SALINITY DISTRIBUTION IN A CHANNELIZED WETLAND AT EMILY AND RICHARDSON PREYER BUCKRIDGE COASTAL RESERVE, TYRRELL COUNTY, NORTH CAROLINA

By

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The Emily and Richardson Preyer Buckridge Coastal Reserve is a low-lying, peatland-dominated freshwater wetland located in the southern Albemarle Estuarine System. The construction of an extensive canal network that facilitated timber harvest and draining of adjacent agricultural lands has altered the water quality and quantity in the Reserve. Brackish conditions observed in the canal network and groundwater system of the Reserve were linked to saltwater intrusion emanating from the Alligator River. Water level, temperature, and specific conductivity data (used as a proxy for salinity) were collected to assess the quantity and quality of the groundwater and surface water system in the Reserve. The driving mechanisms responsible for spatial and temporal variations of salinity in the groundwater and surface water systems were investigated. Seasonal patterns of thermal stratification were observed in the groundwater and surface water systems. Water levels in the Reserve were affected by precipitation events and wind tide events. Specific conductivity levels in the Alligator River and canals were observed to be elevated by wind tides, which are mostly driven by strong southerly winds. The groundwater data reveal that specific conductivity levels

are higher in the south of the Reserve than in the north. These observations suggest that the saltwater present in the groundwater and surface water system is emanating from south of the Reserve. The effects of a tropical storm on storm surge and saltwater intrusion in the Reserve were observed to be minimal in this study. Saltwater intrusion is a concern because it may impact the health of vegetation in the Reserve. To prevent further degradation of the environment, restoration and management efforts should focus on the use of water control structures to retard saltwater intrusion during storms and wind tides, and also account for future effects of sea level rise.

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Angela Simone Giuliano

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CHAPTER 1: INTRODUCTION

Coastal ecosystems, such as estuaries, are complex environments providing habitats for plants and an array of aquatic and terrestrial animals and other organisms. The plants and animals in an estuary are important because they filter pollutants out of the water. Particles in the water are either removed by chemical processes, such as aerobic respiration, sulfate reduction, and/ or methanogenesis; or may be ingested by estuarine animals and bacteria. In addition to important chemical and physical processes, the estuaries serve as a form of protection by shielding uplands from erosion and reducing floods from major storms (Kennish, 2001). During flood events and storms, these estuaries are under the threat of degradation from saltwater intrusion.

Saltwater intrusion is the introduction of saline waters into freshwater bodies or wetlands. Strong wind events or even prevailing winds and storm surges can push saltwater into freshwater systems through both surface and groundwater. Hurricanes can transport saltwater into freshwater systems and salinities can remain elevated for over a year (Michener et al., 1997; Anderson, 2002). The frequency, intensity, and distribution of hurricanes and tropical storms therefore has an impact on freshwater biota and nutrient cycling in coastal wetlands. Freshwater biotas, such as Atlantic white cedar (*Chamaecyparisthyoides* (L.)) (AWC), are intolerant to saltwater intrusion and thus may suffer from poor health as a consequence of elevated salt levels in water bodies. (http://www.USDA.gov).

Freshwater marshes exposed to saltwater intrusion exhibit higher rates of wetland loss (Sasser et al., 1986) than those that are not exposed to saltwater. For example, the deltaic marshes of the Mississippi River and the Nile River are experiencing rapid submergence that increase flooding events (DeLaune et. al, 1994). The recovery of freshwater marsh vegetation after a saltwater intrusion event is strongly influenced by post intrusion salinity, vegetation type, seed bank, and freshwater input into the system (Flynn et. al, 1995). In addition to increased frequency of storms and hurricanes, sea level rise poses a greater threat to coastal water resources and impedes wetland recovery in coastal environments.

In addition to natural changes, anthropogenic alterations in coastal wetlands can cause a shift in the natural system to produce associated responses in water quality, hydrologic processes and ecology (Kennish, 2001). Alterations such as building of canals and ditches in freshwater wetlands can drain both surface and subsurface water, and increase outflow rates, especially during precipitation events. Such artificial channels provide an opportunity for the transportation of saline water into freshwater regions during wind tide and storm events. Threatened by the possibility of saltwater intrusion, the viability of rare and important natural coastal communities are at risk, such as the AWC forests in the Emily and Richardson Preyer Buckridge Coastal Reserve in North Carolina (hereafter Buckridge Reserve or the Reserve).

