawater was present (layers 1-6) (Figure 16) (e.g., Langevin, 2003). A vertical interface was created due to the unknown saltwater concentration under the island in the Surficial aquifer. In Bogue Inlet and Bogue Sound (layers 1-6), a constant chloride concentrations of 12,000 mg/L (representing brackish conditions) was assigned to show the mixing of high saline ocean water and freshwater from inflowing rivers and streams

(Figure 16) (Goff, 1977). An initial chloride concentration of 88 mg/L was assigned to the rest of the model (layers 7-17) (Figure 16). The initial concentration assigned to the rest of the model represented the average chloride concentrations observed in BBWC municipal wells (excluding the wells BB5A, BB12, BB4A which had high chloride concentrations). The density of seawater (1,025 kg/m$^3$) was assigned to areas in the model where saltwater was assumed to be present, whereas for the rest of the model, a freshwater density of 1,000 kg/m$^3$ was applied (Guo and Langevin, 2002).

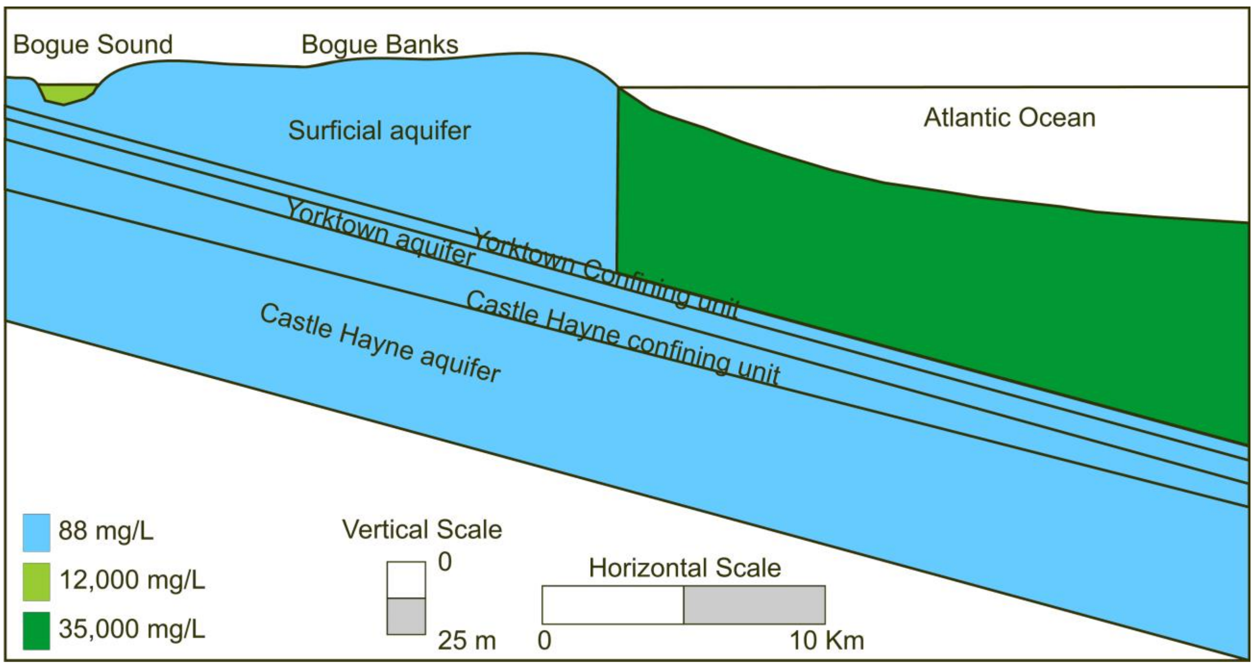


Figure 16. Cross section illustrating assignment of chloride concentrations in the system.

In order to test the hypothesis that saltwater is emanating from overlying surface waters, the following assumptions about the underlying hydrostratigraphy were made. To provide a pathway for surface water bodies (with high chloride concentrations) surrounding the western part of Bogue Banks to move to the Castle Hayne aquifer, it was assumed that portions of the confining units overlying the Castle Hayne aquifer were pinched out (Lautier, 2001; Fine and Kuniansky, 2013). In a number of bore logs located in the central coastal plain, confining units above the Castle Hayne aquifer are not present and pinch out due to unconformities (Lautier, 2001). Removing portions of confining units located directly below the surface water bodies provided a preferred path for saltwater intrusion into the Castle Hayne aquifer. The modeling would determine the most probable locations of these pinched out zones.

Four scenarios comprising varying locations and widths of the pinched out zones were therefore envisioned to determine the most likely locations and dimensions of the pinch outs. The four scenarios would represent (i) Bogue Inlet, (ii) Bogue Sound, (iii) the Atlantic Ocean, and (iv) a paleochannel as potential sources of saltwater intrusion (Figure 17).

Potential zones for scenarios 1-3 were strategically placed to show the most likely locations where pinched out zones could occur that would result in salt concentrations similar to those found in municipal wells on the western part of the island. Potential zones for scenarios 1-3 were placed inside the capture zone of the Castle Hayne aquifer. Groundwater flow in the aquifer naturally flowed west to east before pumping began on the island.

Since no core data exist in the locations that were selected to represent the scenarios, a modeling approach was used to identify the possible locations where confining units were absent on the western part of the model area. A groundwater flow map was created for the Castle Hayne aquifer to identify the capture zone on the western part of the island when maximum groundwater withdrawal occurred (July, 2013) in municipal wells BB5A, BB12, BB4A (Figure 17). Simulated chloride concentrations were then compared to observed chloride concentrations to constrain the locations of the pinched out zones. Scenarios 1-3 inside the capture zone provide probable locations and widths needed to determine if pinch outs are a preferred pathway for saltwater intrusion from overlying surface water sources. Scenario 4 focuses on assessing whether the paleochannel is the source of the saltwater intrusion.

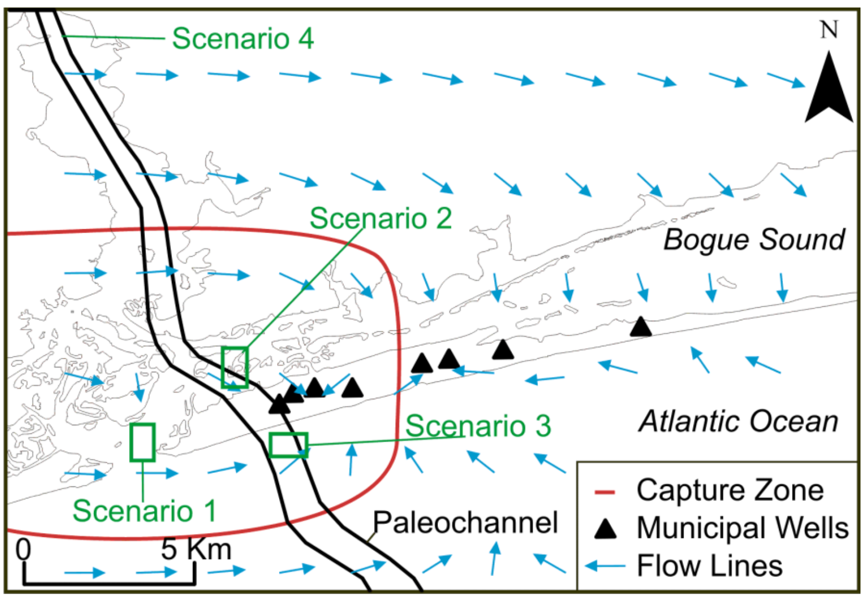


Figure 17. Modeled map view of the study area showing the locations of potential pinched out zones envisioned in scenarios 1-3 along with the capture zone in the Castle Hayne aquifer. Scenario 4 represents the paleochannel.

### 3.10.1 Testing Scenario 1 - Bogue Inlet

In scenario 1, the general location of the pinched out zone was placed below Bogue Inlet to test whether Bogue Inlet was a source of saltwater intrusion (Figure 17).

The widths of the pinched out zones at this location were assumed to be either 363 m or 726 m (with a length of 576 m), whereas the distance away from the nearest municipal well (BB5A) to the pinched out zones was assumed to be 3,380 m or 3,610 m. Widths of the pinched out zones were determined based on the width of the local paleochannel in the region and the assumption that unconformities would have similar areal extents in the region. Lengths of pinched out zones were set at 576 m to show the influence of a pinched out zone within Bogue Inlet. A total of four sub-scenarios were therefore established for scenario 1 (Table 7) to determine whether the pinched out zones envisioned in this scenario represented likely sources of saltwater intrusion.

Table 7. Sub-scenarios representing distances from municipal wells and widths of pinched out zones beneath Bogue Inlet.

| | Sub-scenarios | | | |
|---|---|---|---|---|
| | 1a | 1b | 1c | 1d |
| Distance from well (km) | 3.38 | 3.38 | 3.61 | 3.61 |
| Width of pinch out (m) | 363 | 726 | 363 | 726 |

### 3.10.2 Testing Scenario 2 - Bogue Sound

In scenario 2, the general location of the pinched out zone was placed below Bogue Sound to test whether Bogue Sound was a source of saltwater intrusion (Figure 17). The widths of the pinch out zones were assumed to be either 121, 363, or 726 m (with a length of 864 m), whereas the distance away from the nearest municipal well (BB5A) to the pinched out zones was assumed to be 1,550 or 1,800 m. Widths of the pinched out zones were determined based on the same rationale as in scenario 1 with the addition of the 121 m width to simulate a much smaller unconformity. Lengths of pinched out zones were set at 864 m to show the influence of a pinched out zone within

Bogue Sound. A total of six sub-scenarios were therefore established for scenario 2 (Table 8). These scenarios were then recreated in Visual MODFLOW where flow simulations were used to determine whether the pinched out zones envisioned in this scenario represented likely sources of saltwater intrusion.

Table 8. Sub-scenarios representing distances from municipal wells and widths of pinched out zones beneath Bogue Sound.

| | Sub-scenarios | | | | | |
|---|---|---|---|---|---|---|
| | 2a | 2b | 2c | 2d | 2e | 2f |
| Distance from well (km) | 1.55 | 1.55 | 1.55 | 1.80 | 1.80 | 1.80 |
| Width of pinch out (m) | 121 | 363 | 726 | 121 | 363 | 726 |

### 3.10.3 Testing Scenario 3 - Atlantic Ocean

In scenario 3, the general location of the pinched out zone was placed below the Atlantic Ocean to test whether the Atlantic Ocean was a source of saltwater intrusion (Figure 17). The widths of the pinch out zones were assumed to be either 121 m or 363 m (with a length of 864 m), whereas the distance away from the nearest municipal well (BB5A) to the pinched out zones was assumed to be 2,300 m or 2,470 m. Widths of the pinched out zones were determined based on the same rationale as in scenarios 1 and 2. The length of pinched out zones was set at 864 m to show the influence of a pinched out zone in the Atlantic Ocean. A total of four sub-scenarios were therefore established for scenario 3 (Table 9). These scenarios were then recreated in Visual MODFLOW where flow simulations were used to determine whether the pinched out zones envisioned in this scenario represented likely sources of saltwater intrusion.

Table 9. Sub-scenarios representing distances from municipal wells and widths of pinched out zones beneath the Atlantic Ocean.

| | Sub-scenarios | | | |
|---|---|---|---|---|
| | 3a | 3b | 3c | 3d |
| Distance from well (km) | 2.30 | 2.30 | 2.47 | 2.47 |
| Width of pinch out (m) | 121 | 363 | 121 | 363 |

### 3.10.4 Testing Scenario 4 - Paleochannel

In scenario 4, the general location of the intersection point between the paleochannel and Castle Hayne aquifer is 12,036 m north west of municipal well BB5A with a length of 720 m (Figure 17). The length of the pinch out zone was determined by extending the paleochannel by its current dip to the north until it intersected both the Castle Hayne confining unit and aquifer. The width of paleochannel at the breaching point was 847 m. Scenario 4 was then recreated in Visual MODFLOW where flow simulations were used to determine whether the paleochannel envisioned in this scenario represented the likely source of saltwater intrusion.

### 3.10.5 Predictive Model

To determine how water quality in the municipal wells would be affected by saltwater intrusion in the future, a 100-year predictive model was created. The model that produced the best results from the set of scenarios described above was used to simulate the future effect of groundwater withdrawals on chloride concentrations. Schedules for groundwater withdrawal for each municipal well for the year 2013 were reproduced for the next one hundred years to stress the aquifer. At the end of the simulation, the chloride concentrations that were predicted in 2113 were evaluated.

## CHAPTER 4: RESULTS AND DISCUSSION

The hypothesis that saltwater is emanating from overlying brackish or saline surface waters into the Castle Hayne aquifer was tested by running simulations representing scenarios 1, 2 and 3, whereas the hypothesis that saltwater originating from a paleochannel is being drawn into the Castle Hayne aquifer was tested in scenario 4. Chloride concentrations from simulations representing each scenario were compared to observed concentrations in the three municipal wells that exhibited high chloride concentrations (Tables 10 and 11). Differences in chloride concentrations were used to determine the likely source of saltwater intrusion on Bogue Banks. Chloride concentrations from saltwater plumes derived from model simulations were compared to observed chloride concentrations collected on 10/21/2013. The potentiometric surface map of the Castle Hayne aquifer was also analyzed to assess the effects of pumping on groundwater flow directions (Figure 18).

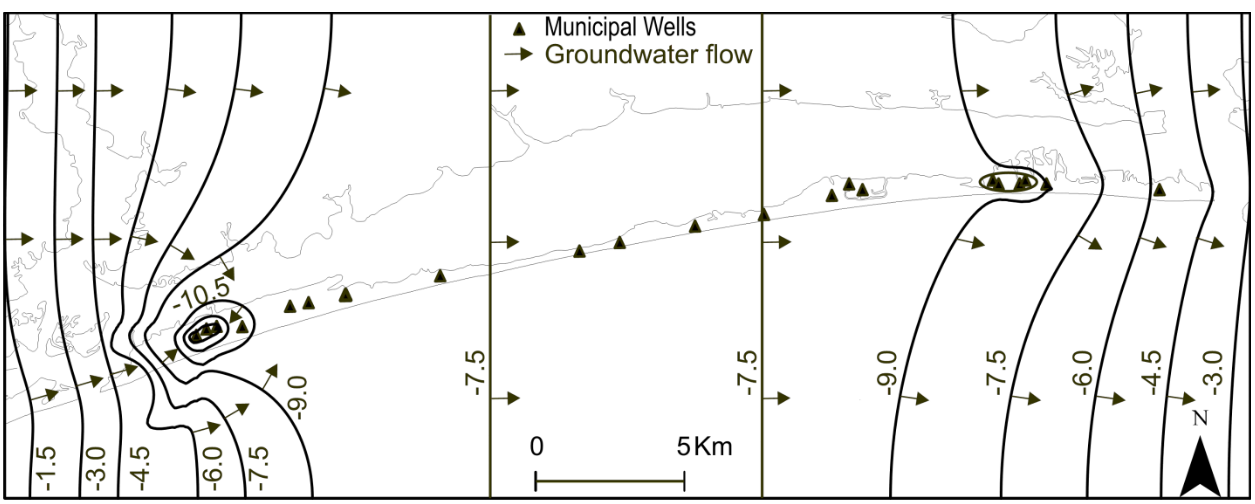


Figure 18. Modeled potentiometric surface (in meters) of the Castle Hayne aquifer on 10/21/2013. Datum is sea-level.

## 4.1 Bogue Inlet

Modeling results from scenario 1 (i.e., sub-scenarios 1a-1d) indicate that simulated chloride concentrations in municipal wells BB5A, BB12, and BB4A did not match observed concentrations in the Castle Hayne aquifer on the western part of Bogue Banks (Figure 19). The results indicate that the model concentrations were lower than the observed concentrations for all sub-scenarios and that the lowest normalized RMS error was 73%. The results also indicate that the plume did not reach the municipal wells in these scenarios. Although the widths of the pinched out zones and the distances from the pinched out zones to the municipal wells influenced travel times and spatial variation of salt concentrations, the results suggest that Bogue Inlet is not likely to be the source of saltwater intrusion in the municipal wells.

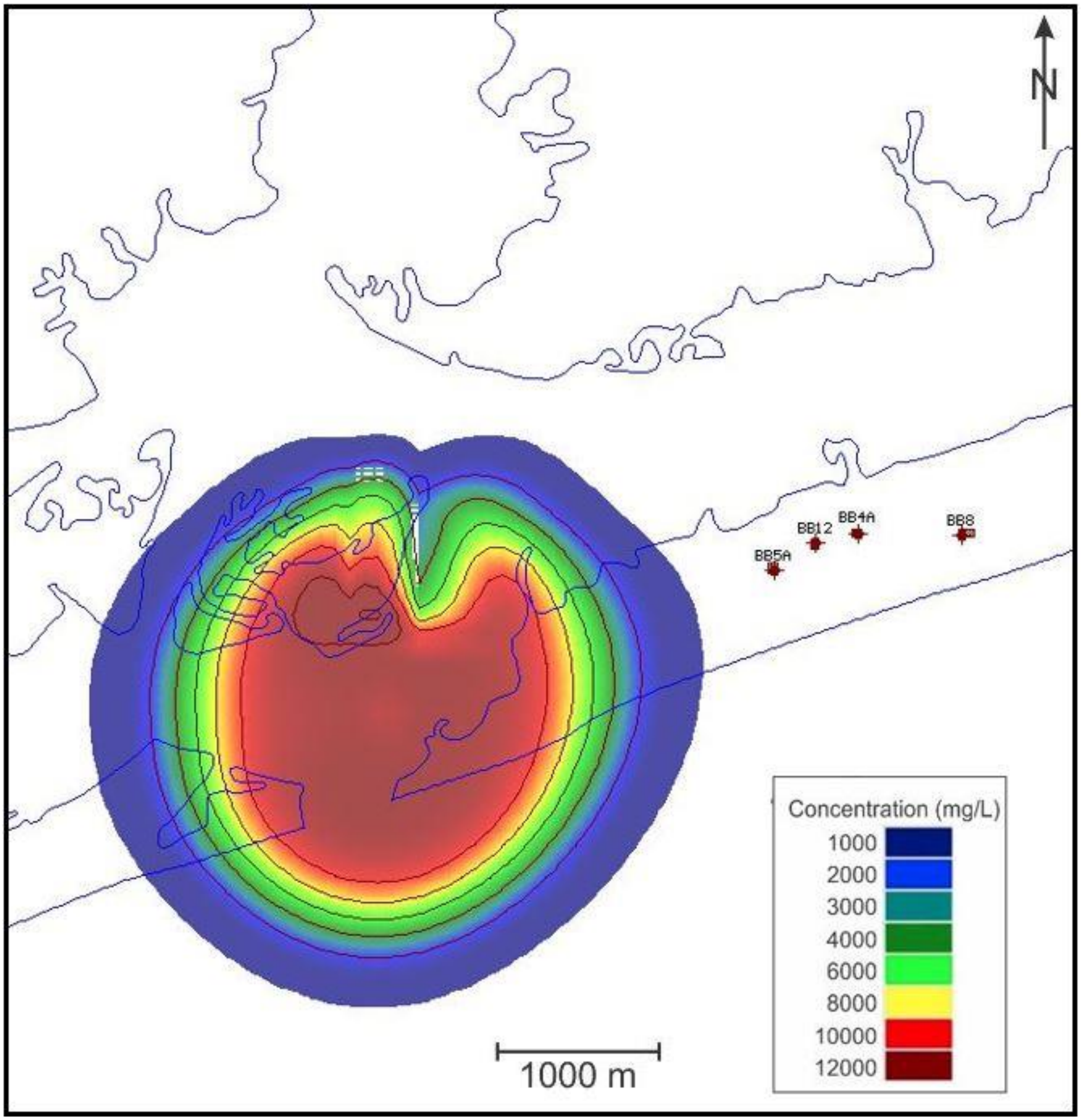


Figure 19. Map view of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 1b.

### 4.2 Bogue Sound

Model results from scenario 2 (i.e., sub-scenarios 2a-2f) indicate that saltwater emanating from Bogue Sound reaches municipal wells BB5A, BB12, and BB4A on the western part of the island (Figures 20, 21, 22). For all sub-scenarios envisioned, the saltwater plume reaches the farthest municipal well from Bogue Inlet that exhibits high chloride concentrations (i.e., BB4A). The results reflect an association among distance of source from municipal well, dimensions of pinched out zones, and chloride concentrations in municipal wells. The closer the well was to the source, the higher the chloride concentrations were in the well. For example municipal well BB5A had an increase in concentration of 4,225 mg/L from sub-scenarios 2a-2d where 2a is 250 m closer than 2d from municipal well BB5A. Increasing the width of the pinched out zones increased the simulated chloride concentration. For example municipal well BB5A had an increase in concentration of 1,434 mg/L from sub-scenarios 2a-2c and an increase of 3,095 mg/L from sub-scenarios 2d-2f. The widths of pinched out zones range from 121 to 726 m in both sub-scenarios. However, doing so increased the errors between simulated and observed concentrations (Tables 10 and 11).

In scenario 2 (i.e., sub-scenarios 2a-2f), the sub-scenario that collectively had the closest match between simulated and observed chloride concentrations was sub-scenario 2d (Table 10 and 11). Sub-scenario 2d provided the best width of the pinched out zones and distance from the pinched out zones to the municipal wells that resulted in a normalized root mean square error of 43%. The greatest difference between simulated and observed concentrations was 1,569 mg/L (Table 10, 11). Simulated chloride concentrations were the greatest in municipal well BB5A and became smaller in BB4A as the saltwater plume became less concentrated.

The results of sub-scenarios 2a-2f suggest that by varying the distance and width of the pinched out zones, simulated chloride concentrations result in similar chloride concentrations to those observed in municipal wells BB5A, BB12, and BB4A. The results suggest that Bogue Sound could be the source of saltwater intrusion in the municipal wells.

Table 10. Observed versus simulated chloride concentrations for scenarios 1-3. (Values in parenthesis are observed concentrations)

| Scenario | Distance (km) | Sub-scenarios | BB5A (1,730 mg/L) | BB12 (2,700 mg/L) | BB4A (1,940 mg/L) | BB8 (245 mg/L) |
|---|---|---|---|---|---|---|
| 1. Bogue Inlet | 3.38 | 1a | 88 | 88 | 88 | 88 |
| | | 1b | 90 | 88 | 88 | 88 |
| | 3.61 | 1c | 88 | 88 | 88 | 88 |
| | | 1d | 96 | 88 | 88 | 88 |
| 2. Bogue Sound | 1.55 | 2a | 6,821 | 2,548 | 489 | 88 |
| | | 2b | 7,291 | 3,212 | 668 | 88 |
| | | 2c | 8,255 | 5,776 | 1,801 | 90 |
| | 1.80 | 2d | 2,596 | 1,622 | 371 | 88 |
| | | 2e | 3,090 | 1,867 | 434 | 88 |
| | | 2f | 5,691 | 4,639 | 1,556 | 90 |
| 3. Atlantic Ocean | 2.30 | 3a | 5,842 | 10,783 | 15,401 | 22,250 |
| | | 3b | 10,475 | 16,118 | 19,776 | 26,197 |
| | 2.47 | 3c | 19,291 | 3,056 | 390 | 89 |
| | | 3d | 20,979 | 3,713 | 496 | 89 |

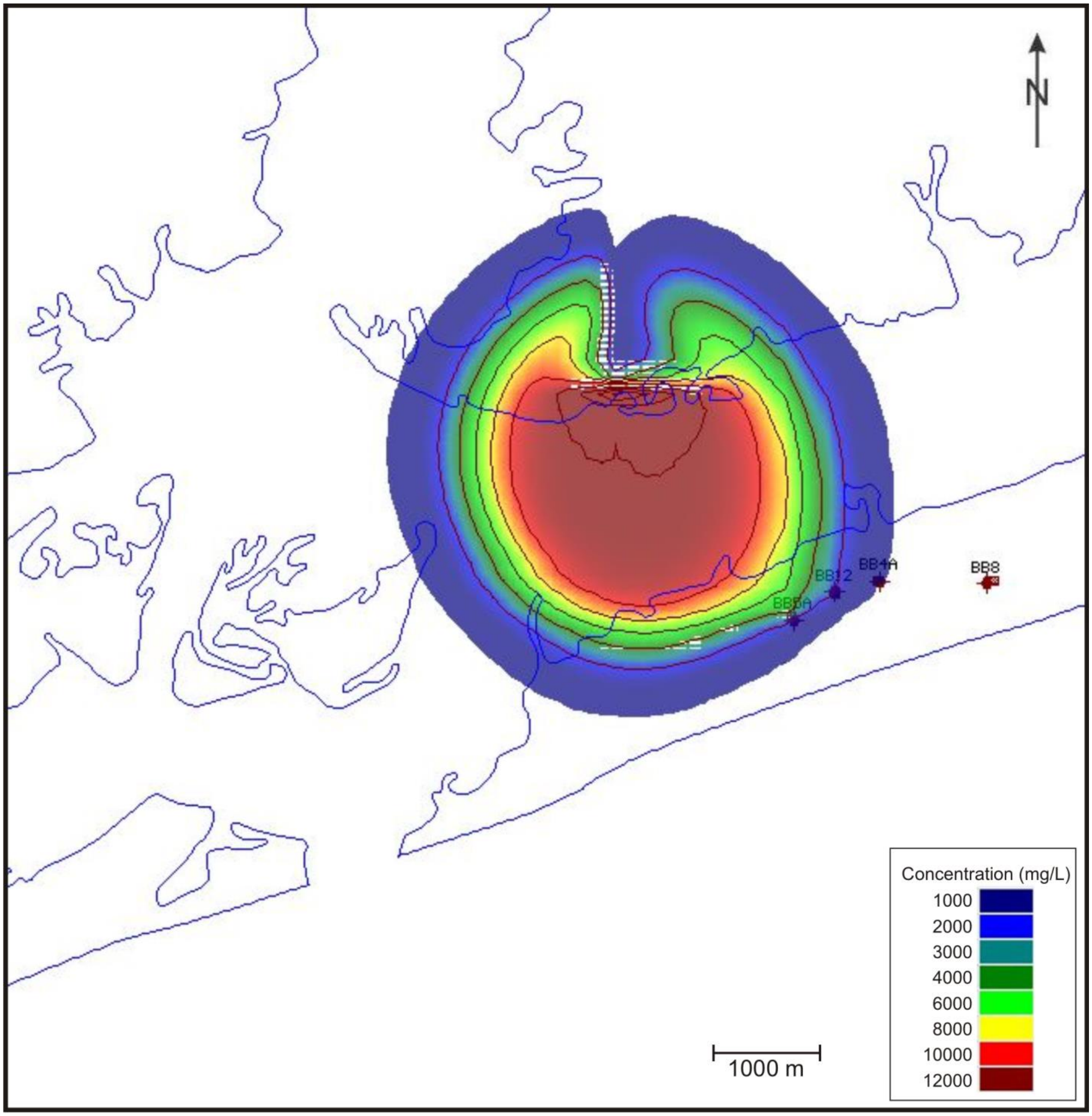


Figure 20. Map view of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 2d.