Objectives and Hypotheses

The goal of this study is to assess the water quality and quantity of the groundwater and surface water systems in the Reserve. Water level, electrical conductivity, and temperature data from a monitoring network of groundwater wells and stilling wells collected from October 1, 2010 to October 31, 2011 were analyzed. The spatial and temporal variations of specific conductivity were compared to weather data to determine the mechanism for distribution.

There are four primary objectives of this study:

1. To assess the spatial and temporal distributions of salinity in the surface and groundwater systems.
2. To determine the origin, distribution and mechanism responsible for variations in salinity.
3. To assess the influence of tropical storm activity on saltwater intrusion and storm surge in the Reserve.
4. To provide restoration and management recommendations that account for the mechanism of saltwater intrusion and projected sea-level rise.

Specific hypotheses that are tested are as follows:

1. Saltwater intrusion occurs mostly in response to wind tides driven by southerly winds.
2. Salinity levels in the groundwater system are lower in the south than the northern boundary of the Reserve.
3. Tropical storms increase saltwater concentrations in surface water and groundwater systems in the Reserve.

CHAPTER 2: TEMPORAL AND SPATIAL VARIATIONS OF SALINITY IN THE SOUTHERN ALBEMARLE ESTUARINE SYSTEM, NORTH CAROLINA, USA

Abstract

The Emily and Richardson Preyer Buckridge Coastal Reserve is a low-lying, peatland-dominated freshwater wetland located in the southern Albemarle Estuarine System. The water quality and quantity of the Reserve has been altered by the construction of a canal network that facilitated timber harvest and draining of adjacent agricultural lands. Brackish conditions observed in the canal network and groundwater system of the Reserve are linked to saltwater intrusion emanating from the Alligator River. Water level, temperature, and specific conductivity data (used as a proxy for salinity) were collected to assess the hydrologic processes in the Reserve. The driving mechanism responsible for spatial and temporal variations of salinity in the groundwater and surface water systems were investigated. Seasonal patterns of thermal stratification are observed in the groundwater and surface water systems. Water levels in the Reserve are affected by precipitation events and are seasonally variable. Salinity levels in the Alligator River and canals are observed to be elevated under the influence of wind tides, driven by strong southerly winds. The groundwater data reveal that specific conductivity levels are higher in the south of the Reserve than in the north. The effects of a tropical storm on saltwater intrusion in the Reserve were observed to be minimal. Saltwater intrusion may impact the health of vegetation in the Reserve. Restoration and management efforts in the Reserve should focus on the use of tide gates to prevent further degradation of the environment.

Keywords: saltwater, freshwater, groundwater, wind tides, Southern Albemarle Estuarine System, tropical storm

Introduction and Site Description

The Emily and Richardson Preyer Buckridge Coastal Reserve is located on the Albemarle-Pamlico peninsula in the southern Albemarle Estuarine System, about 24 km south-southeast of Columbia, Tyrrell County, in eastern North Carolina (Fig. 2-1). The Reserve is bordered to the north by the Frying Pan embayment, the agricultural community of Gum Neck to the west and the Alligator River to the east and south. The Reserve is situated within a large depressional and riverine wetland complex in the Coastal Plain of North Carolina (Fig. 2-2). The Coastal Plain of North Carolina is a flat, dissected alluvial plain formed by deposition of continental sediments onto the shallow continental shelf seafloor later exposed during the Pleistocene (Tant et al., 1998; Fuss, 2001). The wetland comprises late Pleistocene marine and marginal marine deposits overlain by thick peat soils with isolated mineral soils (Tant et al., 1998). The mineral soils consist of sand, silt, clay, and minor amounts of organic matter and are present in minor quantities along the Alligator River.

The predominant soil types at the Reserve are organic-rich soils (Fig. 2-3), the Pungo, Dorovan, and Belhaven mucks (Tant et al., 1998; Fuss, 2001). These mucks are present in a 1-4 meter thick, 16-24 km wide band along the Alligator River (Tant et al., 1998; Fuss, 2001). The Pungo muck boarders the Alligator River and makes up about 34 percent of Tyrrell County (Tant et al., 1998). This poorly drained, black to red-brown mucky loam covers 75 percent of Buckridge Reserve. The Alligator River rarely floods areas characterized by the Pungo muck (Tant et al., 1988; Fuss, 2001). Pungo muck ranges from 1.5 meters to over 3 meters thick and is highly decomposed organic material that hinders agricultural production (Tant et al., 1988). The Dorovan and

Belhaven mucks are commonly associated with the Pungo muck. The water table at Buckridge tends to be at or near the land surface most of the year, suggesting that the peat soils are poorly drained (Fuss, 2001), increasing storm water runoff and groundwater discharge in the channelized wetlands (Daniel, 1981). Evapotranspiration is the main control of groundwater levels in the peat soils (Daniel, 1981).