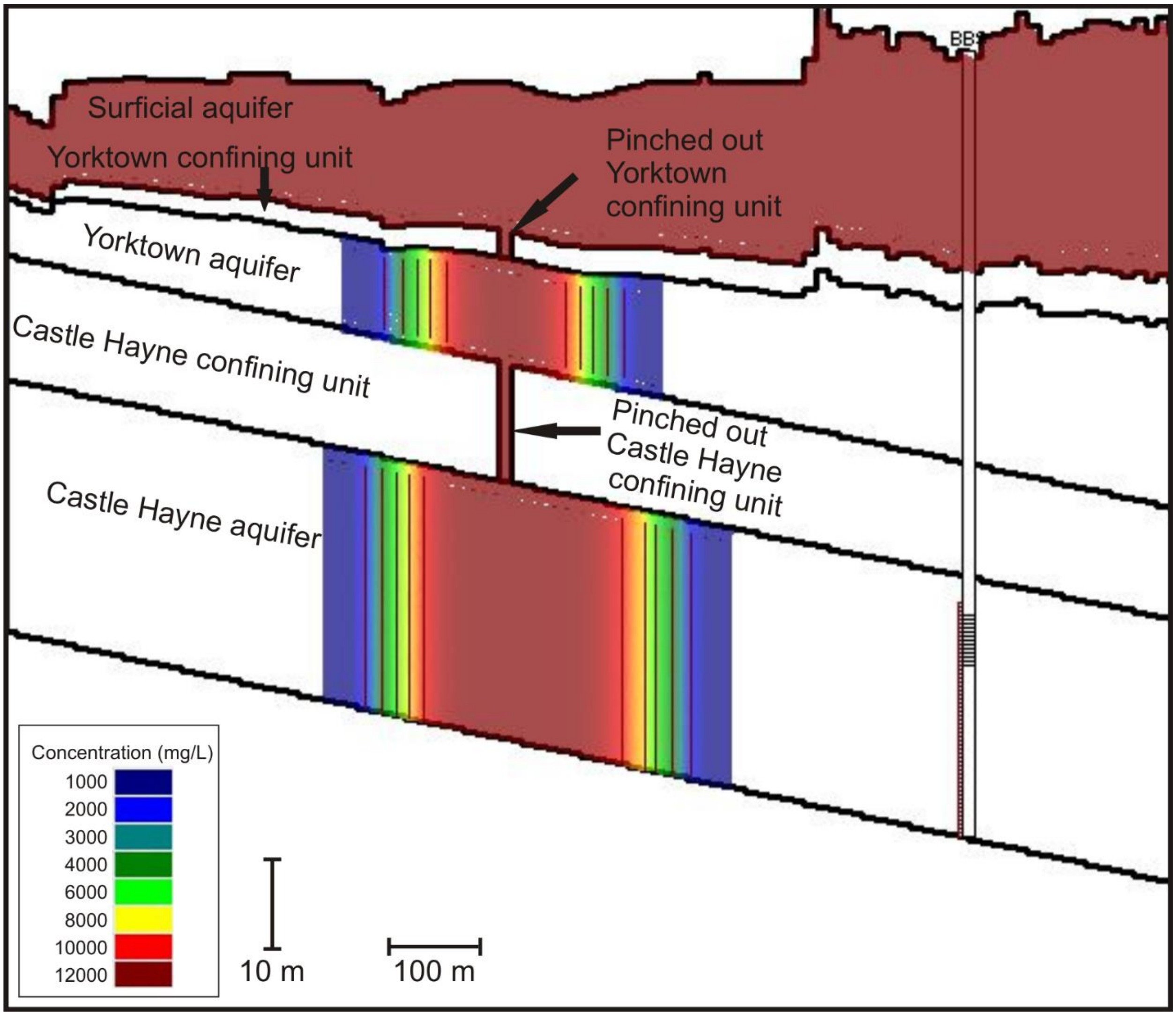


Figure 21. Cross section view (along Row 73) of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 2d. Municipal well BB9 is shown.

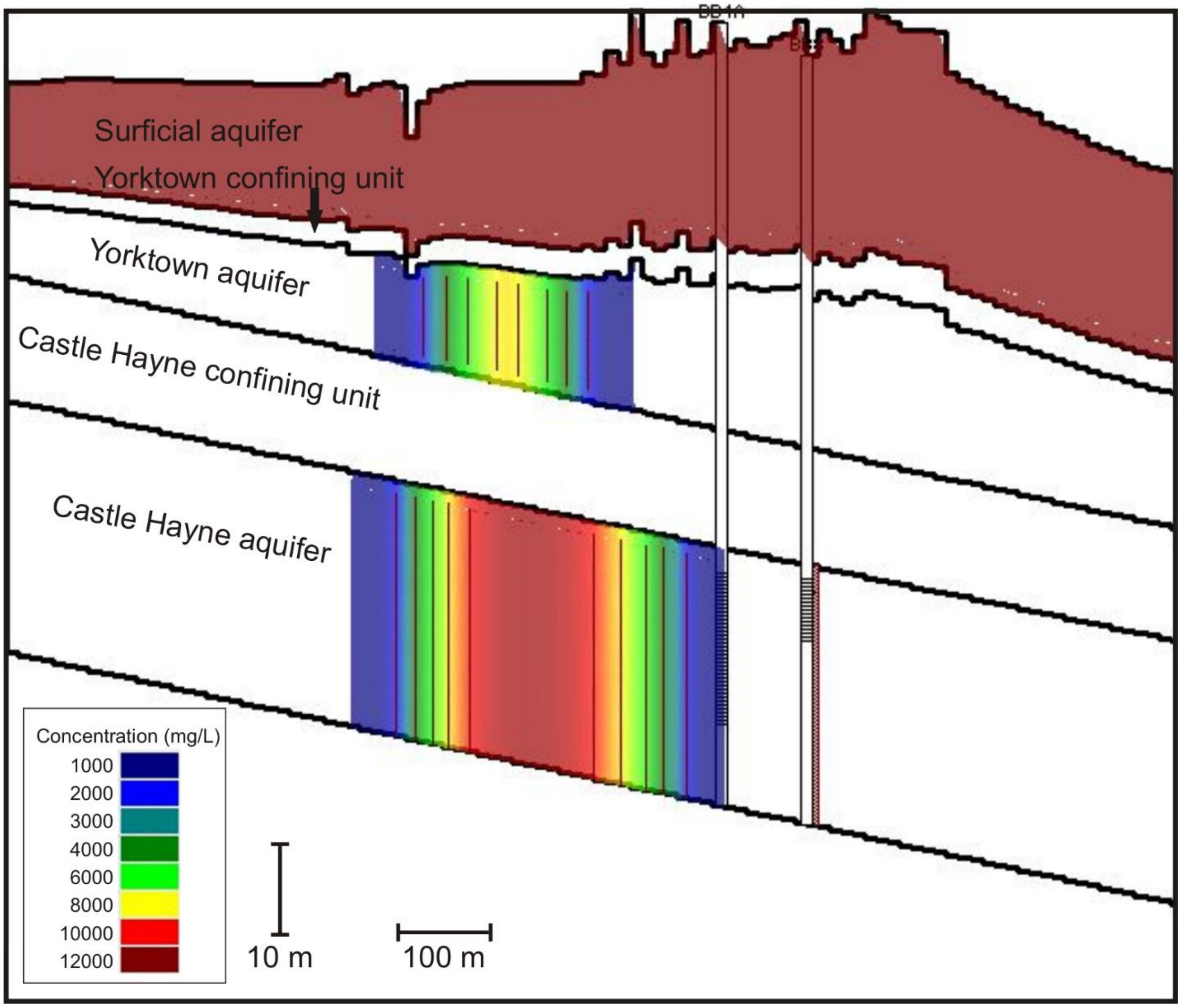


Figure 22. Cross section view (along Row 79) of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 2d. Municipal well BB4A is located on the left, BB8 is on the right.

### 4.3 Atlantic Ocean

Model results from scenario 3 (i.e., sub-scenarios 3a-3d) indicate that saltwater emanating from the Atlantic Ocean reaches municipal wells BB5A, BB12, and BB4A (Figures 23, 24). In all simulations, the saltwater plumes reached municipal well BB4A to the east. However, the saltwater plumes simulated in this scenario reached municipal well BB8, which did not experience high chloride concentrations in the field.

The results indicate that salt concentrations in municipal wells are related to the widths of the pinched out zones and the distances from the pinched out zones to the municipal well (Tables 10 and 11). For example municipal well BB5A had an increase in concentration of 4,633 mg/L from sub-scenarios 3a-3b and an increase of 1,688 mg/L from sub-scenarios 3c-3d. The widths of pinched out zones range from 121 to 363 m in both sub-scenario examples. When the pinched out zones were located 2,300 m away from municipal well BB5A (i.e., sub-scenarios 3a-3b) simulated chloride concentrations were greater in municipal wells BB12, BB4A, and BB8 than when the zones were 2,470 m away (i.e., sub-scenarios 3c-3d)

In scenario 3 (i.e., sub-scenarios 3a-3d), the sub-scenario that collectively had the closest match between simulated and observed chloride concentration was sub-scenario 3c (Table 10 and 11). Sub-scenario 3c provided the best width of the pinched out zones and distance from the pinched out zones to the municipal wells that resulted in a normalized RMS error of 359%. The results of sub-scenarios 3a-3d suggest that by varying the distances and widths of the pinched out zones, simulated chloride concentrations result in greater chloride concentrations to those observed in municipal wells BB5A, BB12, and BB4A. The results suggest that the Atlantic Ocean is not likely the source of saltwater intrusion in the municipal wells due to the high simulated chloride concentrations observed in municipal well BB5A and BB8.

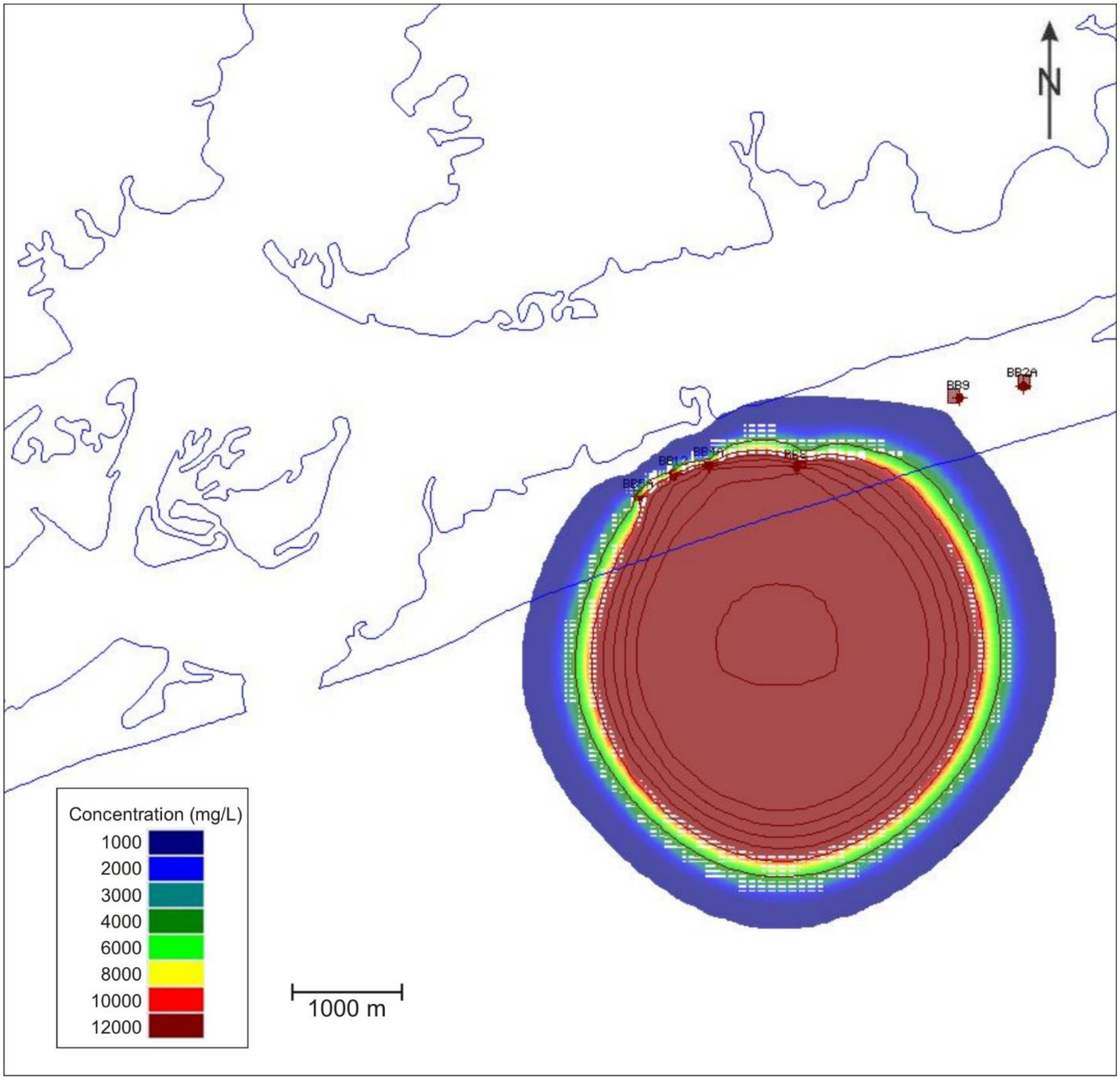


Figure 23. Map view of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 3a.

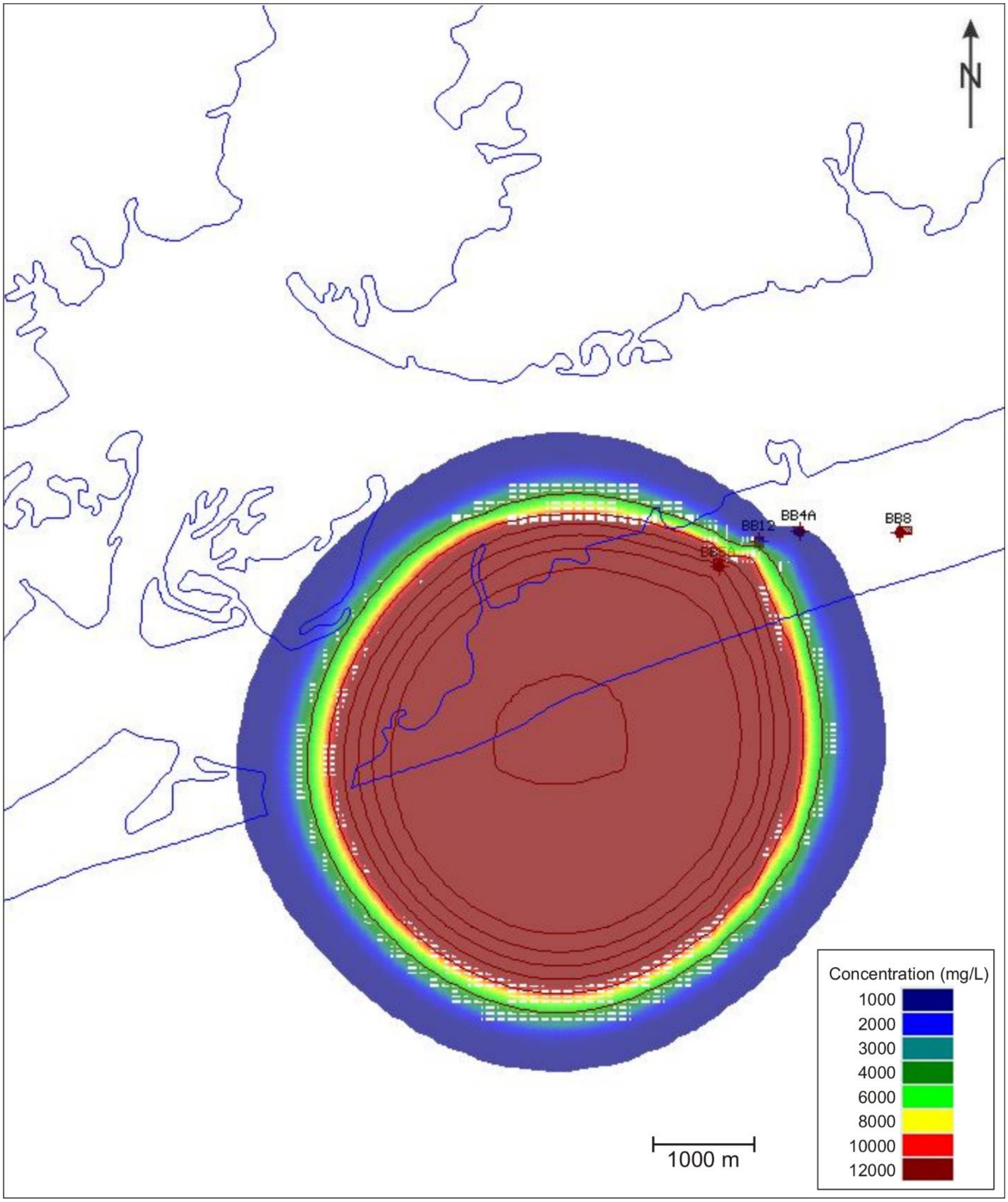


Figure 24. Map view of the modeled saltwater plume in the Castle Hayne aquifer for sub-scenario 3c.

### 4.4 Paleochannel

Model results indicate that even though the paleochannel does breach the Castle Hayne aquifer 709 m south of the northern boundary, saltwater does not migrate to the municipal wells (Figure 25). The results show that saltwater migrates 653 m down gradient from the breaching point of the paleochannel and Castle Hayne aquifer 11,383 m away from municipal well BB5A. The results also indicate that the saltwater plume only traveled 5.4% of the distance to the municipal wells, suggesting that the source of the high chloride concentrations on the western part of the island is unlikely to be the paleochannel.

Table 11. Assessment of errors between simulated and observed chloride concentrations for scenarios 1-3.

| Source | Scenarios | Residual Error | Absolute Error | Root Mean Square Error | Normalized Root Mean Square Error |
|---|---|---|---|---|---|
| 1. Bogue Inlet | 1a | -1,566 | 1,566 | 1,801 | 73% |
| | 1b | -1,565 | 1,565 | 1,800 | 73% |
| | 1c | -1,566 | 1,566 | 1,801 | 73% |
| | 1d | -1,564 | 1,564 | 1,799 | 73% |
| 2. Bogue Sound | 2a | -833 | 1,713 | 2,649 | 115% |
| | 2b | -1,127 | 1,827 | 2,813 | 147% |
| | 2c | 2,341 | 2,450 | 3,604 | 147% |
| | 2d | 322 | 955 | 1,081 | 43% |
| | 2e | 526 | 914 | 1,050 | 44% |
| | 2f | -1,317 | 1,564 | 2,172 | 88% |
| 3. Atlantic Ocean | 3a | 11,916 | 11,916 | 13,672 | 557% |
| | 3b | 16,488 | 16,488 | 17,665 | 720% |
| | 3c | 4,053 | 4,906 | 8,817 | 359% |
| | 3d | 6,315 | 6,893 | 11,737 | 478% |

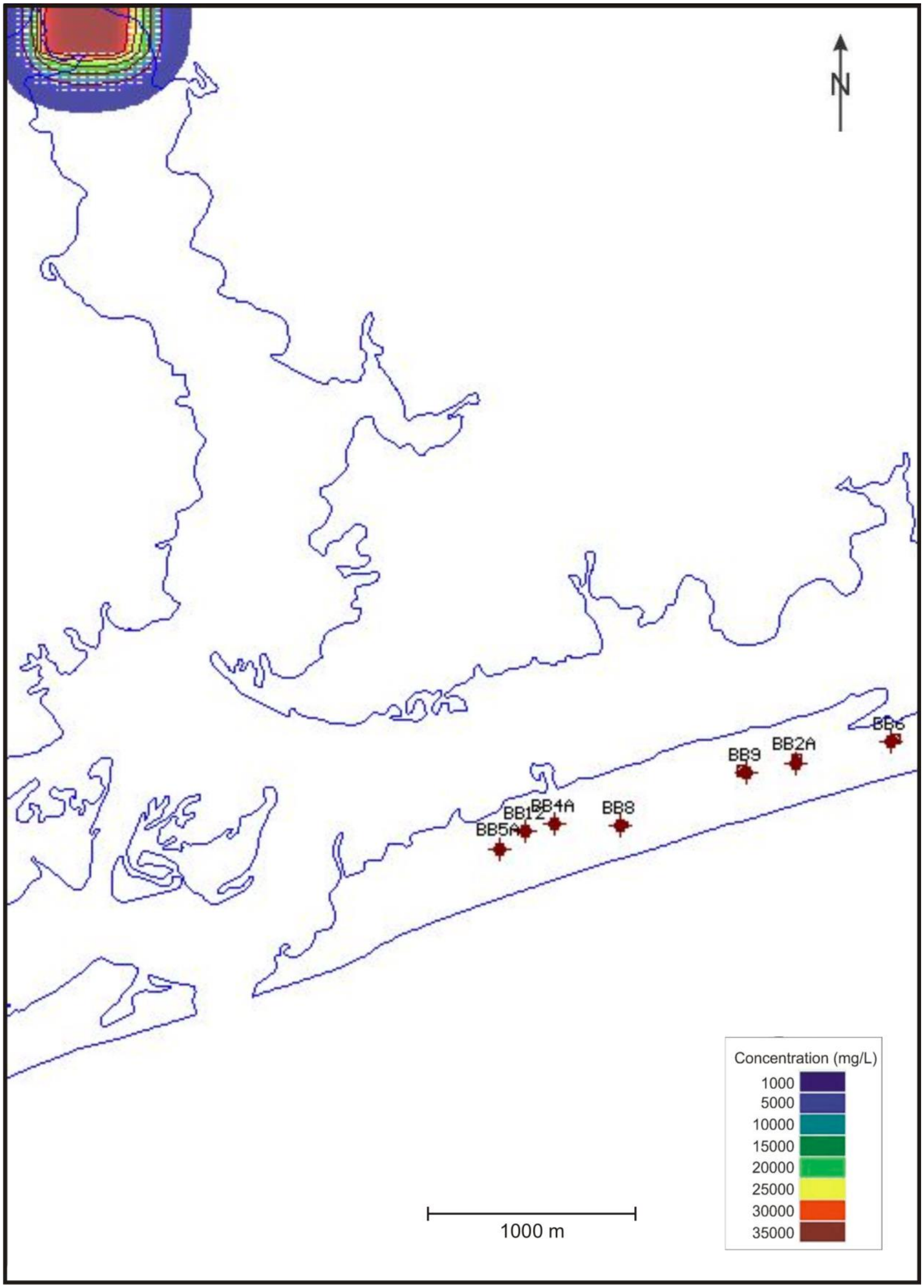


Figure 25. Map view of the modeled saltwater plume in the paleochannel.

### 4.5 Future chloride concentrations

A predictive model was created using the model from sub-scenario 2d to simulate the impact that chloride concentrations would have on municipal wells in the future. The predictive model was run for one hundred years using 2013 groundwater withdrawal rates. Results indicate that chloride concentrations continue to increase from 2013 to 2113 in municipal wells affected by high chloride concentrations (i.e., BB5A, BB12, BB4A) (Figure 26). Salt concentrations in each well increase to 7,235 mg/L, 6,639 mg/L, 2,314 mg/L, respectively for BB5A, BB12, and BB4A. Although concentrations increased in the municipal wells, the leading edge of the saltwater plume (using the 1,000 mg/L contour) did not advance past its 2013 position (Figures 27, 28). Current groundwater withdrawal from BB5A, BB12, and BB4A prevented any migration of saltwater towards the east. Saltwater still migrated from Bogue Sound into the aquifer increasing concentrations in the municipal wells but due to groundwater withdrawal, the plume did not advance farther. The predictive model suggests that if BBWC continues withdrawing groundwater from the Castle Hayne aquifer at the 2013 rates, then the saltwater plume is not expected to advance from its 2013 position but BB5A, BB12, and BB4A would have an increase in chloride concentrations.

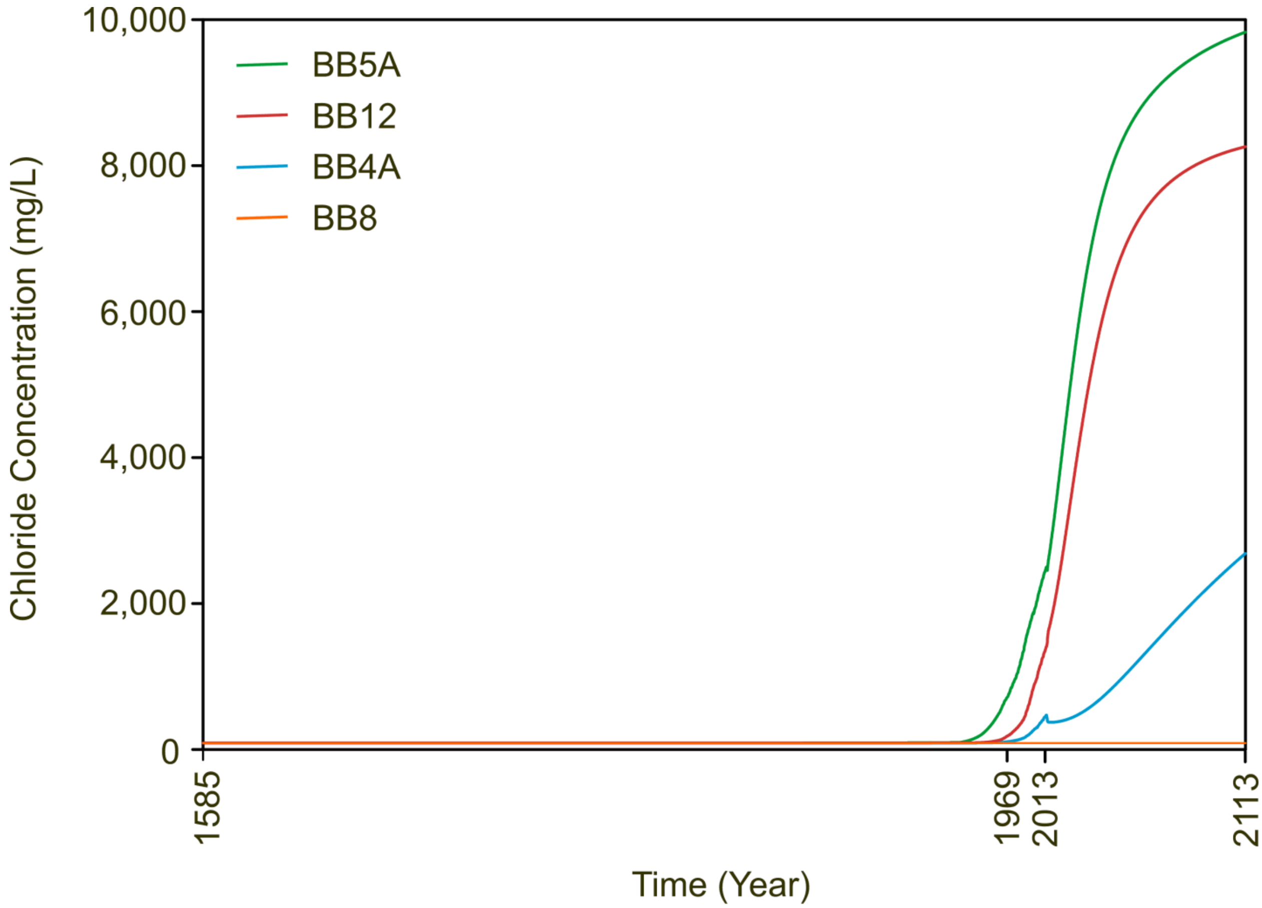


Figure 26. Modeled chloride concentrations over time in municipal wells affected by high chloride concentrations on the western part of the island.

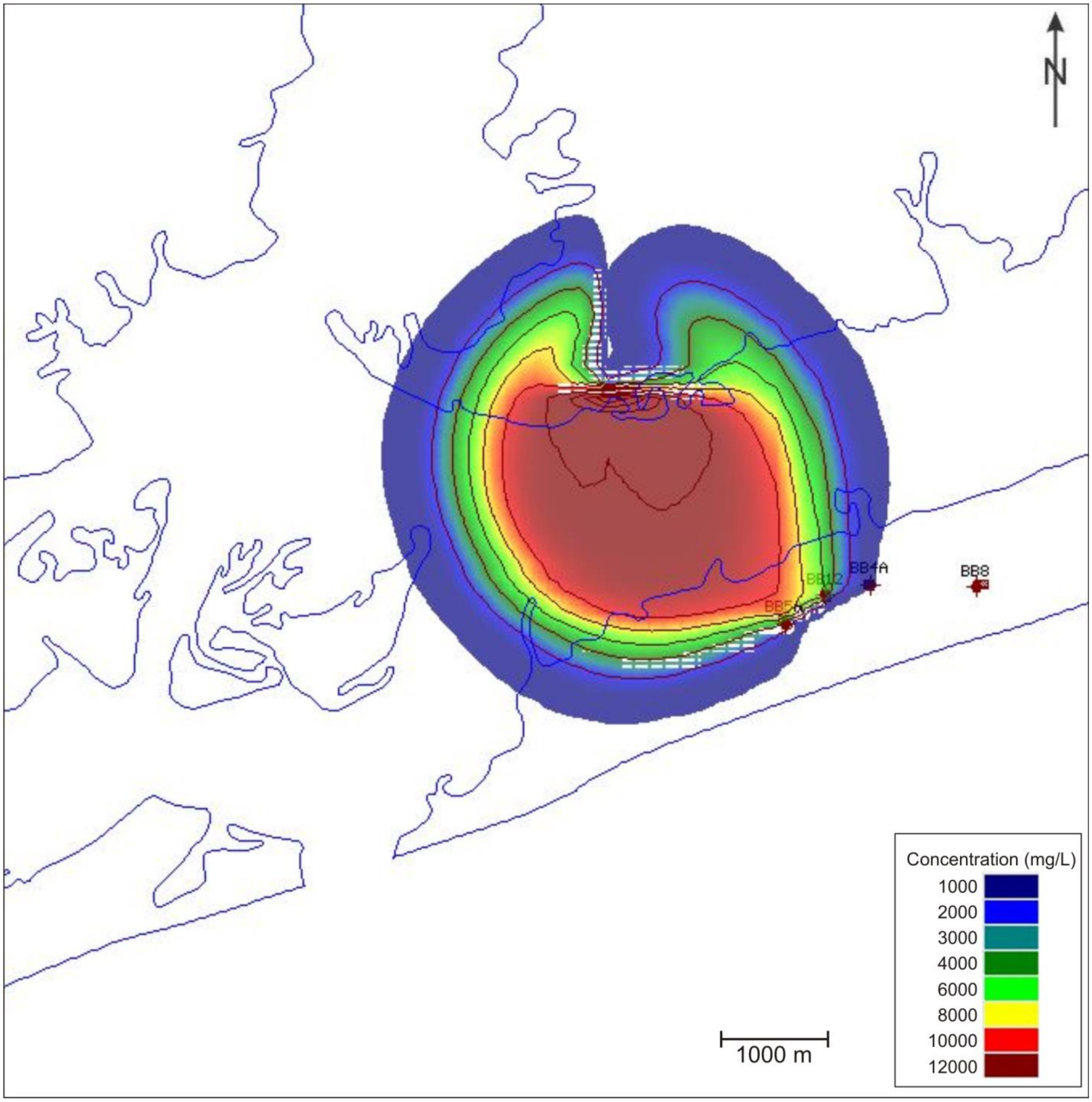


Figure 27. Map view of the modeled saltwater plume in the Castle Hayne aquifer after 100 years of groundwater withdrawal from 2013.

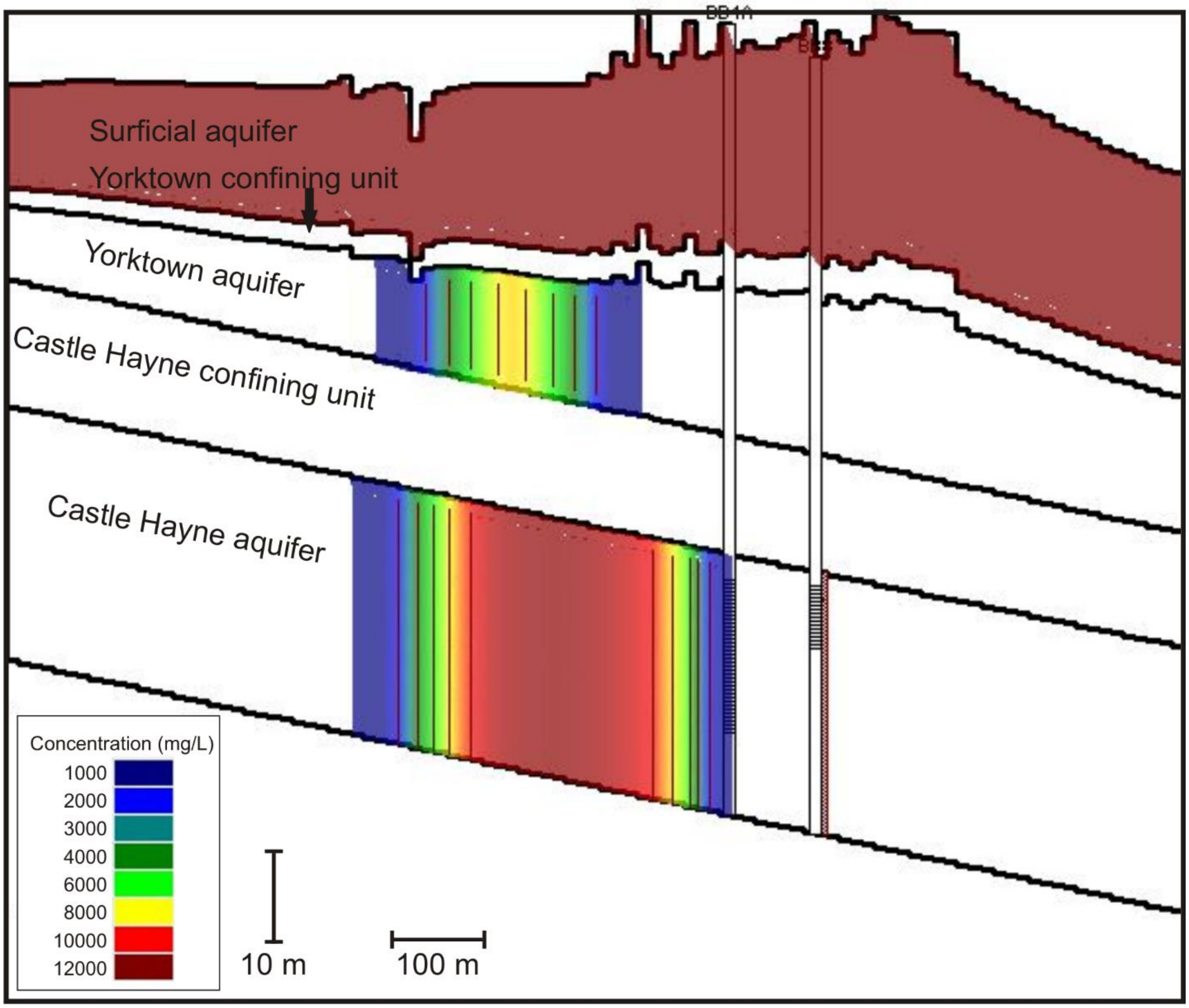


Figure 28. Cross section view (along Row 79) of the modeled saltwater plume in the Castle Hayne aquifer in 2113.

### 4.6 Model Limitations

Differences between observed and simulated heads are limited to model properties and assumptions made during model building. In the confining unit for the Yorktown aquifer, the storage coefficient was assumed to be the same as that in the Castle Hayne confining unit ($1.0x10^{-10}$). No aquifer tests were conducted in the Yorktown aquifer on the island, so the storage coefficient had to be assumed. Hydraulic heads during non-pumping conditions and storage coefficients in the Yorktown aquifer were assumed to have the same values as the Castle Hayne aquifer. An equivalent porous medium was assumed for the karstic Castle Hayne aquifer, thus the aquifer was assumed to be homogeneous in the model. Another aspect that may have influenced the model results is that the bottom of the model as a no-flow boundary although the boundary truncated the Castle Hayne aquifer.

# CHAPTER 5: CONCLUSIONS

The results of this study show brackish surface waters surrounding the island may be the source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks. With the development of a three dimensional multi-layer, multi-density groundwater flow model possible sources of saltwater intrusion were identified. The hypotheses that saltwater intrusion is from surface waters surrounding the island and/or a paleochannel underlying the island were therefore tested.

Model results indicate that saltwater originating from overlying surface waters first travels through the pinched out portions of the Yorktown confining unit into the Yorktown aquifer. Once in the Yorktown aquifer, saltwater begins to migrate laterally and vertically. When the saltwater plume reaches the bottom of the Yorktown aquifer, it then travels through the pinched out portions of the Castle Hayne confining unit into the Castle Hayne aquifer. After entering the Castle Hayne aquifer, saltwater begins to disperse in all directions with more saltwater heading in the direction of groundwater flow. Of the possible sources, model results suggest that the likely source of saltwater intrusion is the surface water surrounding the island. Bogue Sound rather than Bogue Inlet or the Atlantic Ocean is likely to be the source of the saltwater intrusion. Bogue Sound provided the smallest difference between simulated and observed chloride concentrations of all the scenarios.

In conclusion, the most likely source of saltwater intrusion on the western part of the island is brackish surface water traveling from Bogue Sound into the Castle Hayne aquifer. Pumping conditions on the island influence groundwater flow from Bogue

Sound into municipal wells BB5A, BB12, and BB4A in turn raising the chloride concentration in excess of 1,700 mg/L. These results may be useful to water managers on Bogue Banks in addressing potential threats to water resources that are driven by future reductions in freshwater storage on the island.

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# APPENDIX A: SALTWATER WEDGE BENEATH BOGUE BANKS

To determine the location of the saltwater wedge, data from the Division of Water Resources Ground Water Management Branch Mapserver of the North Carolina Department of Environment and Natural Resources (NC DENR) were used (NC DENR, 2014d). Using chloride samples collected by water providers in the Castle Hayne aquifer in North Carolina, the mapserver provides the estimated location of the transition zone between salty and fresh water (Figure 1a, 1b). To the east of the transition zone, groundwater is salty, while to the west, groundwater it fresh.

To determine the location of the saltwater wedge underlying Bogue Banks, contacts of hydrogeological units were extended until the units intersected the transition zone boundary to the east (Figure 1c). A line representing the saltwater wedge was then drawn from the top of the Castle Hayne aquifer (i.e. starting at the point of intersection of the hydrogeologic unit with the transition zone) to the bottom of the aquifer on the western end of the island (Figure 1c). The area under the line represents saltwater in the Castle Hayne aquifer (Figure 1c). The locations and depths of municipal wells suggest that the saltwater wedge is not influencing chloride concentrations in the wells on the western part of the island.

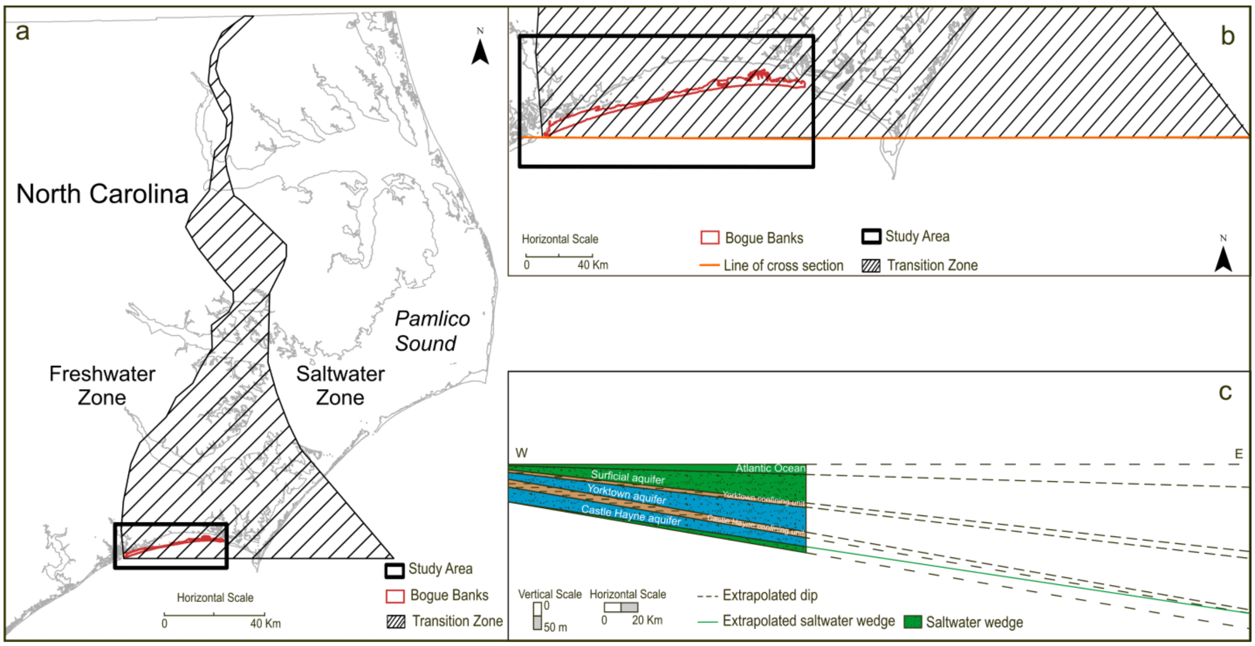



Figure 1. Location of the saltwater wedge in the Castle Hayne aquifer underlying Bogue Banks. (a) Map view of the transition zone in the Castle Hayne aquifer. (b) Map view of the study area in reference to the transition zone. (c) Cross section view showing the location of the saltwater wedge.

## APPENDIX B: SIMULATING GROUNDWATER FLOW

A three dimensional multi-layer, multi-density groundwater flow model of the hydrostratigraphy underlying Bogue Banks was created to determine the source of saltwater intrusion in the Castle Hayne aquifer on the western part of Bogue Banks. Visual MODFLOW was used to verify groundwater flow, and simulate saltwater intrusion (McDonald and Harbaugh, 1988). Visual MODFLOW simulates groundwater flow in three dimensions using the groundwater flow equation (Anderson and Woessner, 2002):

$$\frac{d}{dx}\left(K_x h \frac{dh}{dx}\right) + \frac{d}{dy}\left(K_y h \frac{dh}{dy}\right) + \frac{d}{dz}\left(K_z h \frac{dh}{dz}\right) = S_s \frac{dh}{dt} - R$$

Kx, Ky, Kz = Hydraulic Conductivity (m/day)

$S_s$ = Specific Storage ($m^{-1}$)

R = General sink/source term defines volume of inflow to the system per unit volume of aquifer per unit time ($m^3$/day)

h = Head (m)

t = Time (day)

## APPENDIX C: LAYER ELEVATIONS

Elevations needed for the models created in this study included land surface and seafloor, along with confining units and aquifers. For land surface and seafloor elevations, a Digital Elevation Model (DEM) of the land surface with integrated bathymetric elevations of Bogue Sound, Bogue and Beaufort Inlets, White Oak River, and the surrounding Atlantic Ocean were used (Grothe, et al., 2012). The DEM has 1/3 arc-second (≈10 m) grid spacing and has about a 9.4 m cell size (Grothe, et al., 2012).

Elevations for the top of Yorktown confining unit and aquifer were acquired by Groundwater Management Associates, Inc. from municipal well BB5A. The dips of the units were assumed to be the same as the Castle Hayne confining unit.

The elevations of the Castle Hayne confining unit and aquifer were determined by selecting three wells located in the model area (NC DENR, 2014e). Data from the three wells indicated that the hydrogeologic units generally dip to the south-east. To interpolate the upper surface of the Castle Hayne confining unit, the elevations of the unit as determined from logs of wells X 18E (-26 m), Y 20D2 (-40 m) and X 19U (-56m) were utilized. The elevations of the top of the Castle Hayne aquifer as determined from the well logs were -35 m, -48 m, and -67 m. No hydrostratigraphic framework data existed for the top of the Beaufort aquifer in the study area, so the bottom of the deepest municipal well on the island (i.e., AB6) was used to establish the bottom of the model at a depth of (-134 m). The bottom of the model was assigned the same dip as the top of the Castle Hayne aquifer.

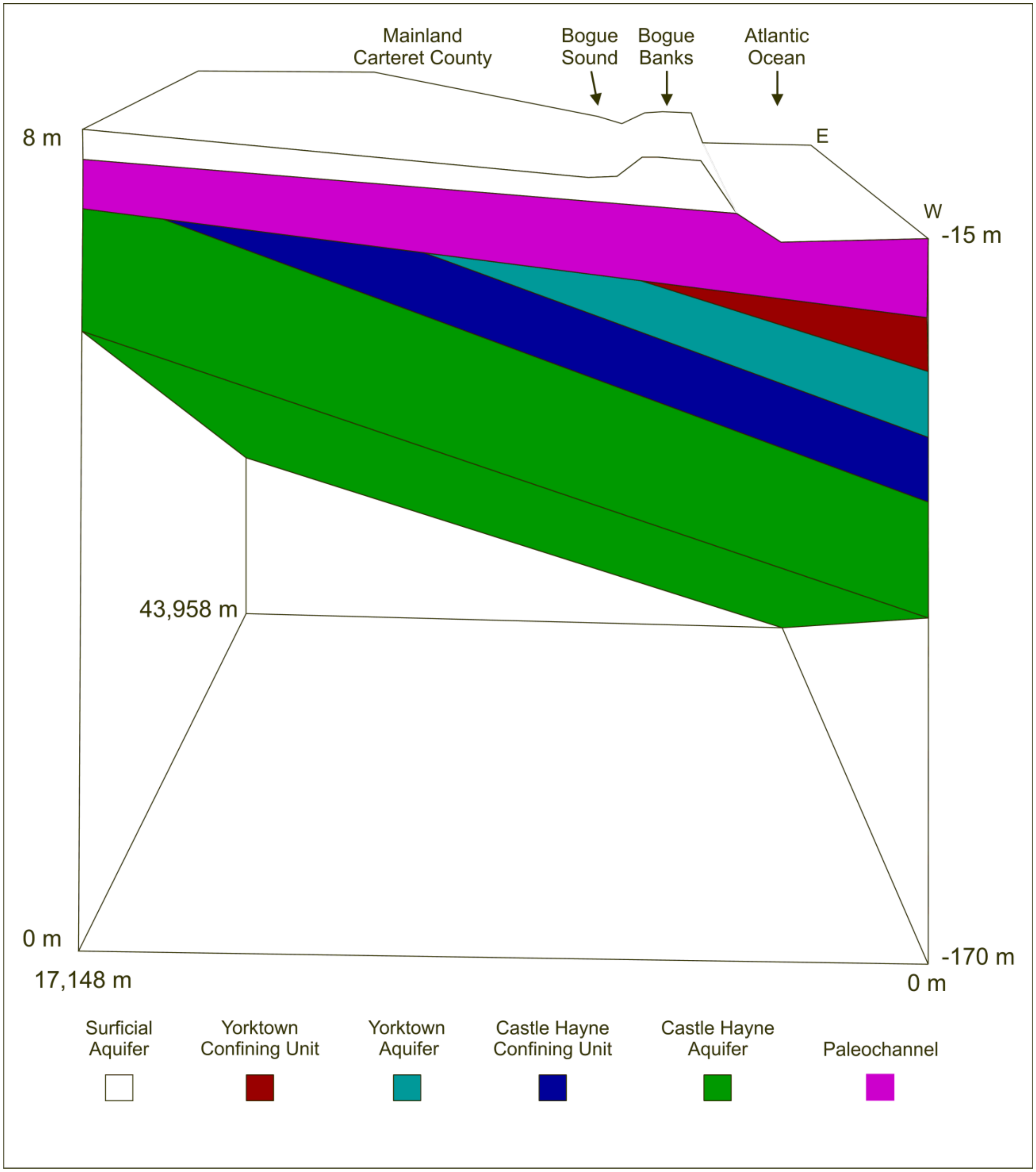
## APPENDIX D: RANGES OF HYDRAULIC PROPERTY VALUES USED TO CALIBRATE MODEL

| Hydrogeologic Unit | $K_x/K_y$ (m/day) | $K_z$ (m/day) | S (%/m$^{-1}$) |
|---|---|---|---|
| Surficial Aquifer | 3.0-15.2 | 0.3-1.52 | 0.10-0.35 |
| Yorktown Aquifer | 5.8-10.1 | 0.58-1.01 | $6.0 \times 10^{-6}$ |
| Castle Hayne Aquifer | 8.0-61 | 0.8-6.1 | $5.0 \times 10^{-6}$ |

## APPENDIX E: LIST OF SOURCES FOR INPUTS IN GROUNDWATER FLOW MODEL

| Model Input | Source |
|---|---|
| Surficial Aquifer properties | NC DENR, 2014e<br>Heath, 1983; Johnson, 1996; Healy and Cook, 2002<br>Peel et al., 2007;Sisco, 2013 |
| Yorktown Confining Unit properties | Heath, 1983<br>Giese et al., 1991<br>Groundwater Management Associates, Inc., 2013 |
| Yorktown Aquifer properties | Heath, 1983<br>Giese et al., 1997 |
| Castle Hayne Confining Unit properties | Heath, 1983<br>Giese et al., 1991<br>Groundwater Management Associates, Inc., 2013 |
| Castle Hayne Aquifer properties | Heath, 1983<br>Giese et al., 1997<br>Groundwater Management Associates, Inc., 2013 |
| Paleochannel properties | Heath, 1983<br>Groundwater Management Associates, Inc., 2013 |
| Elevations | Grothe et al., 2012; NC DENR, 2014e |
| Well Data | NC DENR, 2014a,b,c |
| Longitudinal Dispersivity | Guo and Langevin, 2002 |
| Head Convergence Criterion | Guo and Langevin, 2002 |
| Courant Number | Guo and Langevin, 2002 |