The Reserve is a groundwater recharge and discharge system (Fuss, 2001). The generalized movement of surface to subsurface water is sheet flow from the mineral soil in the west toward the peat soils in the east. Discharge and recharge occurs along the Alligator River and Frying Pan embayment and canals. The Alligator River is not influenced by lunar tides, but by wind tides. Wind-driven movements and freshwater discharge, and salinity-induced currents often dominate the non-tidal motion of estuaries (Pritchard & Vieira, 1984; van de Kreeke & Robaczewska, 1989, Weisberg and Pietrafesa, 1983).

Covering an area of 108 km^2, the vegetation in the Reserve consists of black gum, Bald cypress, pond pine, red maple, and Atlantic White cedar (AWC). The Coastal Plain Flatwoods Region of North Carolina contains the largest contiguous regenerating community of AWC. Timber harvesting, hydrologic modifications of riverine wetlands and saltwater intrusion have caused a significant decline in these communities (Fuss, 2001). During the more than 100 years of extensive logging practices in the Reserve, 50 km (31 mi) of roads and 64 km (40 mi) of ditches have been constructed to lower the water table (Fuss, 2001). The roads are constructed of the material (peat, clay and sand) dug out to build the adjacent canals and ditches, which range from 3-10 meters wide (average 7.5 meters), 1-3 meters deep (average about 2.5 meters), and have