## APPENDIX F: BLOCK DIAGRAM OF THE HYDROSTRATIGRAPHY IN THE MODEL AREA

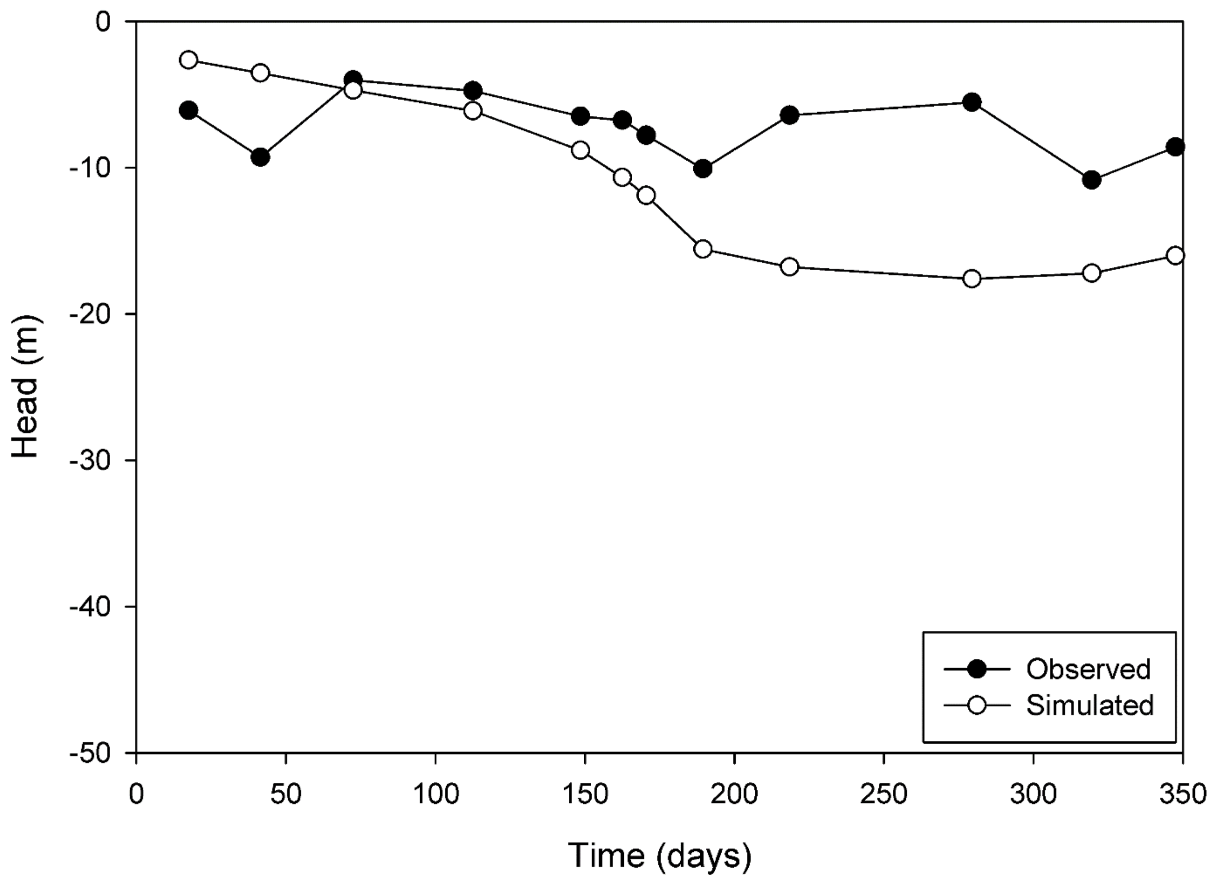


## APPENDIX G: OBSERVED AND SIMULATED HEADS

Observed versus simulated heads during groundwater withdrawal in 2004.

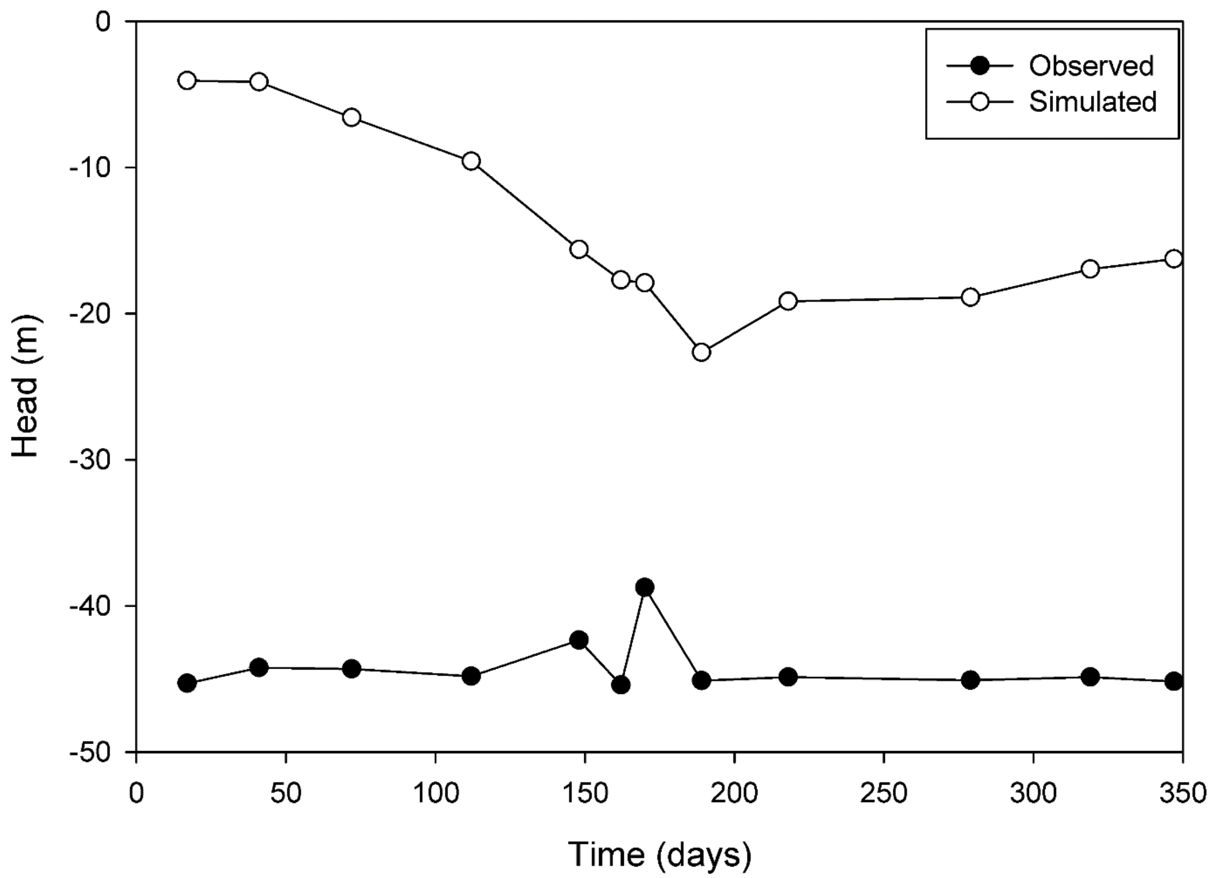
BB = Bogue Banks Well Corporation

BB1



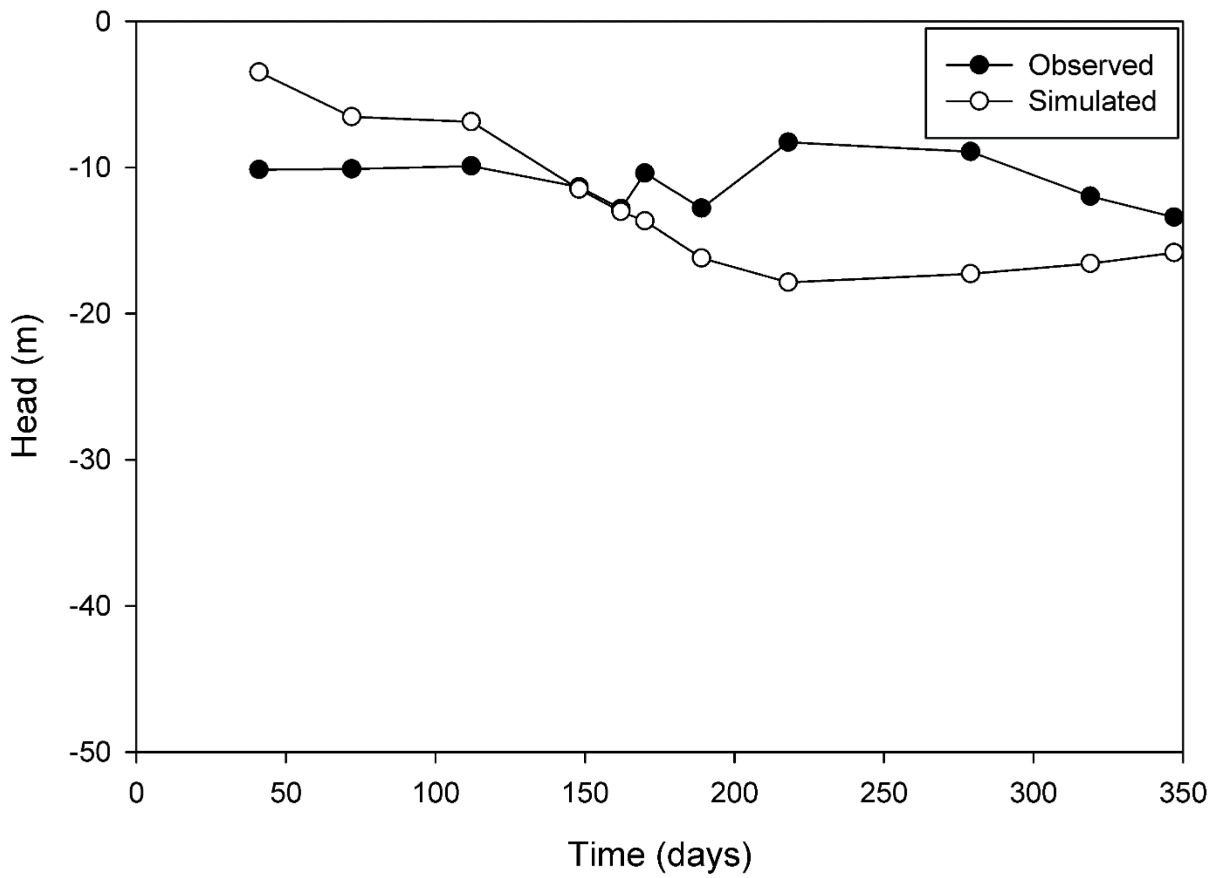
0
-10
-20
-30
-40
-50
Head (m)
0
50
100
150
200
250
300
350
Time (days)
Observed
Simulated

BB2A



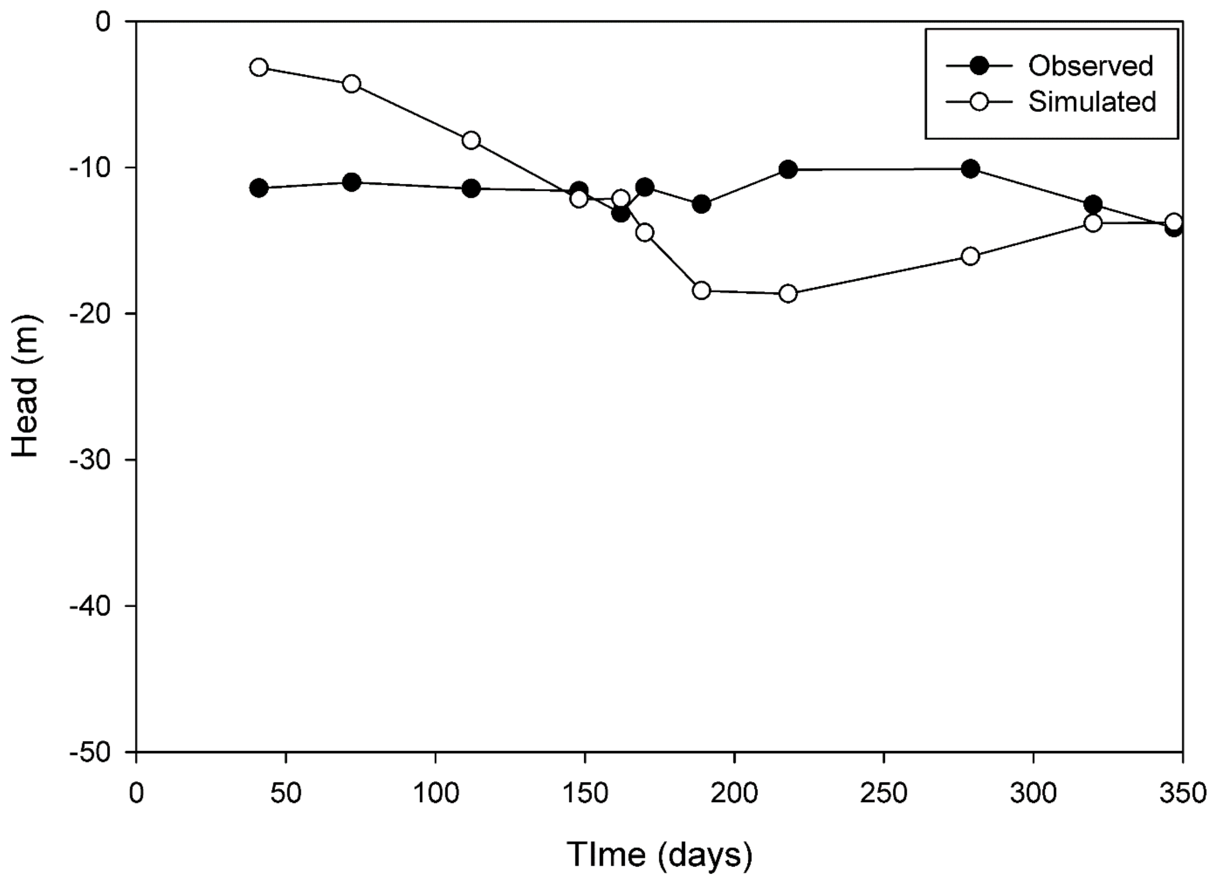
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

BB3A



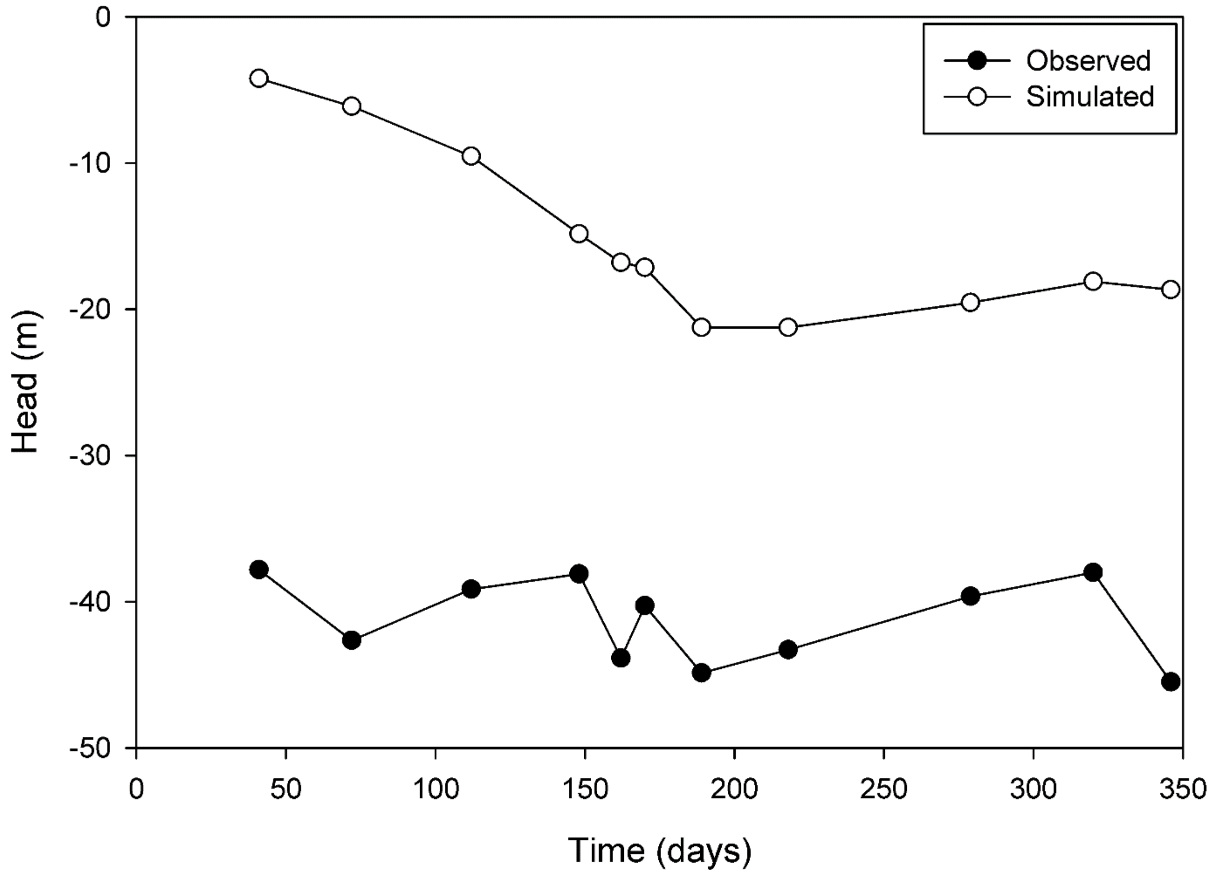
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

BB4A



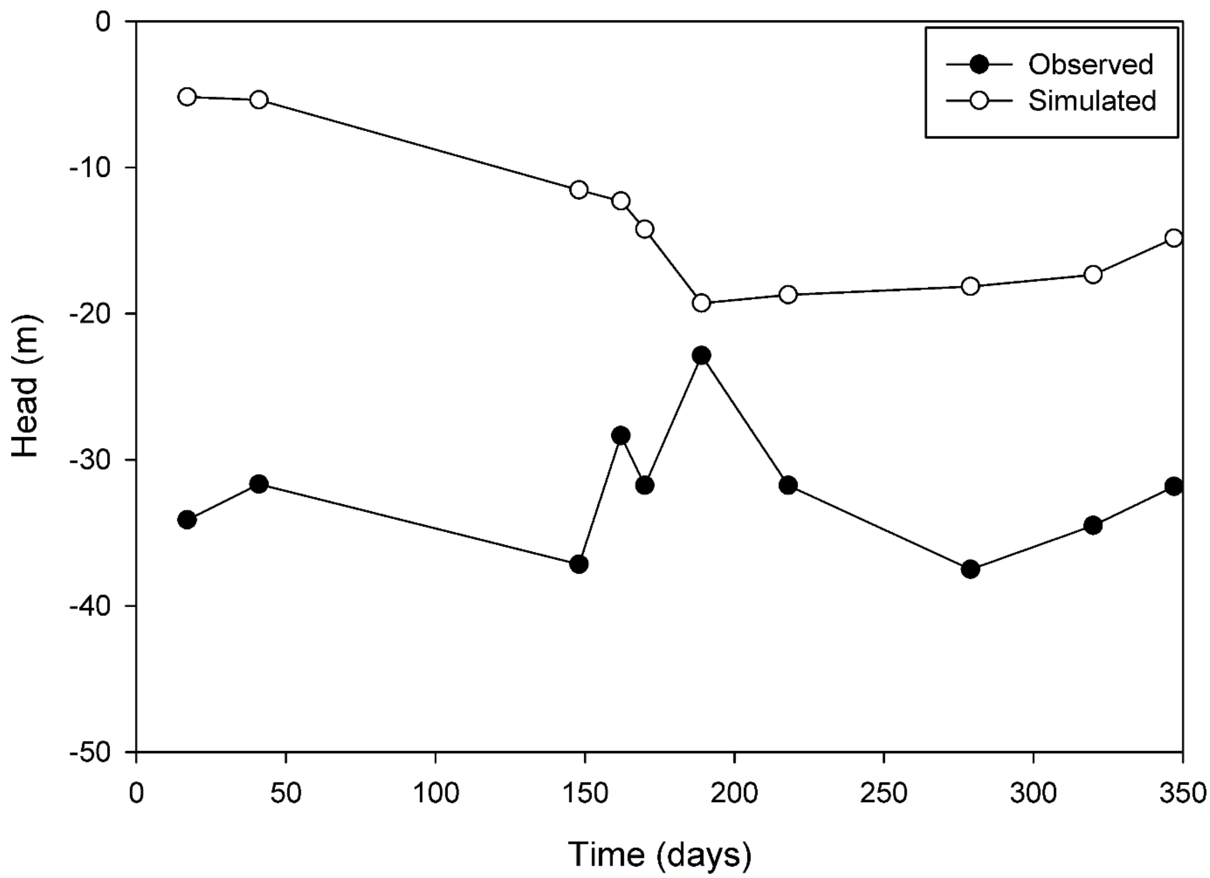
0
-10
-20
-30
-40
-50
Head (m)
0
50
100
150
200
250
300
350
TIme (days)
Observed
Simulated

BB6



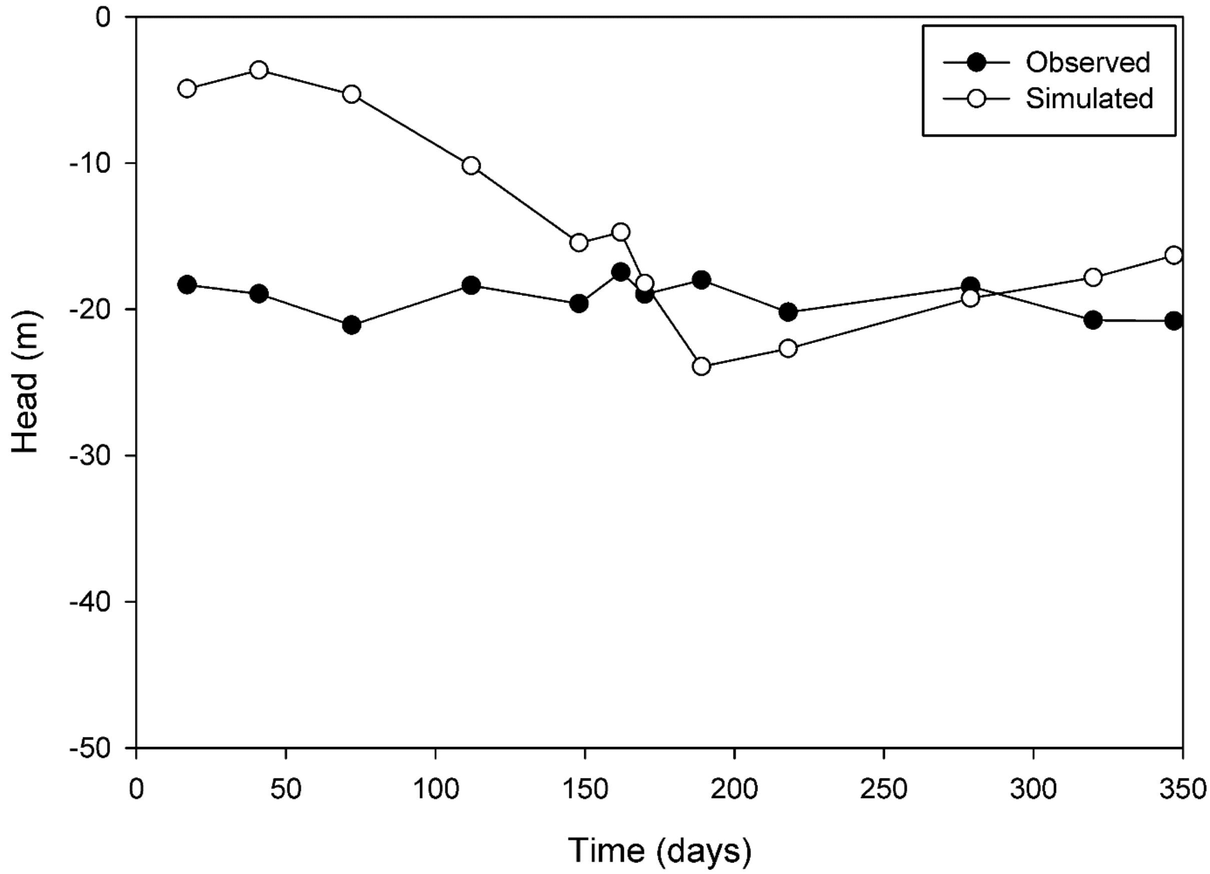
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

BB7A



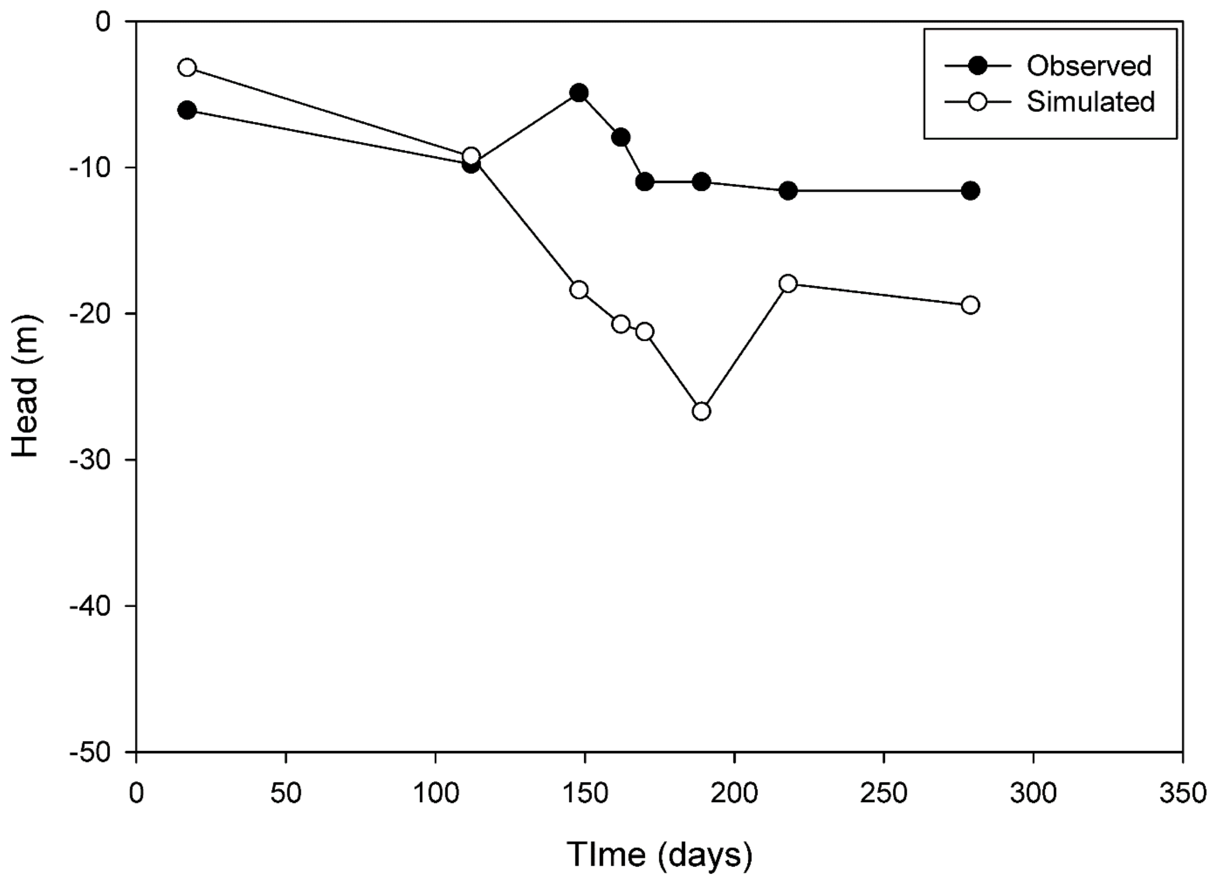
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

BB8



Observed
Simulated
Head (m)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350
Time (days)

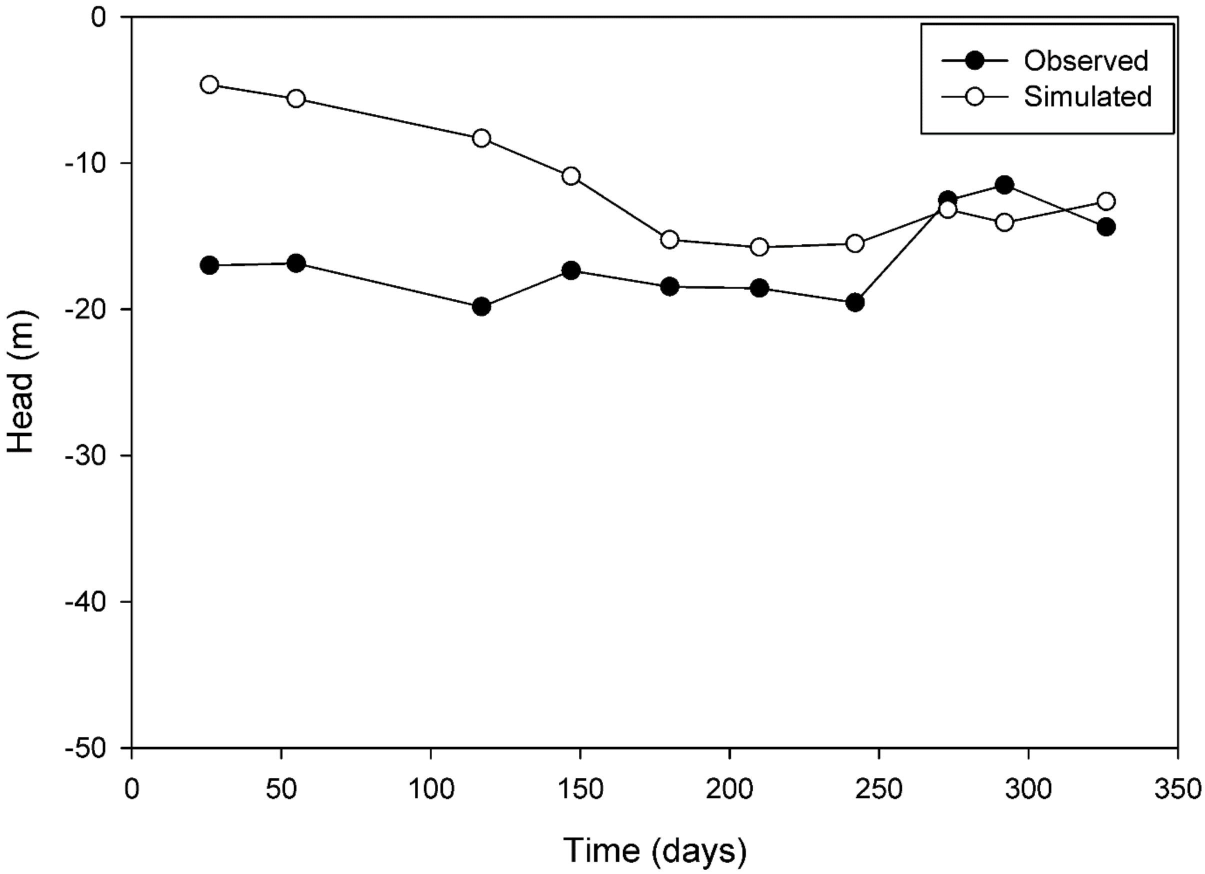
BB9



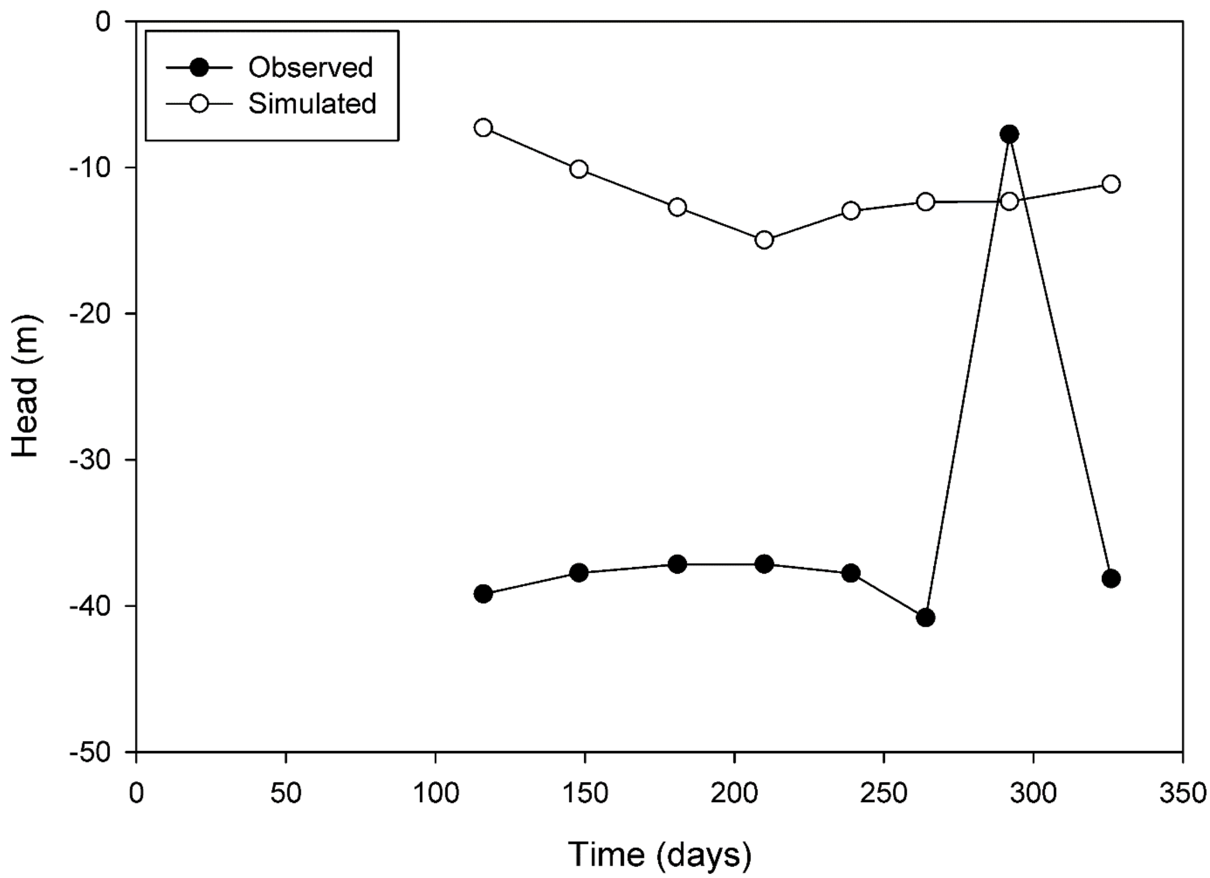
Observed
Simulated
Head (m)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350
TIme (days)

AB = Town of Atlantic Beach

AB1

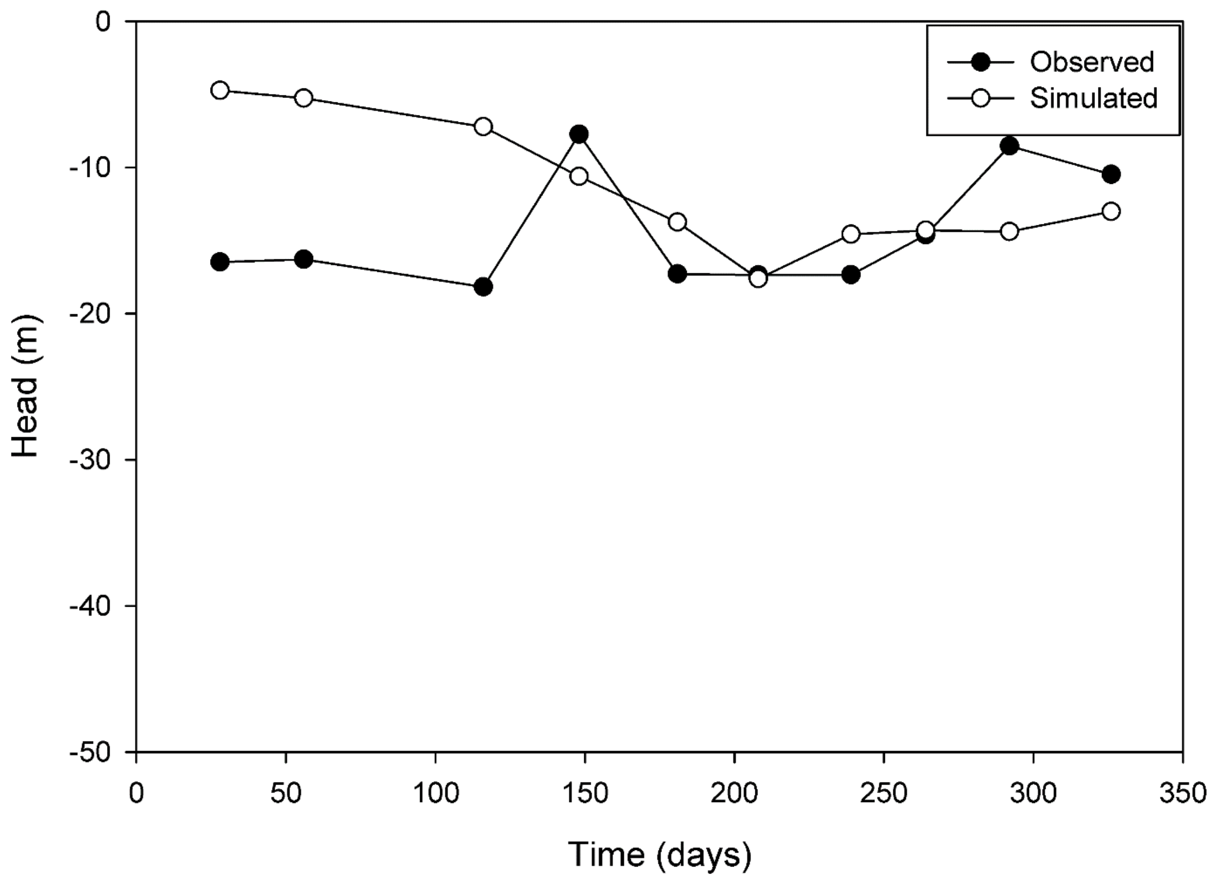

Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

AB2



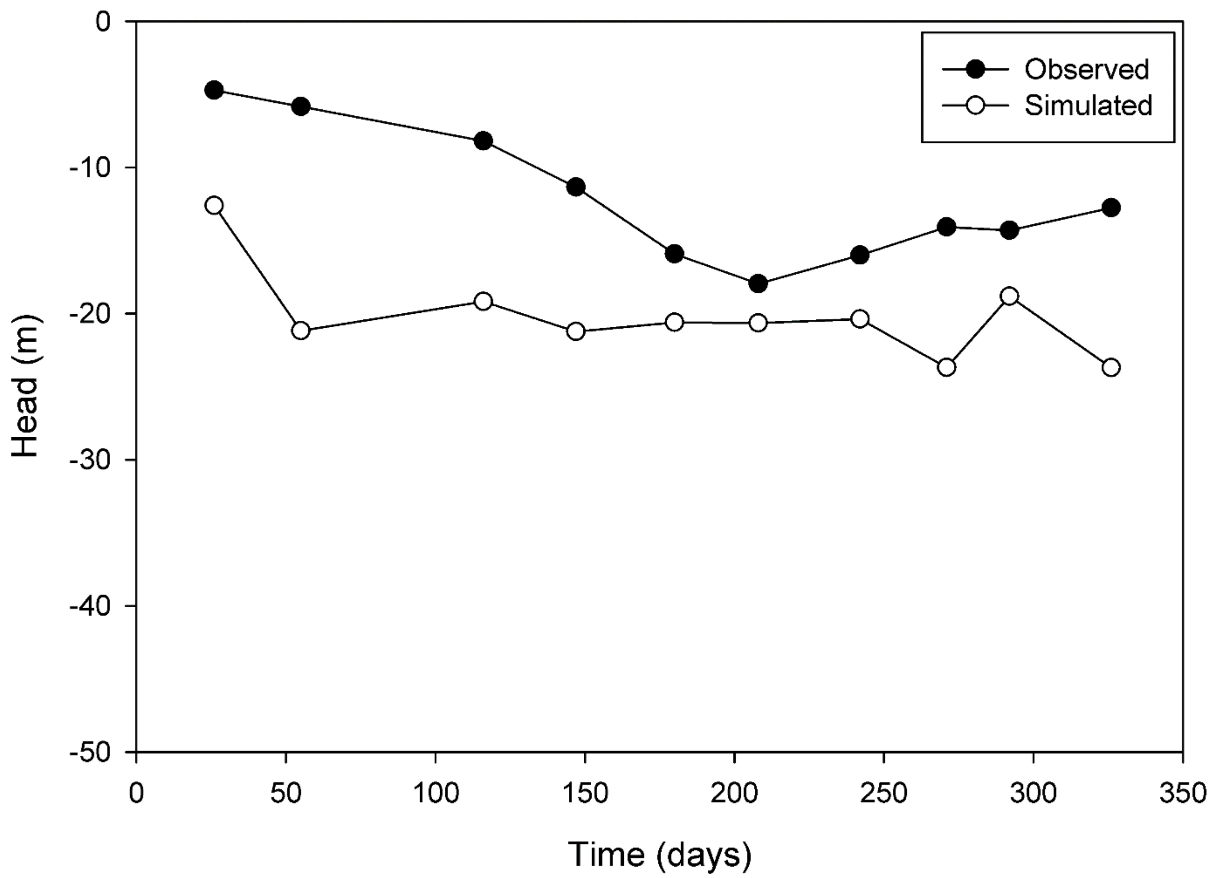
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

AB3



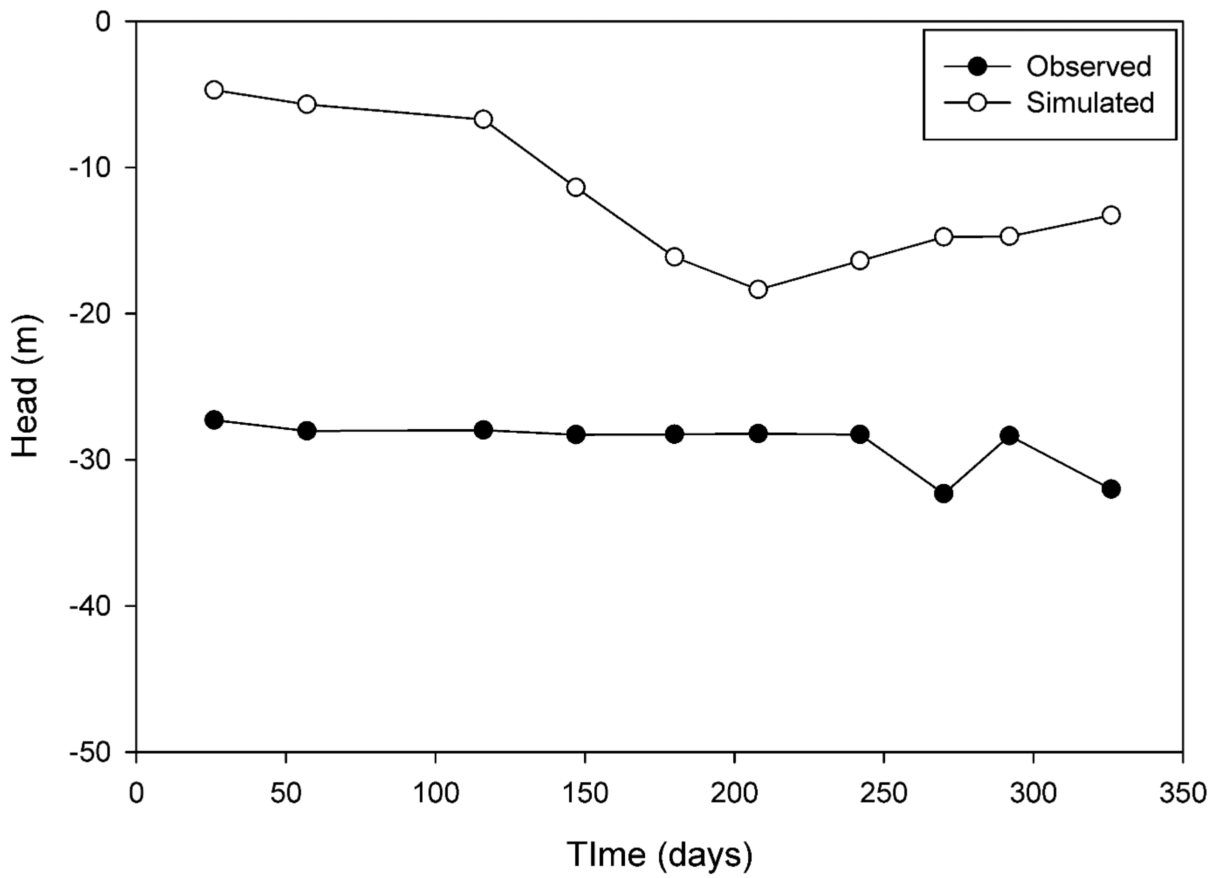
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

AB4



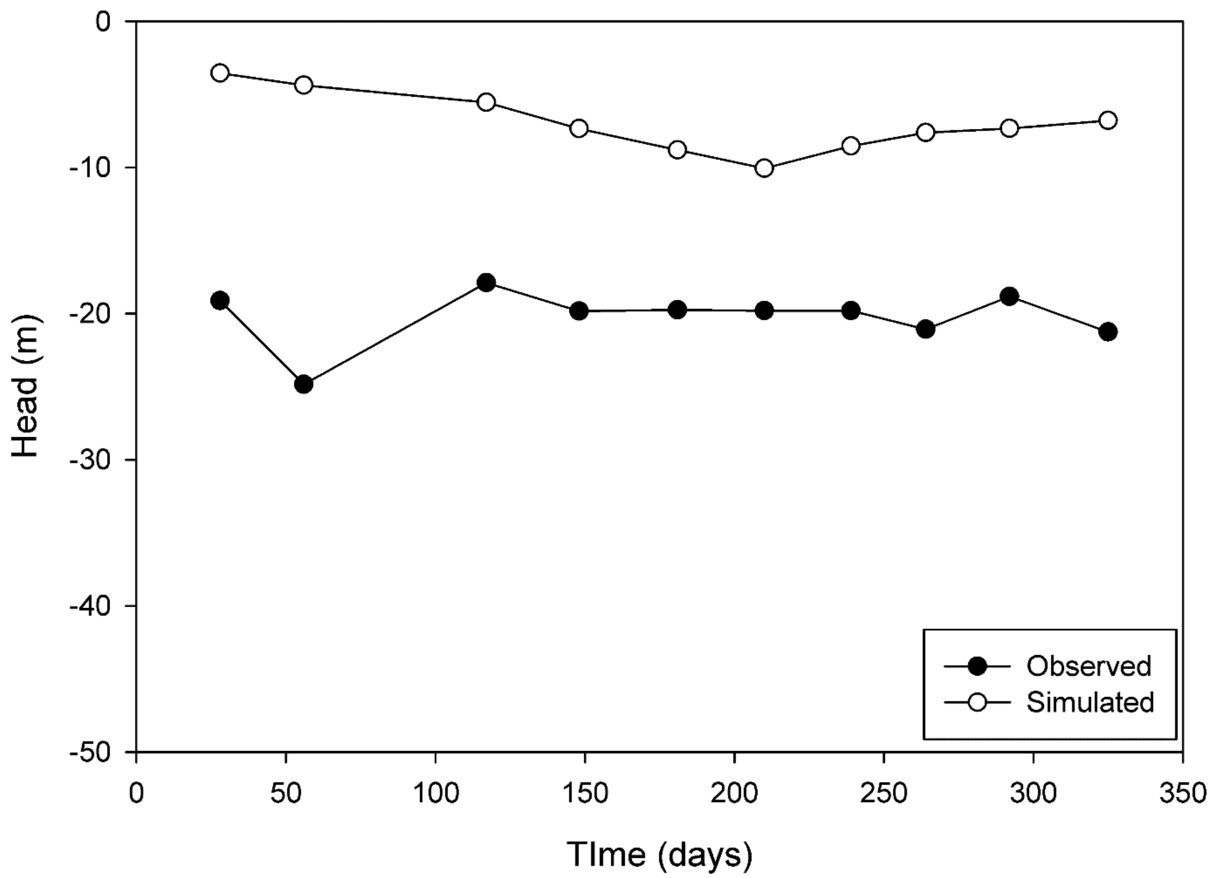
Observed
Simulated
Head (m)
Time (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

AB5



Observed
Simulated
Head (m)
TIme (days)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350

AB6

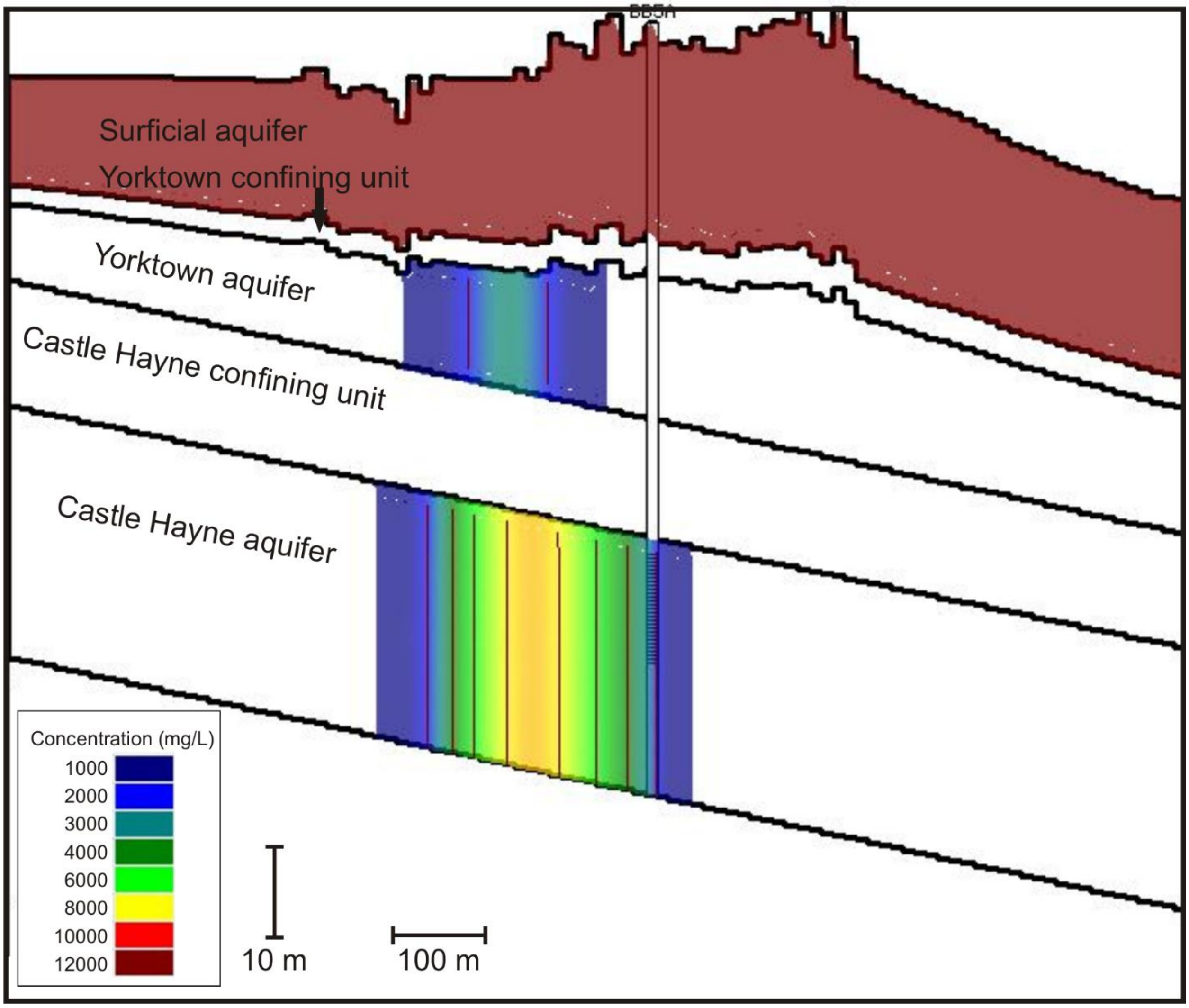


Head (m)
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350
TIme (days)
Observed
Simulated