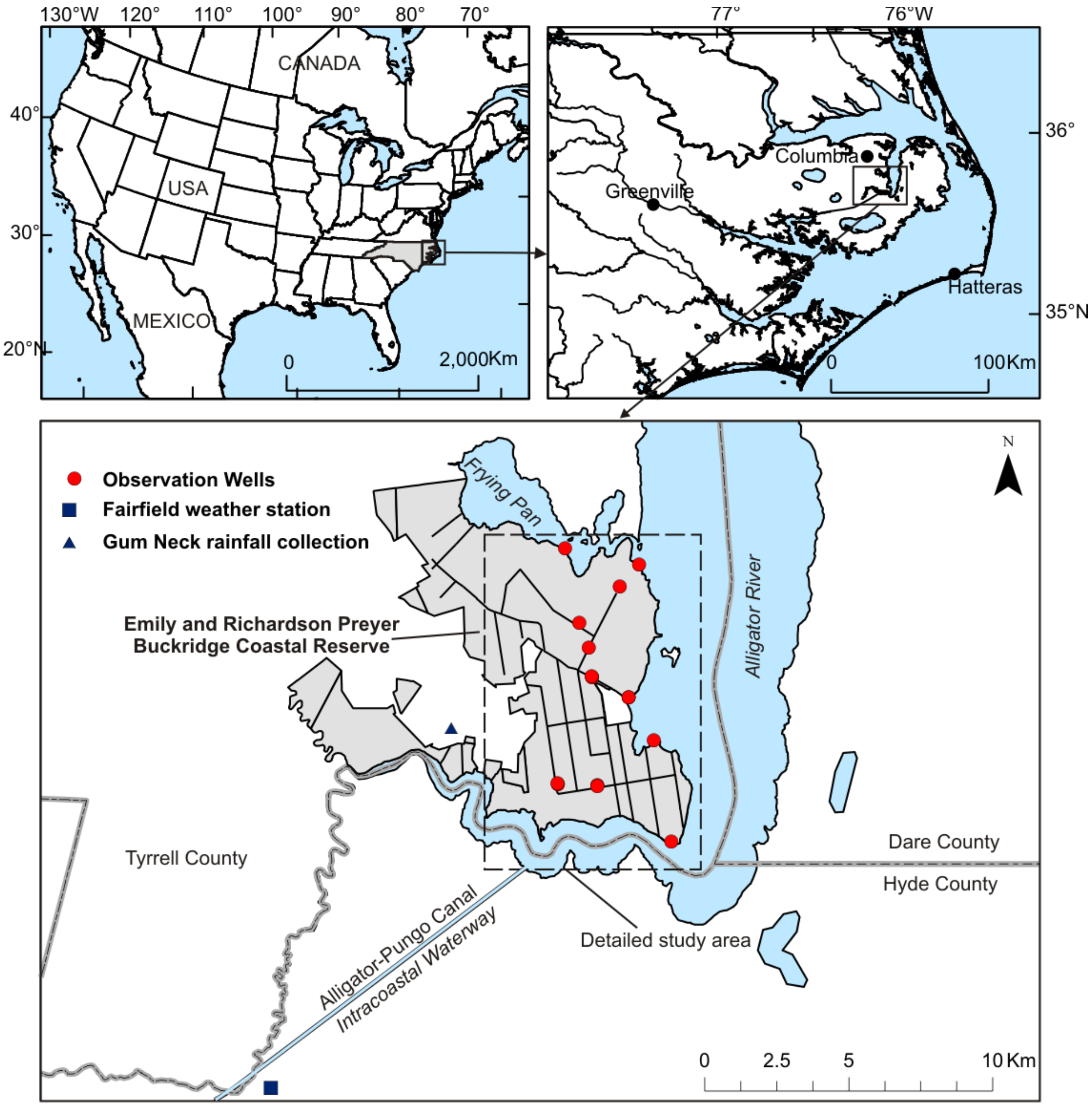

Figure 2-1: Location of the Emily and Richardson Preyer Buckridge Coastal Reserve in Tyrrell County, eastern North Carolina, USA. *Inset* shows the study area with the approximate location of the Fairfield weather station, Gum Neck rainfall collection station, and observation wells

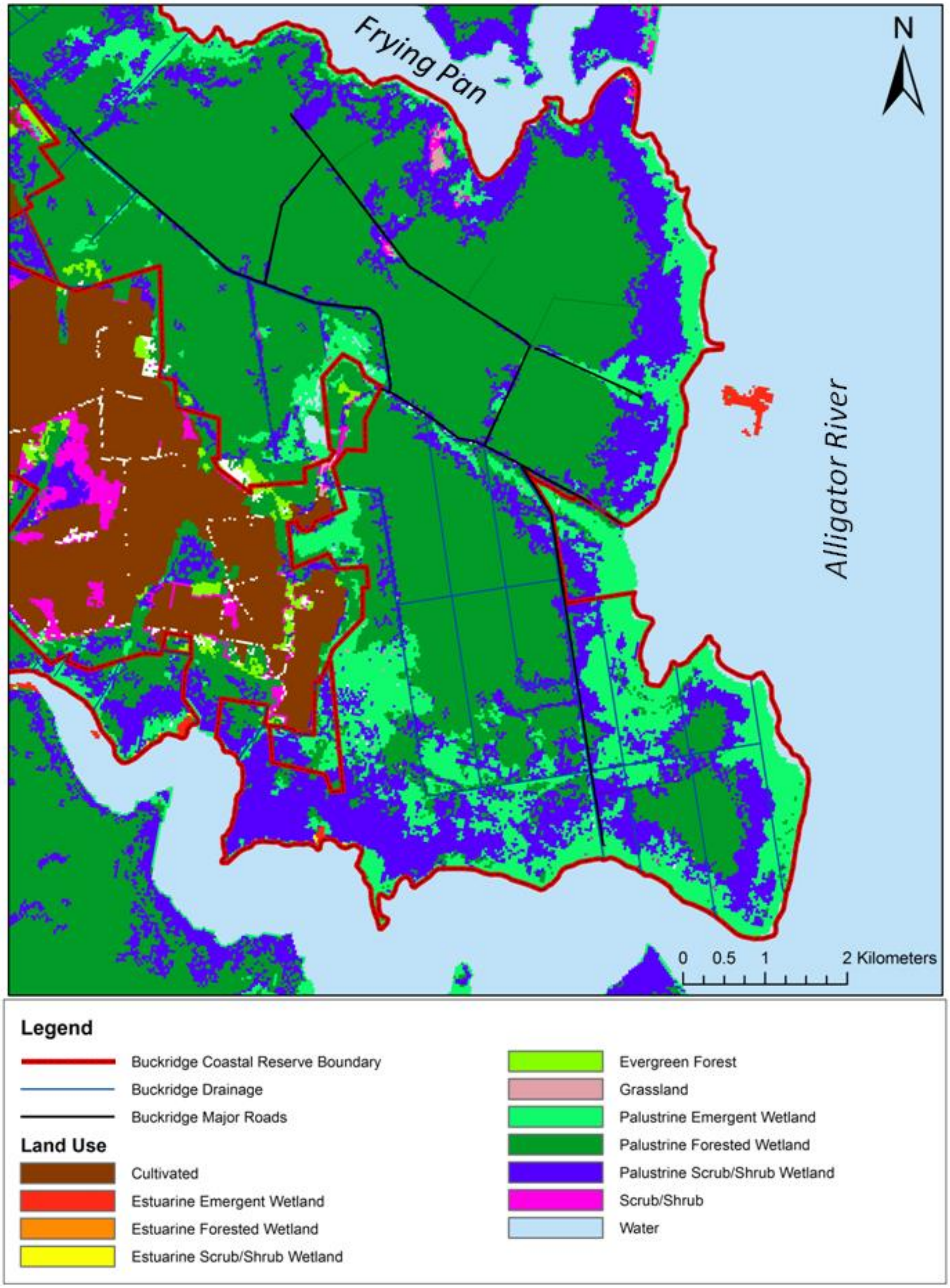

Figure 2-2: Land use in Buckridge Coastal Reserve (NCDNR).