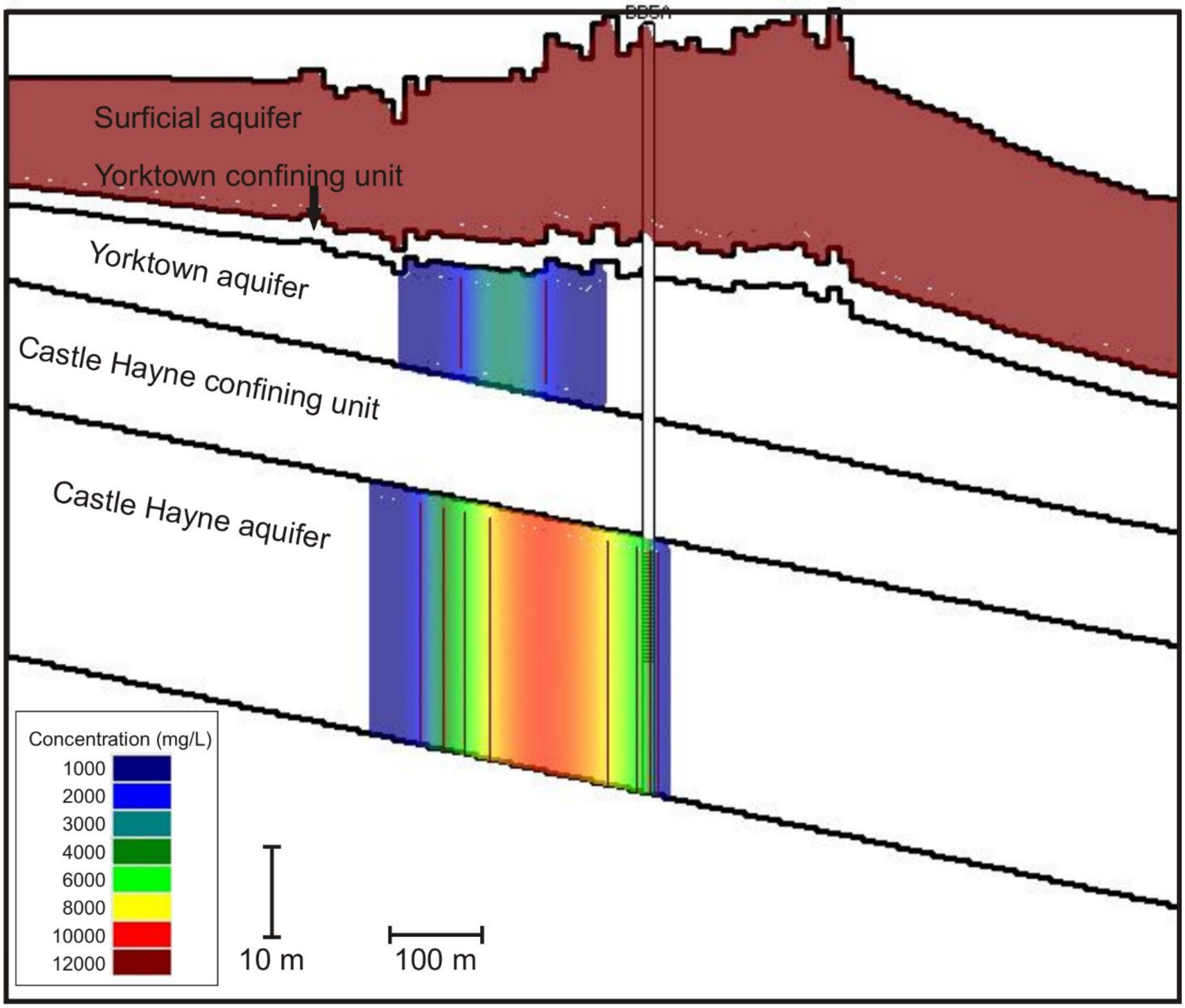
## APPENDIX H: CROSS SECTIONAL VIEWS FROM PREDICTIVE MODEL

Cross sectional view of the salt plumes around wells BB5A, BB12, and BB4A, on 10/21/2013 and 10/21/2113 from the predictive model.

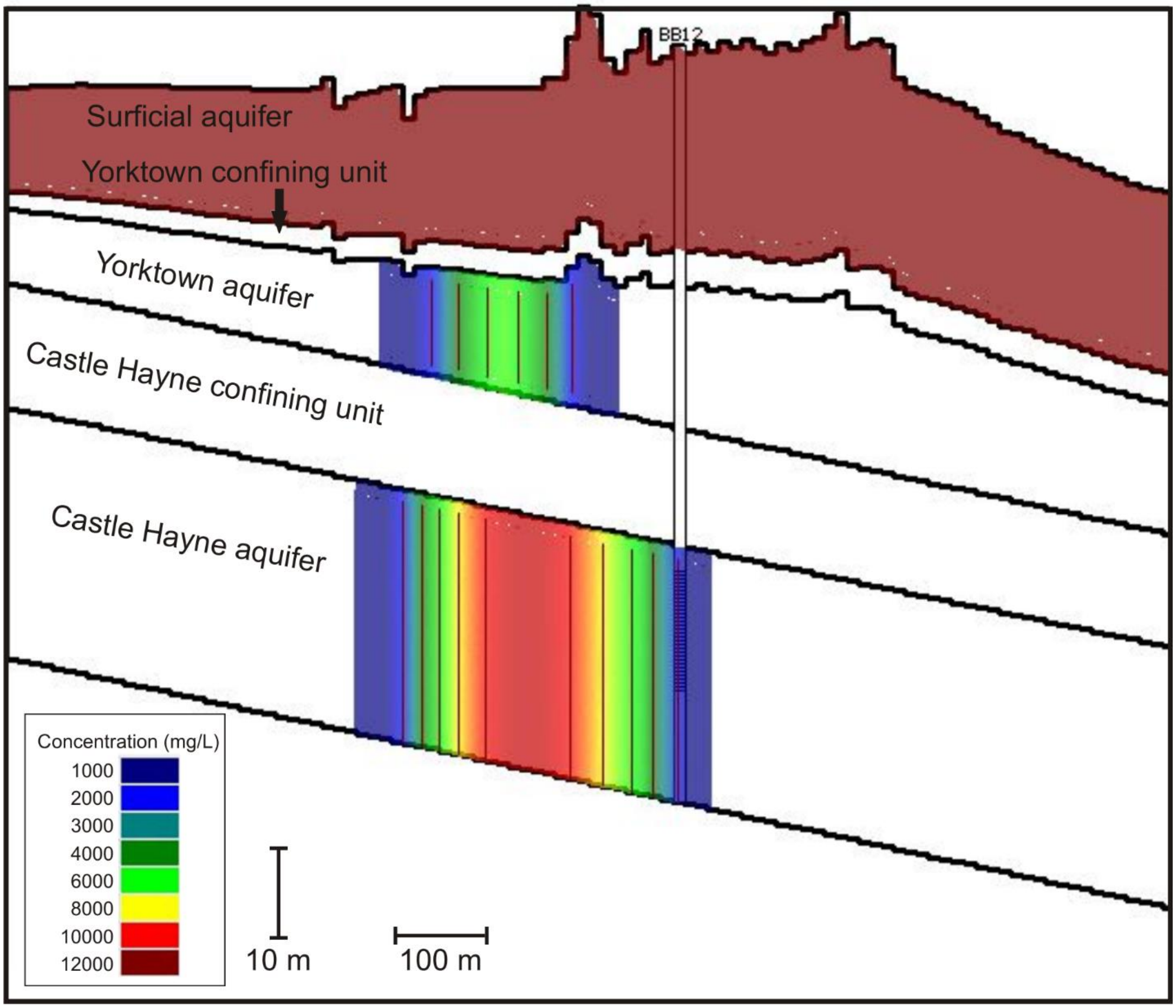
BB5A 2013 row 84



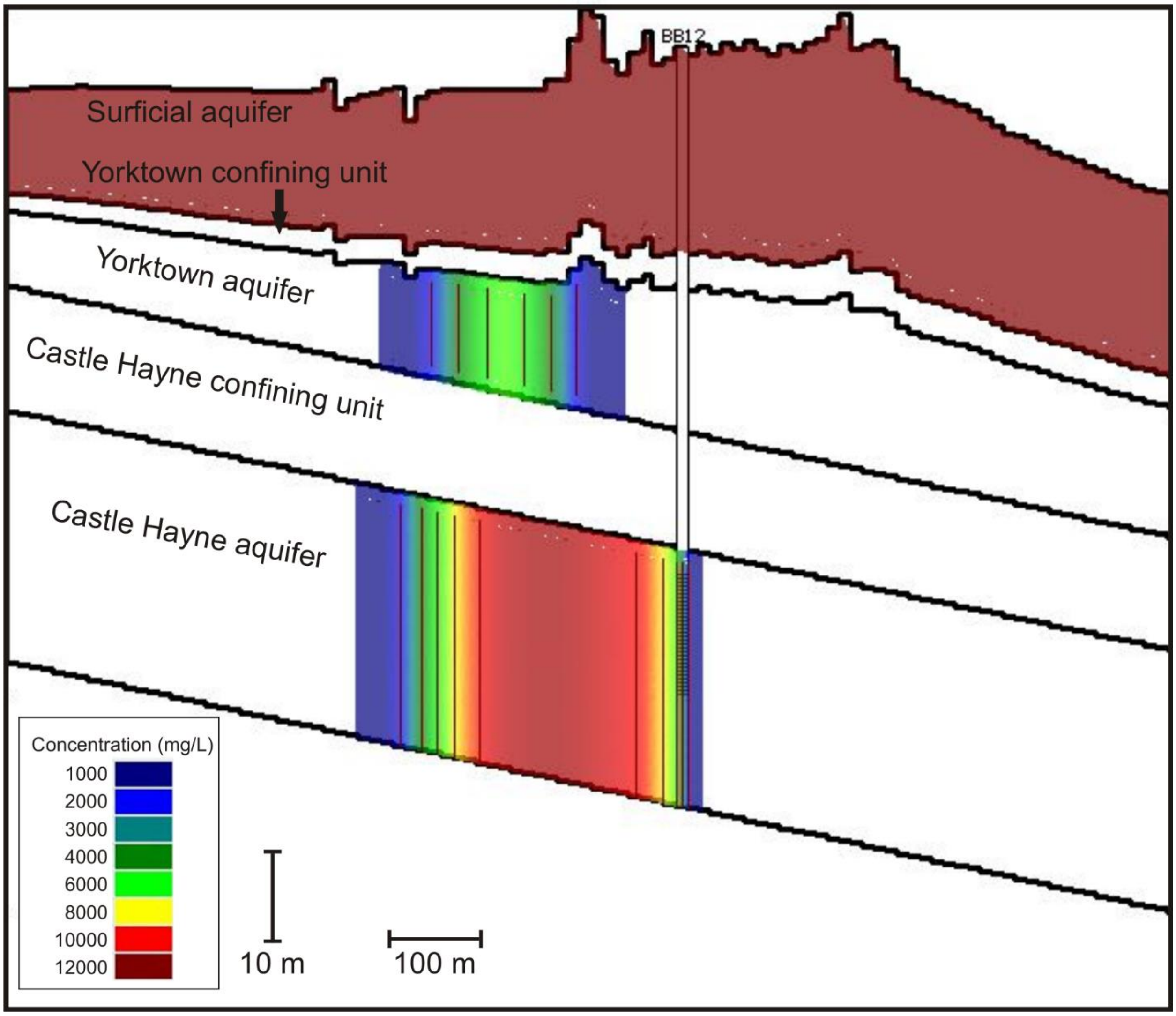
BB5A 2113 row 84



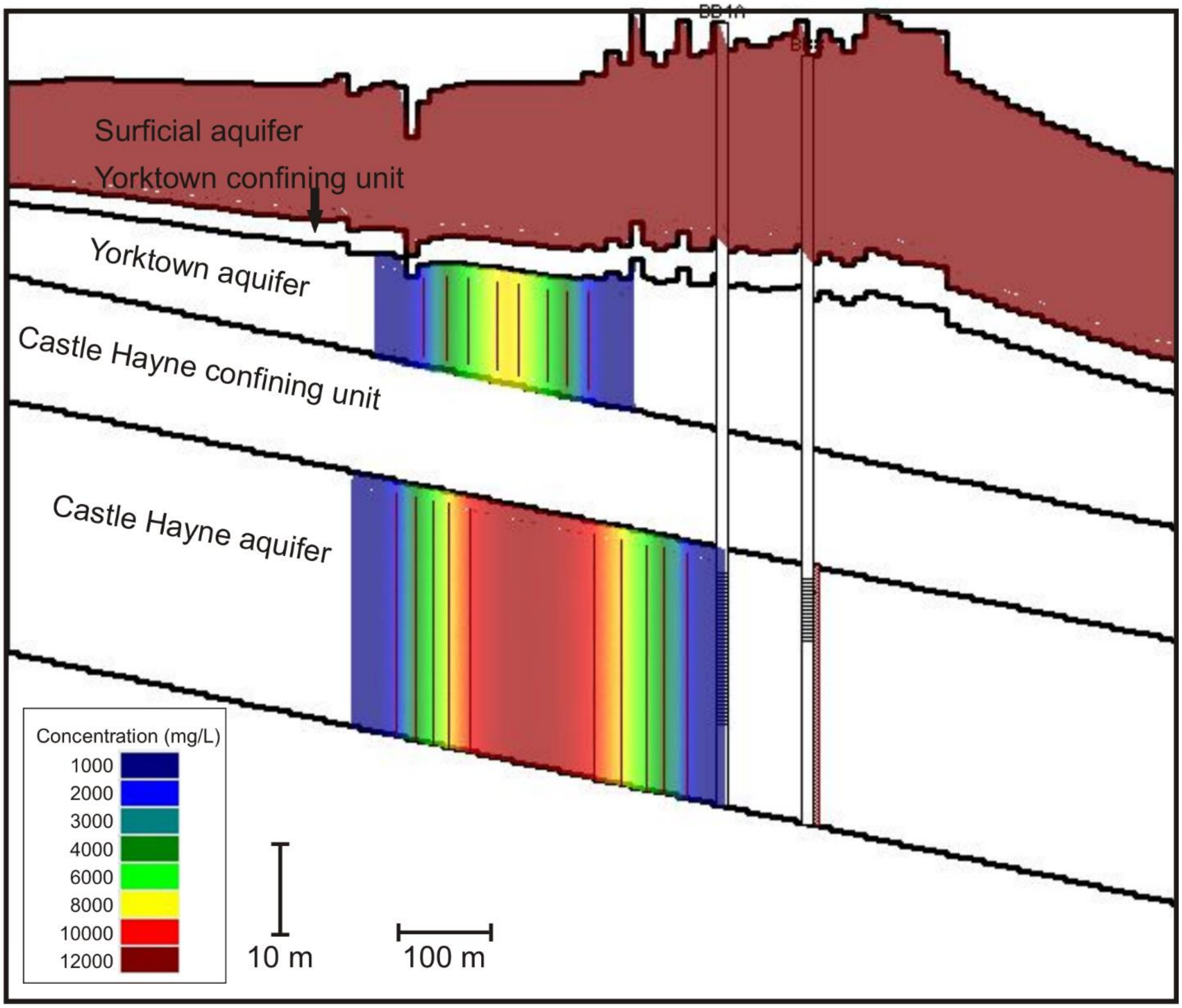
BB12 2013 row 84



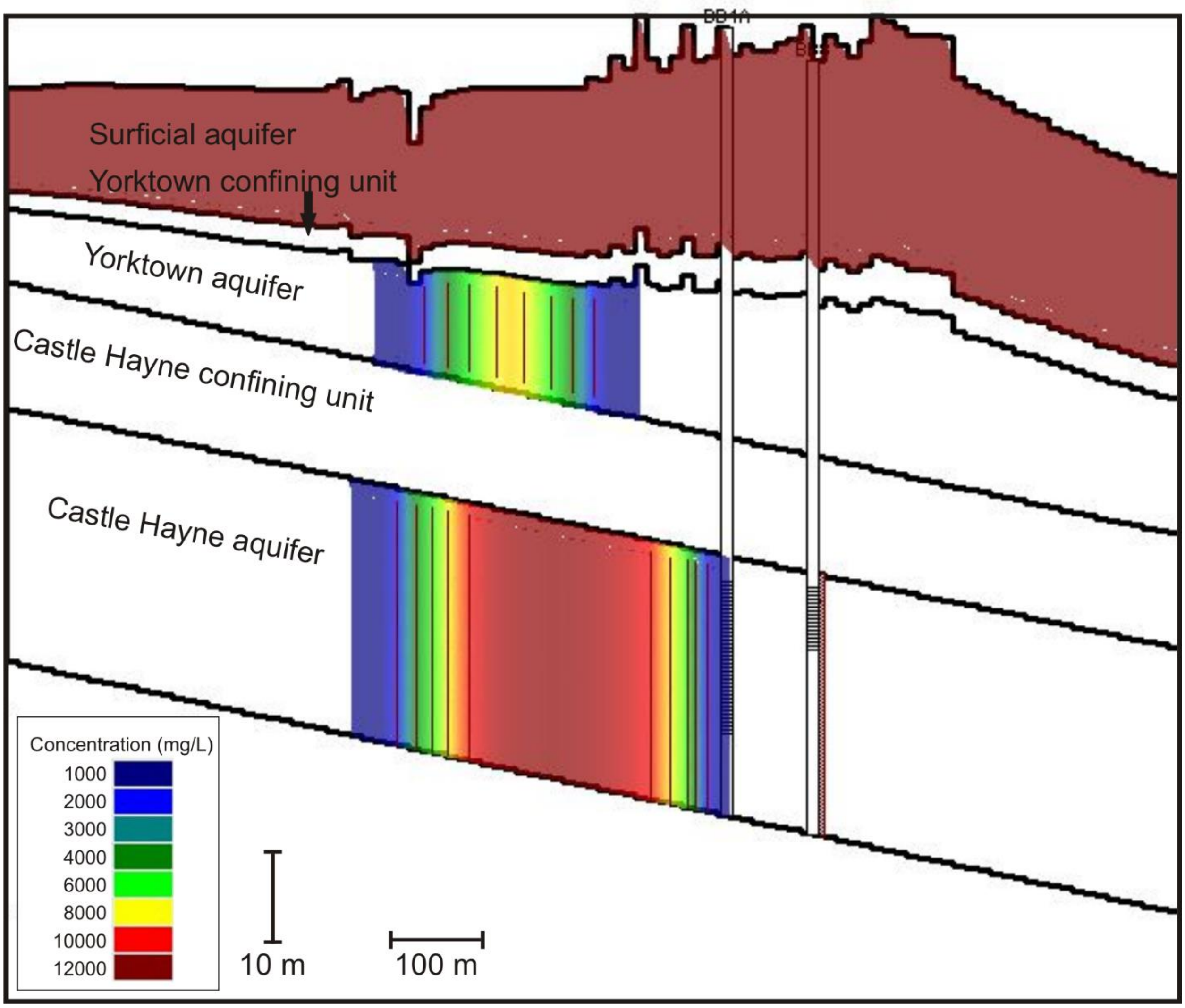
BB12 2113 row 84



BB4A 2013 row 79



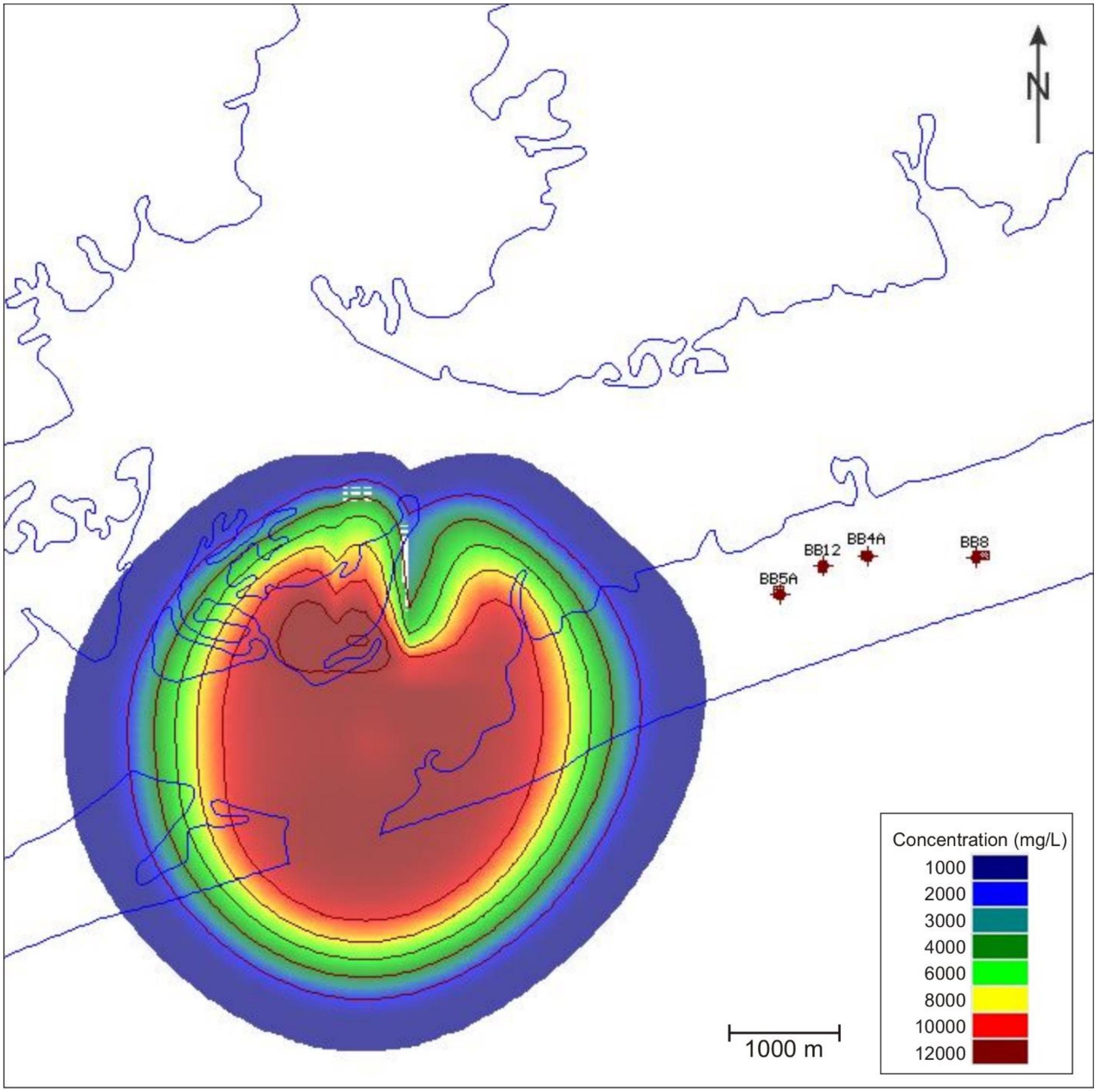
BB4A 2113 row 79



## APPENDIX I: MAP VIEWS FROM PREDICTIVE MODEL

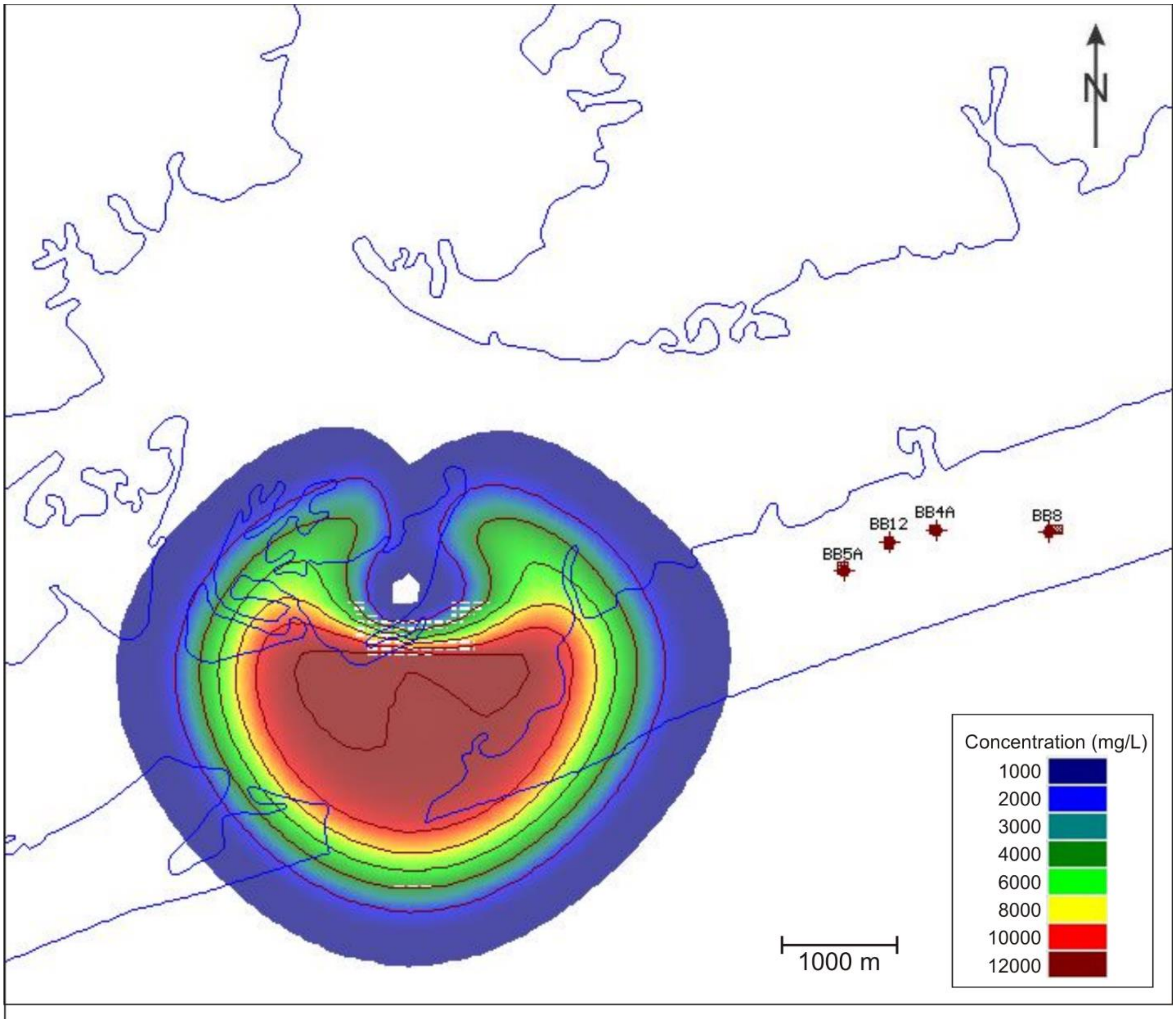
Map view of BB5A, BB12, and BB4A for sub-scenarios:

1a

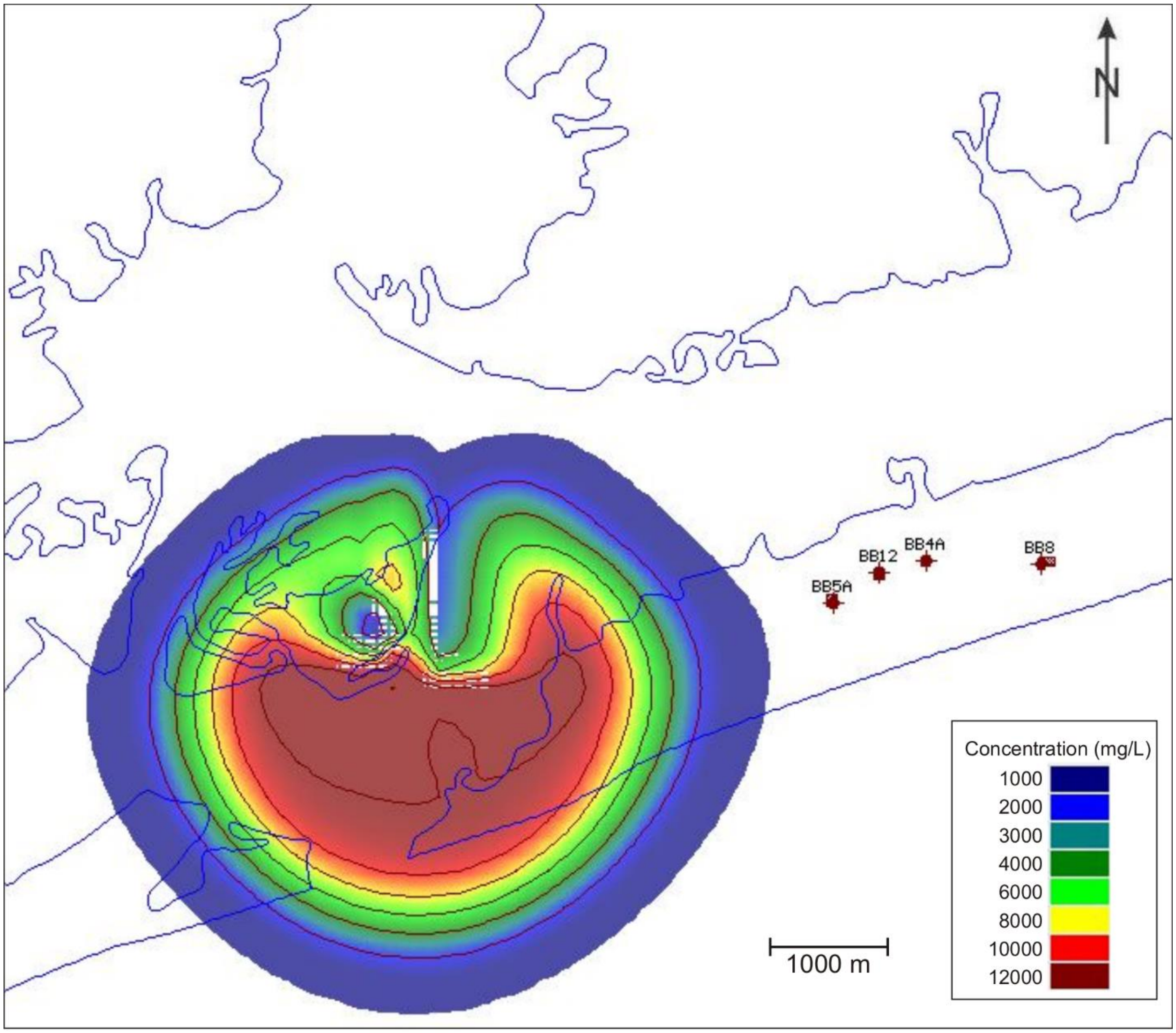


N
BB12
BB4A
BB8
BB5A
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

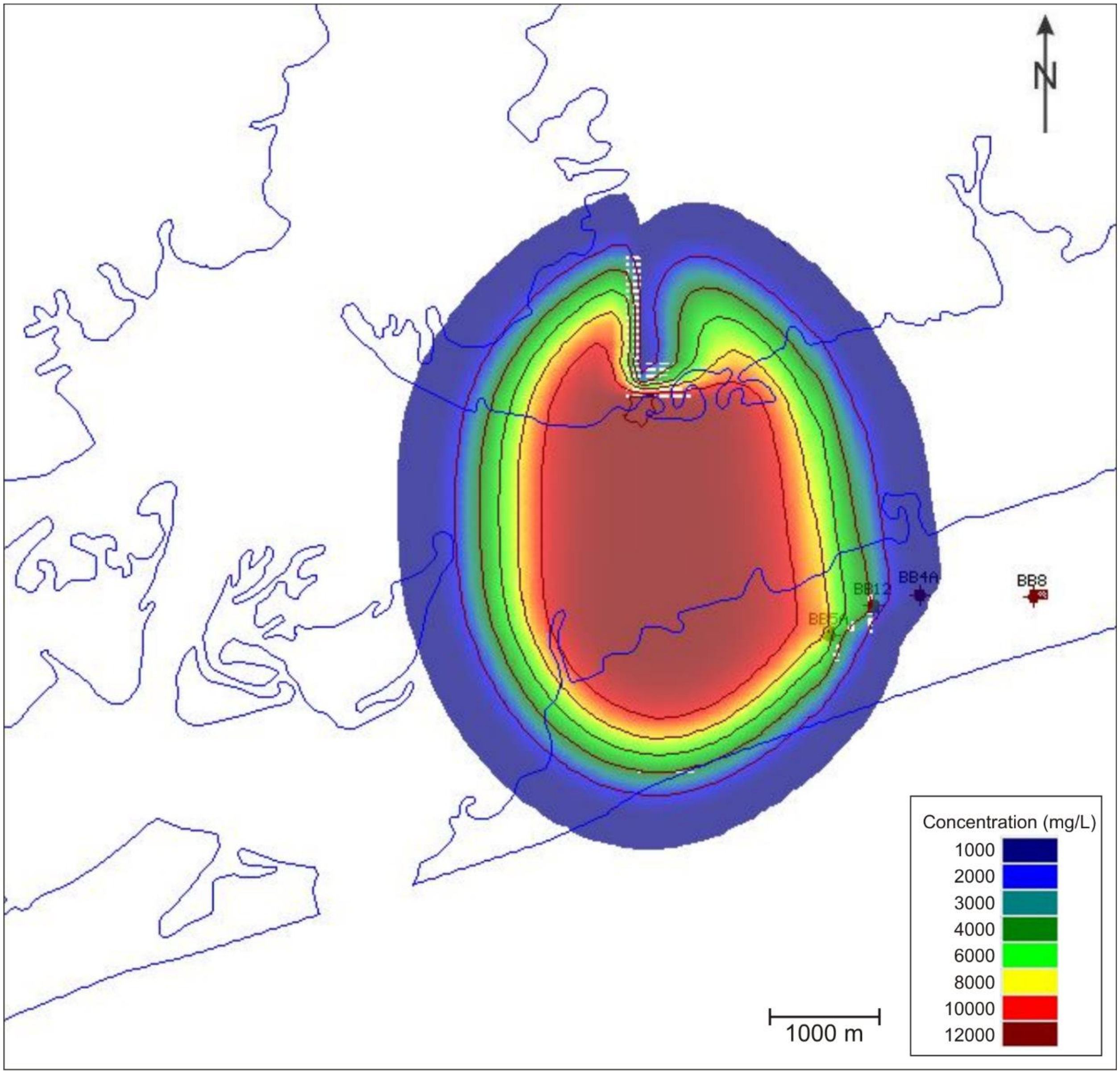
1c


N
BB12
BB4A
BB8
BB5A
1000 m
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000

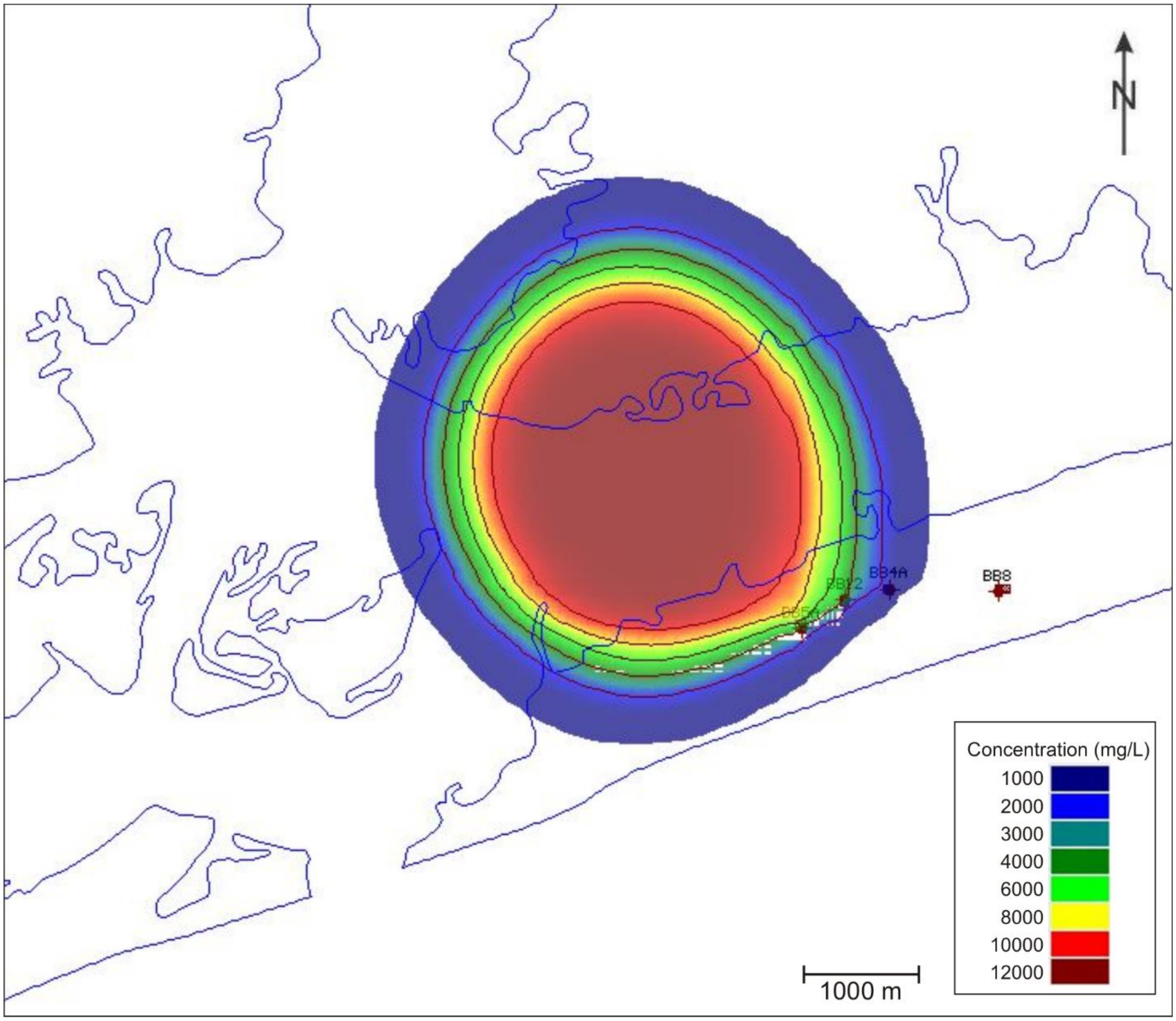
1d


N
BB12
BB4A
BB8
BB5A
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

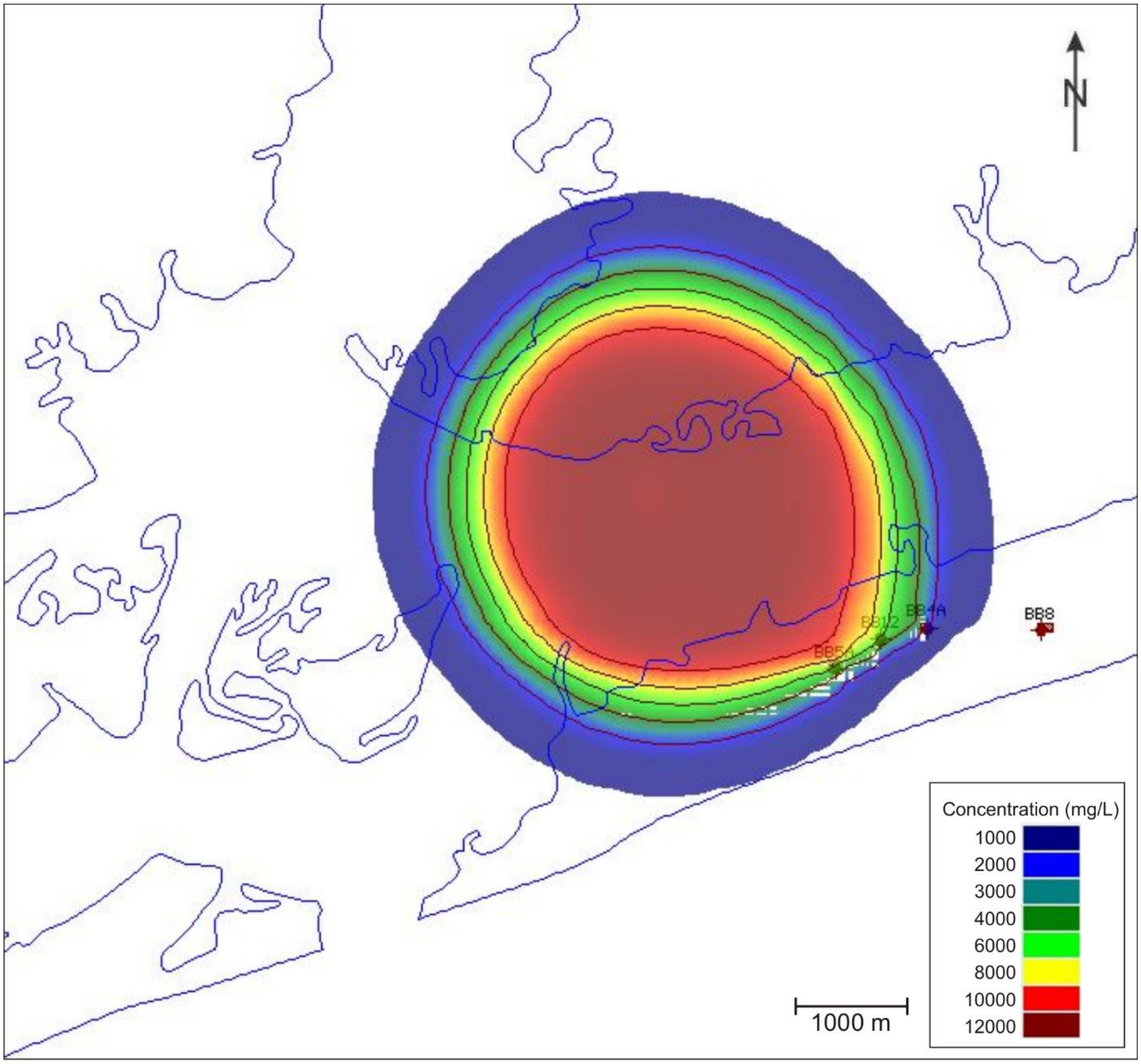
2a


N
BB12
BB4A
BB8
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

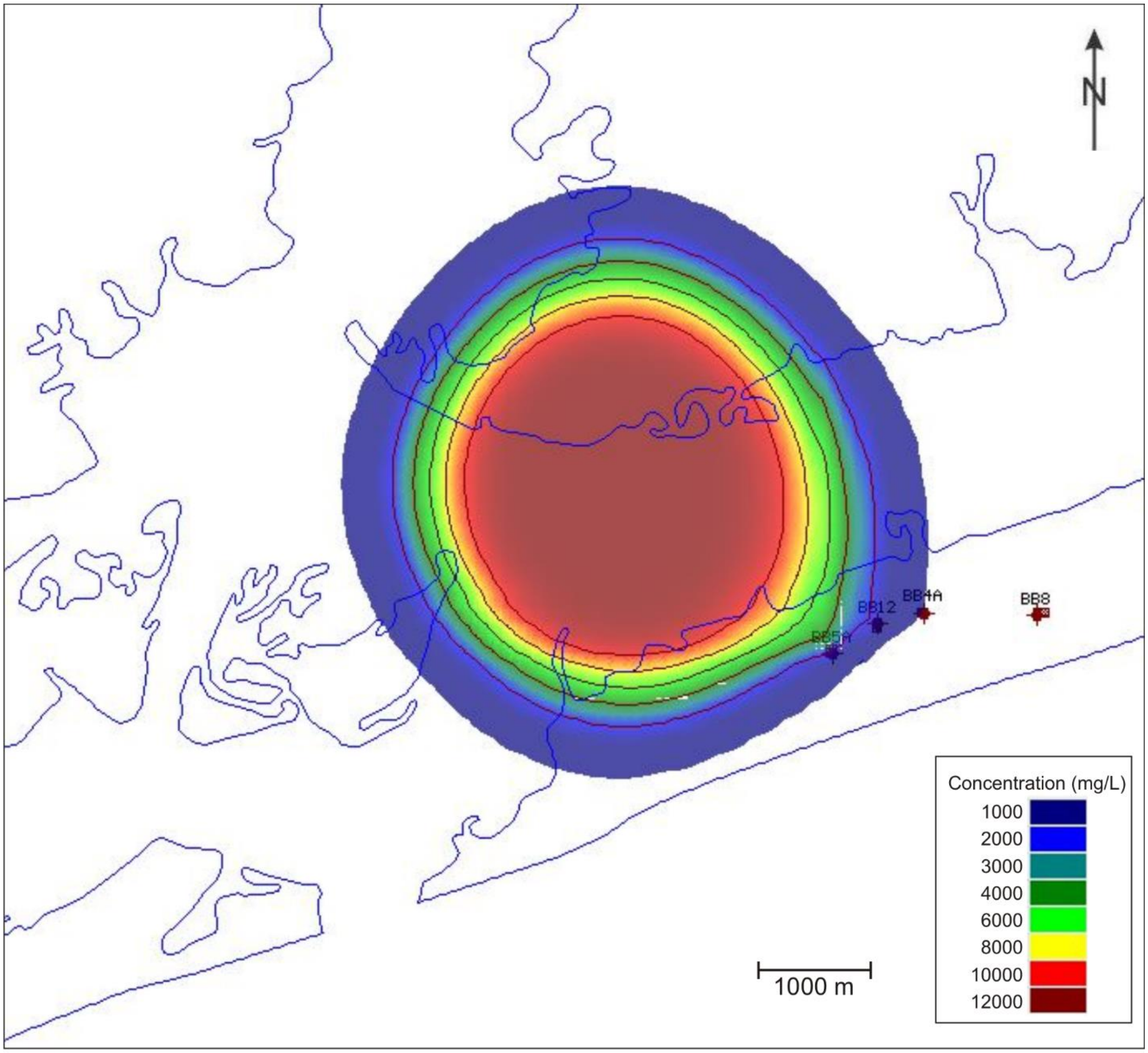
2b


N
BB8
BB4A
BB12
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

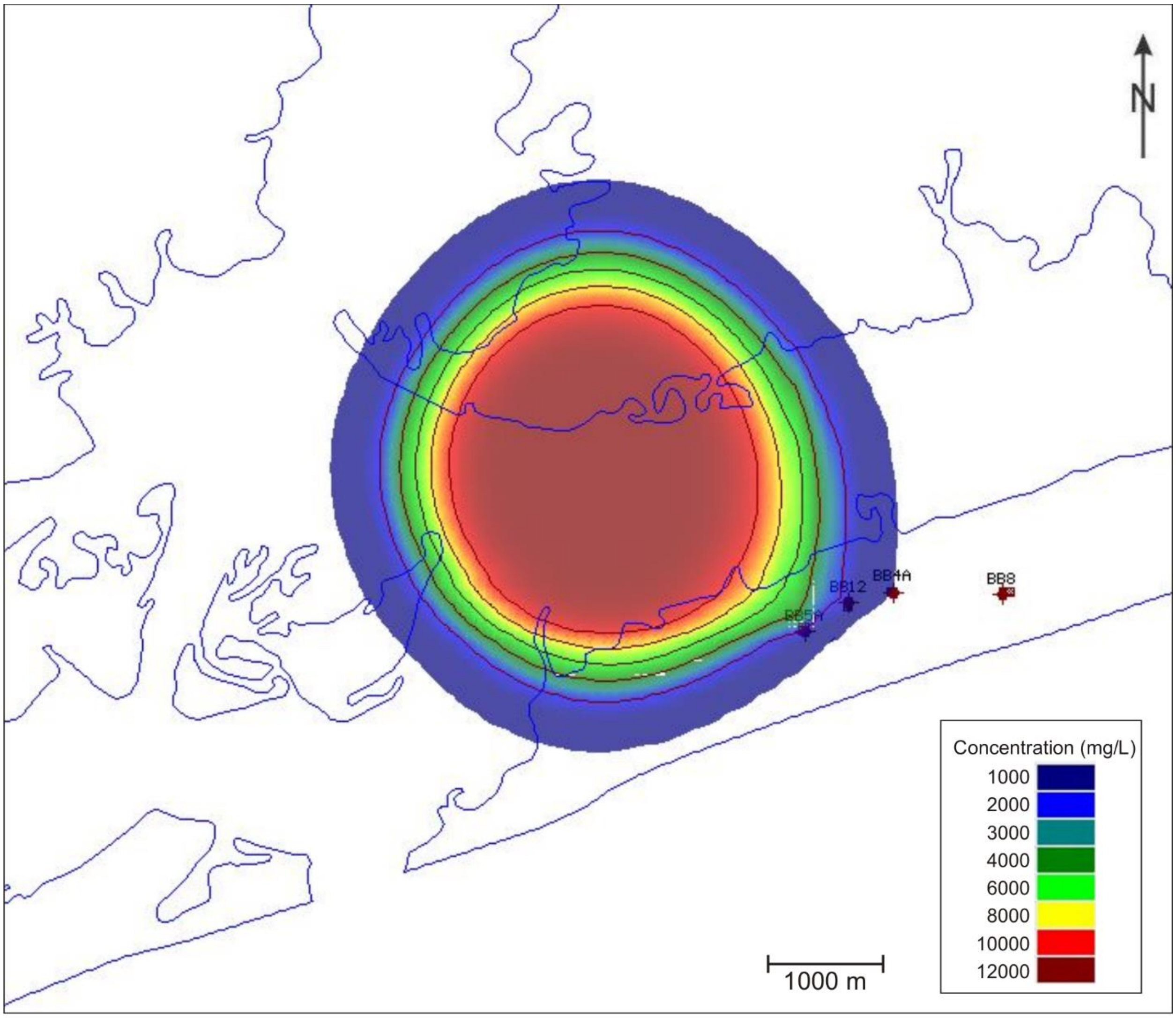
2c


N
BB4A
BB12
BB5A
BB8
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

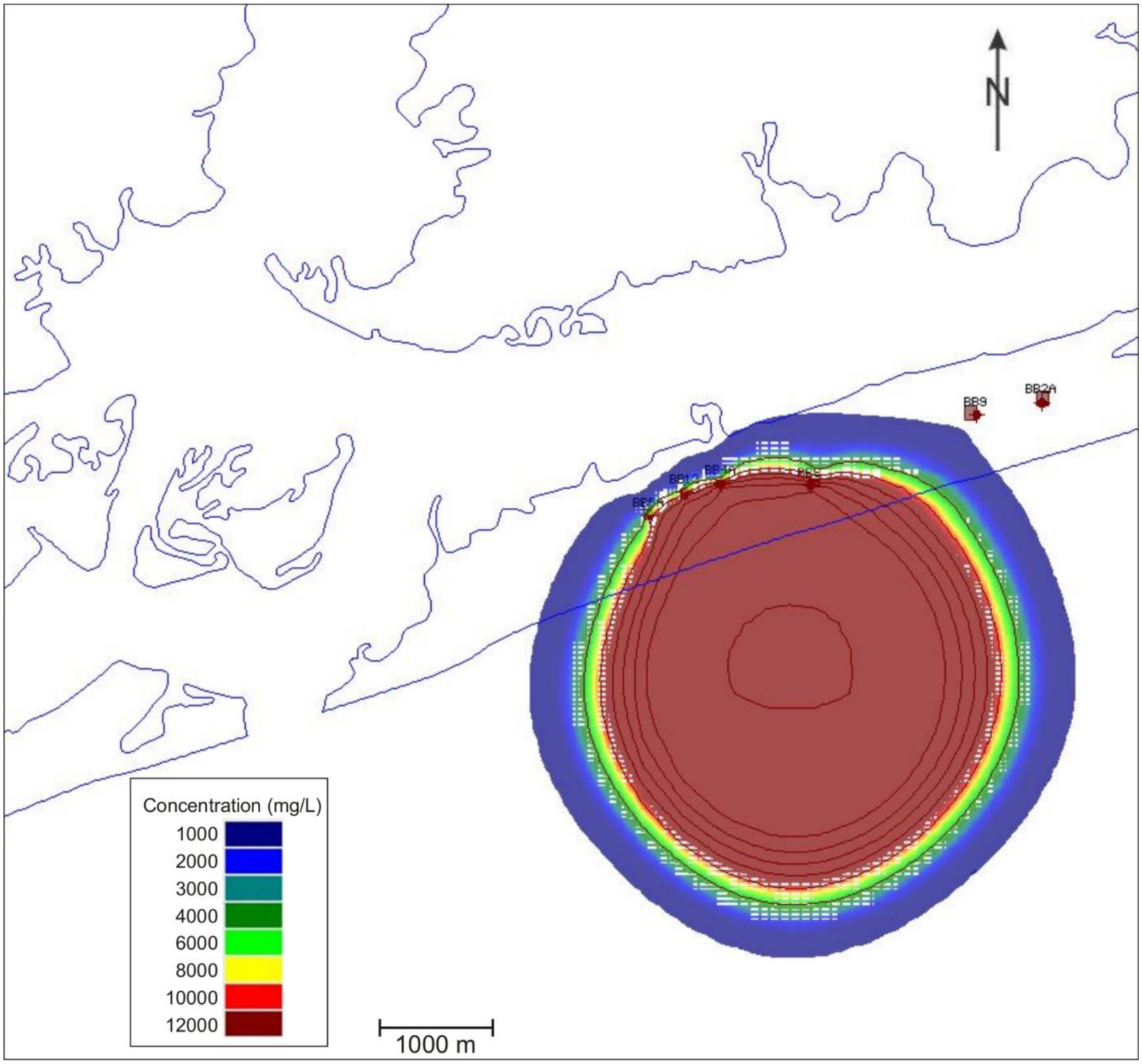
2e


N
BB12
BB4A
BB8
BB5A
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

2f

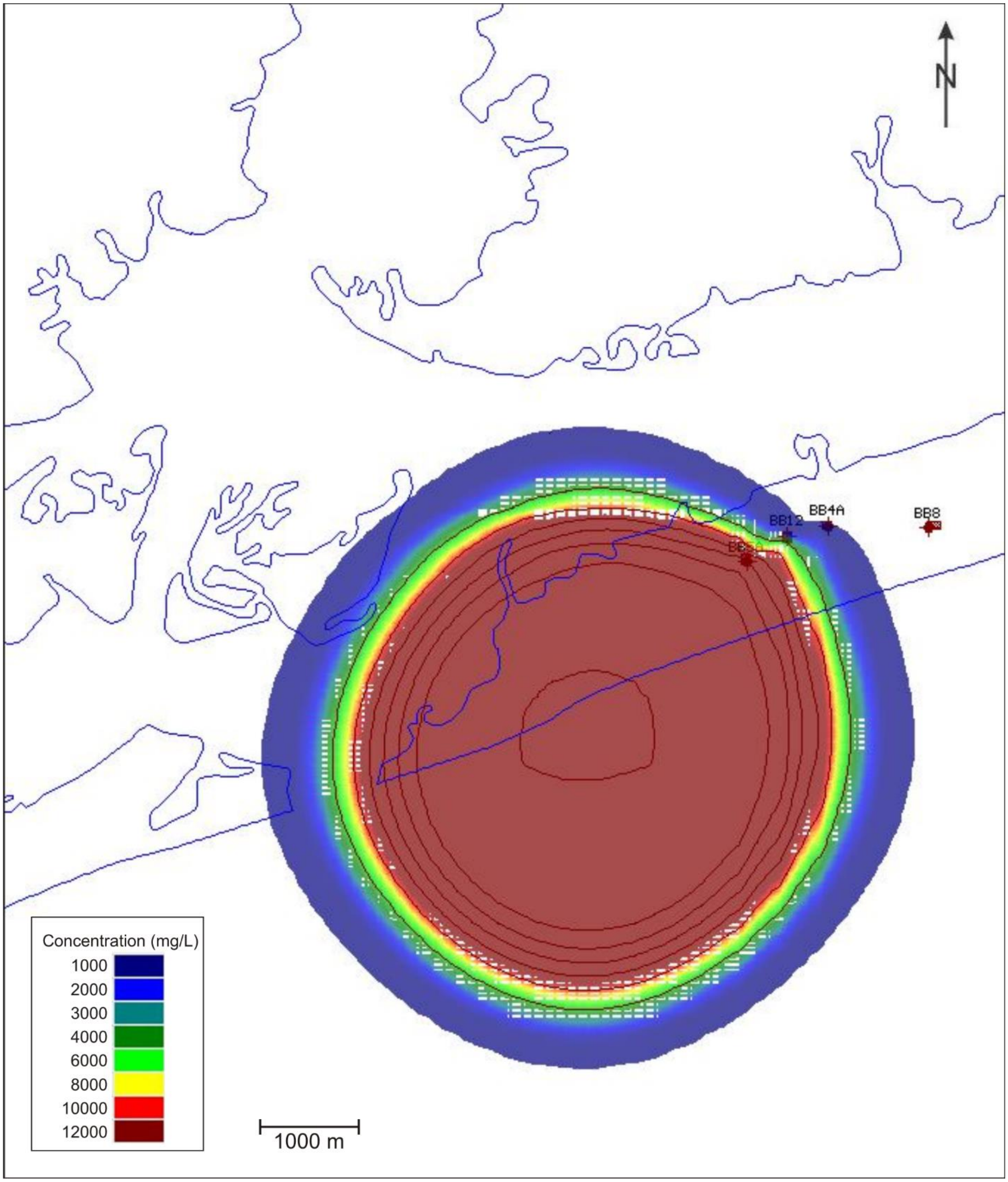

N
BB12
BB4A
BB8
BB5A
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

3b



N
BB9
BB2A
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

3d


N
BB4A
BB12
BB8
Concentration (mg/L)
1000
2000
3000
4000
6000
8000
10000
12000
1000 m

## APPENDIX J: PUMPING SCHEDULES FOR GROUNDWATER WITHDRAWALS FROM BOGUE BANKS WATER CORPORATATION

Bogue Banks Water Corporation Municipal Wells BB1-BB4A

| Well | Time in | Time Out | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day |
|---|---|---|---|---|---|---|---|---|---|
| BB1 | 0 | 140160 | 0 | BB2A | 0 | BB3A | 0 | BB4A | 0 |
| BB1 | 140160 | 144176 | -2408 | BB2A | -2408 | BB3A | -2408 | BB4A | -2408 |
| BB1 | 144176 | 147464 | -18117 | BB2A | -18117 | BB3A | -18117 | BB4A | -18117 |
| BB1 | 147464 | 147495 | -1135989 | BB2A | -25033 | BB3A | -317242 | BB4A | -199284 |
| BB1 | 147495 | 147523 | -1257702 | BB2A | -2839 | BB3A | -410717 | BB4A | -165882 |
| BB1 | 147523 | 147554 | -1562947 | BB2A | -287325 | BB3A | -292576 | BB4A | -337268 |
| BB1 | 147554 | 147584 | -1441421 | BB2A | -190028 | BB3A | -160754 | BB4A | -540809 |
| BB1 | 147584 | 147615 | -1605571 | BB2A | -333849 | BB3A | -697737 | BB4A | -801408 |
| BB1 | 147615 | 147645 | -1136759 | BB2A | -150155 | BB3A | -571345 | BB4A | -1673908 |
| BB1 | 147645 | 147676 | -1266769 | BB2A | -189881 | BB3A | -986771 | BB4A | -1903817 |
| BB1 | 147676 | 147707 | -1489864 | BB2A | -120034 | BB3A | -793959 | BB4A | -1416842 |
| BB1 | 147707 | 147737 | -733360 | BB2A | -103216 | BB3A | -333242 | BB4A | -696642 |
| BB1 | 147737 | 147768 | -653899 | BB2A | -93903 | BB3A | -130536 | BB4A | -1055397 |
| BB1 | 147768 | 147798 | -300498 | BB2A | -87064 | BB3A | -42649 | BB4A | -928056 |
| BB1 | 147798 | 147829 | -211556 | BB2A | -120400 | BB3A | -454616 | BB4A | -919977 |
| BB1 | 147829 | 147860 | -120523 | BB2A | -82058 | BB3A | -65207 | BB4A | -826440 |
| BB1 | 147860 | 147888 | -242739 | BB2A | -83549 | BB3A | -35556 | BB4A | -670694 |
| BB1 | 147888 | 147919 | -969309 | BB2A | -95734 | BB3A | -175838 | BB4A | -598461 |
| BB1 | 147919 | 147949 | -839478 | BB2A | -112427 | BB3A | -710269 | BB4A | -618410 |
| BB1 | 147949 | 147980 | -448754 | BB2A | -124796 | BB3A | -720083 | BB4A | -717274 |
| BB1 | 147980 | 148010 | -1183004 | BB2A | -186242 | BB3A | -1061429 | BB4A | -1671132 |
| BB1 | 148010 | 148041 | -978956 | BB2A | -673437 | BB3A | -894456 | BB4A | -1232212 |
| BB1 | 148041 | 148072 | -5129 | BB2A | -1555559 | BB3A | -217600 | BB4A | -1341012 |
| BB1 | 148072 | 148102 | 0 | BB2A | -1372211 | BB3A | -145612 | BB4A | -1561229 |
| BB1 | 148102 | 148133 | -653899 | BB2A | -93903 | BB3A | -130536 | BB4A | -1055397 |
| BB1 | 148133 | 148163 | -300498 | BB2A | -87064 | BB3A | -42649 | BB4A | -928056 |
| BB1 | 148163 | 148194 | -211495 | BB2A | -120400 | BB3A | -454616 | BB4A | -919977 |
| BB1 | 148194 | 148225 | 0 | BB2A | -70946 | BB3A | 0 | BB4A | -877605 |
| BB1 | 148225 | 148253 | 0 | BB2A | -70300 | BB3A | 0 | BB4A | -538069 |
| BB1 | 148253 | 148284 | 0 | BB2A | -148852 | BB3A | -95612 | BB4A | -934019 |
| BB1 | 148284 | 148314 | 0 | BB2A | -463965 | BB3A | -115203 | BB4A | -397468 |
| BB1 | 148314 | 148345 | 0 | BB2A | -592234 | BB3A | -331162 | BB4A | -1987340 |
| BB1 | 148345 | 148375 | 0 | BB2A | -415007 | BB3A | -1034553 | BB4A | -2127905 |
| BB1 | 148375 | 148406 | -117958 | BB2A | -1006919 | BB3A | -1116696 | BB4A | -1321719 |
| BB1 | 148406 | 148437 | -257408 | BB2A | -1119016 | BB3A | -920221 | BB4A | -8670 |
| BB1 | 148437 | 148467 | -125865 | BB2A | -1230258 | BB3A | -580682 | BB4A | -7192 |
| BB1 | 148467 | 148498 | 0 | BB2A | -677833 | BB3A | -186218 | BB4A | -56781 |
| BB1 | 148498 | 148528 | 0 | BB2A | -150281 | BB3A | -377784 | BB4A | -1512145 |
| BB1 | 148528 | 148559 | 0 | BB2A | -366330 | BB3A | -366330 | BB4A | -366330 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| BB1 | 148559 | 148590 | 0 | BB2A | -244220 | BB3A | 0 | BB4A | -610550 |
| BB1 | 148590 | 148619 | 0 | BB2A | -130531 | BB3A | 0 | BB4A | -652657 |
| BB1 | 148619 | 148650 | 0 | BB2A | -9891 | BB3A | 0 | BB4A | -904469 |
| BB1 | 148650 | 148680 | 0 | BB2A | -538285 | BB3A | -212362 | BB4A | -1265463 |
| BB1 | 148680 | 148711 | -26925 | BB2A | -768682 | BB3A | -199650 | BB4A | -1365922 |
| BB1 | 148711 | 148741 | -558727 | BB2A | -1042628 | BB3A | -505100 | BB4A | -1456626 |
| BB1 | 148741 | 148772 | -1348644 | BB2A | -1679623 | BB3A | -830226 | BB4A | -1224641 |
| BB1 | 148772 | 148803 | -522081 | BB2A | -1370441 | BB3A | -708604 | BB4A | -829005 |
| BB1 | 148803 | 148833 | -394818 | BB2A | -1114677 | BB3A | -487056 | BB4A | -443524 |
| BB1 | 148833 | 148864 | 0 | BB2A | -702010 | BB3A | -48844 | BB4A | -331040 |
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Bogue Banks Water Corporation Municipal Wells BB5A-BB8

| Well | Time in | Time Out | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day |
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| BB5A | 159605 | 159635 | -819667 | BB6 | -179807 | BB7A | -639230 | BB8 | 0 |
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| BB5A | 159758 | 159788 | -2081849 | BB6 | -4669 | BB7A | -650586 | BB8 | -2776 |
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| BB5A | 160123 | 160153 | -2081849 | BB6 | -4669 | BB7A | -650586 | BB8 | -2776 |
| BB5A | 160153 | 160184 | -1324649 | BB6 | -28085 | BB7A | -394293 | BB8 | -2076 |
| BB5A | 160184 | 160214 | -1158966 | BB6 | -3407 | BB7A | -126685 | BB8 | -1767 |
| BB5A | 160214 | 160245 | -1160778 | BB6 | -8181 | BB7A | -92394 | BB8 | 0 |

Bogue Banks Water Corporation Municipal Wells BB9-BB12

| Well | Time in | Time Out | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day |
|---|---|---|---|---|---|---|---|
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| BB9 | 150141 | 150172 | -1045506 | BB10 | 0 | BB12 | 0 |
| BB9 | 150172 | 150202 | -1098526 | BB10 | 0 | BB12 | 0 |
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| BB9 | 150567 | 150598 | -1293023 | BB10 | 0 | BB12 | 0 |
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| BB9 | 151085 | 151116 | -46768 | BB10 | 0 | BB12 | 0 |
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| BB9 | 157294 | 157325 | -50920 | BB10 | -27597 | BB12 | -1091419 |
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| BB9 | 157384 | 157415 | -184142 | BB10 | 0 | BB12 | -682839 |
| BB9 | 157415 | 157445 | -253244 | BB10 | 0 | BB12 | -1042628 |
| BB9 | 157445 | 157476 | 0 | BB10 | -180723 | BB12 | -941224 |
| BB9 | 157476 | 157506 | -347627 | BB10 | -665097 | BB12 | -2433388 |
| BB9 | 157506 | 157537 | -324202 | BB10 | -622395 | BB12 | -2401904 |
| BB9 | 157537 | 157568 | -219187 | BB10 | -622761 | BB12 | -2393478 |
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| BB9 | 157871 | 157902 | -324202 | BB10 | -622395 | BB12 | -2401904 |
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| BB9 | 157963 | 157994 | -382937 | BB10 | -399055 | BB12 | -1355299 |
| BB9 | 157994 | 158024 | -30031 | BB10 | -159997 | BB12 | -1228239 |
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| BB9 | 160214 | 160245 | -50920 | BB10 | -27597 | BB12 | -1091419 |

## APPENDIX K: PUMPING SCHEDULES FOR GROUNDWATER WITHDRAWALS FROM THE TOWN OF ATLANTIC BEACH

Town of Atlantic Beach Municipal Wells AB1-AB3

| Well | Time in | Time Out | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day |
|---|---|---|---|---|---|---|---|
| AB1 | 0 | 151847 | 0 | AB2 | 0 | AB3 | 0 |
| AB1 | 151847 | 151878 | -226758 | AB2 | -236771 | AB3 | -223706 |
| AB1 | 151878 | 151906 | -197247 | AB2 | -200492 | AB3 | -216715 |
| AB1 | 151906 | 151937 | -284638 | AB2 | -284638 | AB3 | -304420 |
| AB1 | 151937 | 151967 | -400623 | AB2 | -452609 | AB3 | -479990 |
| AB1 | 151967 | 151998 | -467437 | AB2 | -557066 | AB3 | -562194 |
| AB1 | 151998 | 152028 | -449581 | AB2 | -583206 | AB3 | -598221 |
| AB1 | 152028 | 152059 | -528126 | AB2 | -716541 | AB3 | -723990 |
| AB1 | 152059 | 152090 | -411999 | AB2 | -561584 | AB3 | -572330 |
| AB1 | 152090 | 152120 | -315451 | AB2 | -438350 | AB3 | -439612 |
| AB1 | 152120 | 152151 | -285615 | AB2 | -381960 | AB3 | -384891 |
| AB1 | 152151 | 152181 | -307501 | AB2 | -378162 | AB3 | -386238 |
| AB1 | 152181 | 152212 | -266078 | AB2 | -221508 | AB3 | -322737 |
| AB1 | 152212 | 152243 | -264368 | AB2 | -187927 | AB3 | -279266 |
| AB1 | 152243 | 152271 | -248215 | AB2 | -301346 | AB3 | -220230 |
| AB1 | 152271 | 152302 | -371703 | AB2 | -467803 | AB3 | -349845 |
| AB1 | 152302 | 152332 | -401380 | AB2 | -543080 | AB3 | -388509 |
| AB1 | 152332 | 152363 | -486242 | AB2 | -660859 | AB3 | -485998 |
| AB1 | 152363 | 152393 | -533238 | AB2 | -861812 | AB3 | -594057 |
| AB1 | 152393 | 152424 | -502727 | AB2 | -540093 | AB3 | -593821 |
| AB1 | 152424 | 152455 | -398445 | AB2 | -122 | AB3 | -496743 |
| AB1 | 152455 | 152485 | -299426 | AB2 | -82143 | AB3 | -340813 |
| AB1 | 152485 | 152516 | -261193 | AB2 | -472321 | AB3 | -248494 |
| AB1 | 152516 | 152546 | -206936 | AB2 | -334504 | AB3 | -193182 |
| AB1 | 152546 | 152577 | -171442 | AB2 | -215890 | AB3 | -167046 |
| AB1 | 152577 | 152608 | -295628 | AB2 | 0 | AB3 | -232986 |
| AB1 | 152608 | 152636 | -205494 | AB2 | 0 | AB3 | -201843 |
| AB1 | 152636 | 152667 | -202825 | AB2 | -160819 | AB3 | -106236 |
| AB1 | 152667 | 152697 | -226998 | AB2 | -381822 | AB3 | -217787 |
| AB1 | 152697 | 152728 | -258629 | AB2 | -435078 | AB3 | -244953 |
| AB1 | 152728 | 152758 | -356712 | AB2 | -605413 | AB3 | -330845 |
| AB1 | 152758 | 152789 | -401131 | AB2 | -751953 | AB3 | -370726 |
| AB1 | 152789 | 152820 | 0 | AB2 | 0 | AB3 | 0 |
| AB1 | 152820 | 152850 | -241257 | AB2 | -378920 | AB3 | -247061 |
| AB1 | 152850 | 152881 | -259972 | AB2 | 0 | AB3 | -277922 |
| AB1 | 152881 | 152911 | -283275 | AB2 | 0 | AB3 | -311035 |
| AB1 | 152911 | 152942 | -209419 | AB2 | 0 | AB3 | -216379 |
| AB1 | 152942 | 152973 | -198673 | AB2 | 0 | AB3 | -207587 |
| AB1 | 152973 | 153002 | -169038 | AB2 | 0 | AB3 | -176478 |
| AB1 | 153002 | 153033 | -202214 | AB2 | 0 | AB3 | -202947 |
| AB1 | 153033 | 153063 | -226494 | AB2 | -303716 | AB3 | -198355 |

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| AB1 | 153063 | 153094 | -299658 | AB2 | -545465 | AB3 | -261438 |
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| AB1 | 153124 | 153155 | -396491 | AB2 | -923762 | AB3 | -372436 |
| AB1 | 153155 | 153186 | -293064 | AB2 | -628989 | AB3 | -280120 |
| AB1 | 153186 | 153216 | -224475 | AB2 | -461568 | AB3 | -212740 |
| AB1 | 153216 | 153247 | -235672 | AB2 | -447533 | AB3 | -227857 |
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| AB1 | 153308 | 153339 | -179135 | AB2 | -310282 | AB3 | -168756 |
| AB1 | 153339 | 153367 | -170343 | AB2 | -276741 | AB3 | -152363 |
| AB1 | 153367 | 153398 | -175472 | AB2 | -323469 | AB3 | -162528 |
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| AB1 | 153428 | 153459 | -250570 | AB2 | -459134 | AB3 | -232497 |
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| AB1 | 153520 | 153551 | -316875 | AB2 | -708971 | AB3 | -339832 |
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| AB1 | 154097 | 154128 | -160453 | AB2 | -286714 | AB3 | -164116 |
| AB1 | 154128 | 154158 | -328321 | AB2 | -469517 | AB3 | -234695 |
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| AB1 | 154555 | 154585 | -217409 | AB2 | -744338 | AB3 | -249080 |

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| AB1 | 156261 | 156289 | -83414 | AB2 | -250648 | AB3 | -80170 |
| AB1 | 156289 | 156320 | -113196 | AB2 | -292453 | AB3 | -127117 |
| AB1 | 156320 | 156350 | -132616 | AB2 | -279363 | AB3 | -135139 |
| AB1 | 156350 | 156381 | -193544 | AB2 | -447533 | AB3 | -188660 |
| AB1 | 156381 | 156411 | -229774 | AB2 | -737650 | AB3 | -219049 |
| AB1 | 156411 | 156442 | -306618 | AB2 | -988236 | AB3 | -331651 |
| AB1 | 156442 | 156473 | -280853 | AB2 | -864905 | AB3 | -350578 |
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| AB1 | 156503 | 156534 | -205023 | AB2 | -604078 | AB3 | -250203 |
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| AB1 | 159209 | 159240 | -113196 | AB2 | -292453 | AB3 | -127117 |
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| AB1 | 159301 | 159331 | -229774 | AB2 | -737650 | AB3 | -219049 |
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| AB1 | 159423 | 159454 | -205023 | AB2 | -604078 | AB3 | -250203 |
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Town of Atlantic Beach Municipal Wells AB4-AB6

| Well | Time in | Time Out | Liters Per Day | Well | Liters Per Day | Well | Liters Per Day |
|---|---|---|---|---|---|---|---|
| AB4 | 0 | 151847 | 0 | AB5 | 0 | AB6 | 0 |
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| AB4 | 151878 | 151906 | -289449 | AB5 | -256191 | AB6 | -339335 |
| AB4 | 151906 | 151937 | -434712 | AB5 | -70702 | AB6 | -472321 |
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| AB4 | 151967 | 151998 | -769904 | AB5 | -226880 | AB6 | -885908 |
| AB4 | 151998 | 152028 | -776009 | AB5 | -796450 | AB6 | -908625 |
| AB4 | 152028 | 152059 | -935240 | AB5 | -982131 | AB6 | -1124999 |
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| AB4 | 152090 | 152120 | -575004 | AB5 | -615508 | AB6 | -678219 |
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| AB4 | 152151 | 152181 | -510399 | AB5 | -118231 | AB6 | -579672 |
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| AB4 | 152212 | 152243 | -334704 | AB5 | 0 | AB6 | -489417 |
| AB4 | 152243 | 152271 | -337713 | AB5 | -52996 | AB6 | -443163 |
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