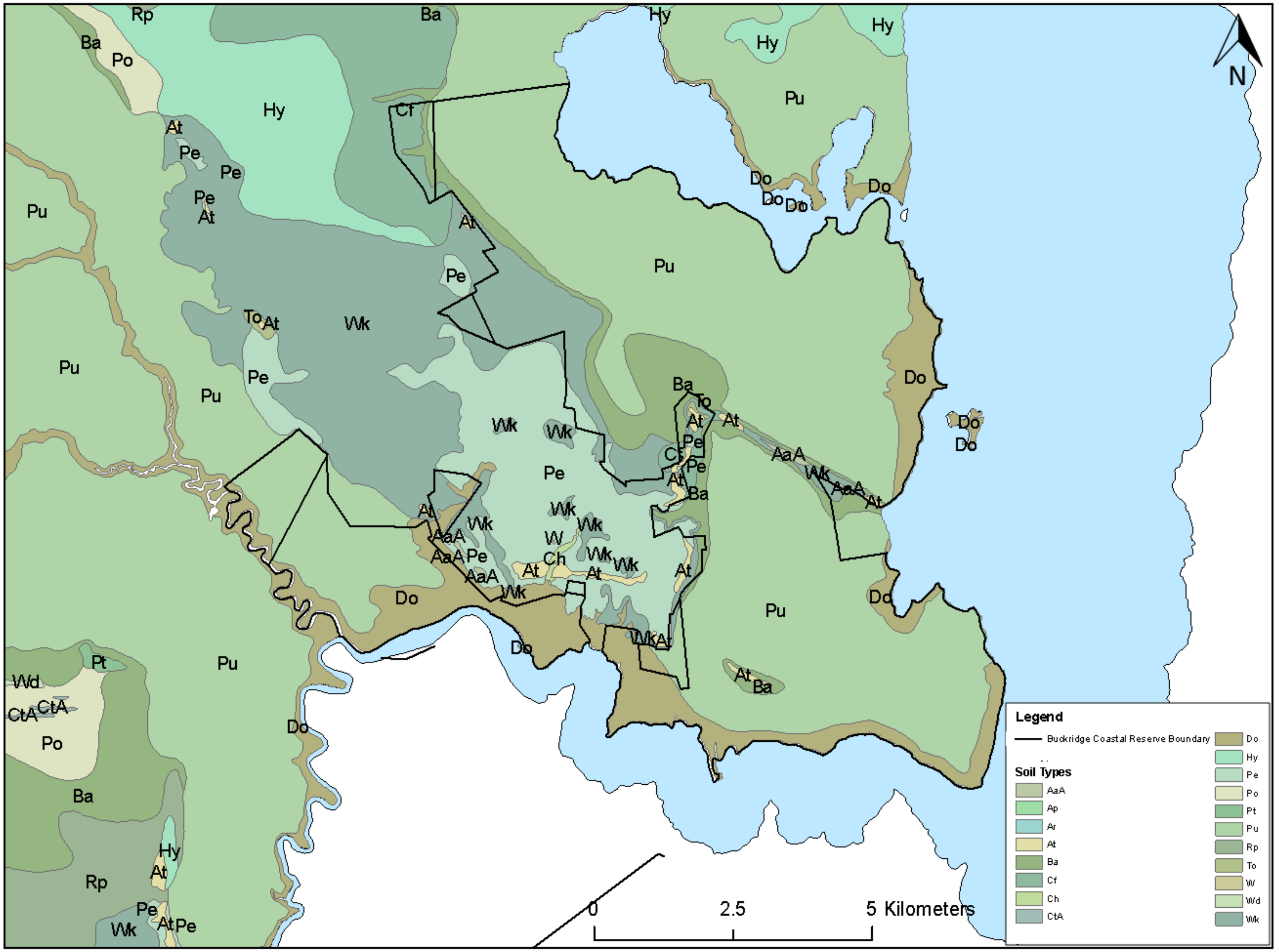

Figure 2-3: Soil Types in Buckridge Coastal Reserve. Soil type names and description are located in Appendix A (Tant et al, 1988).

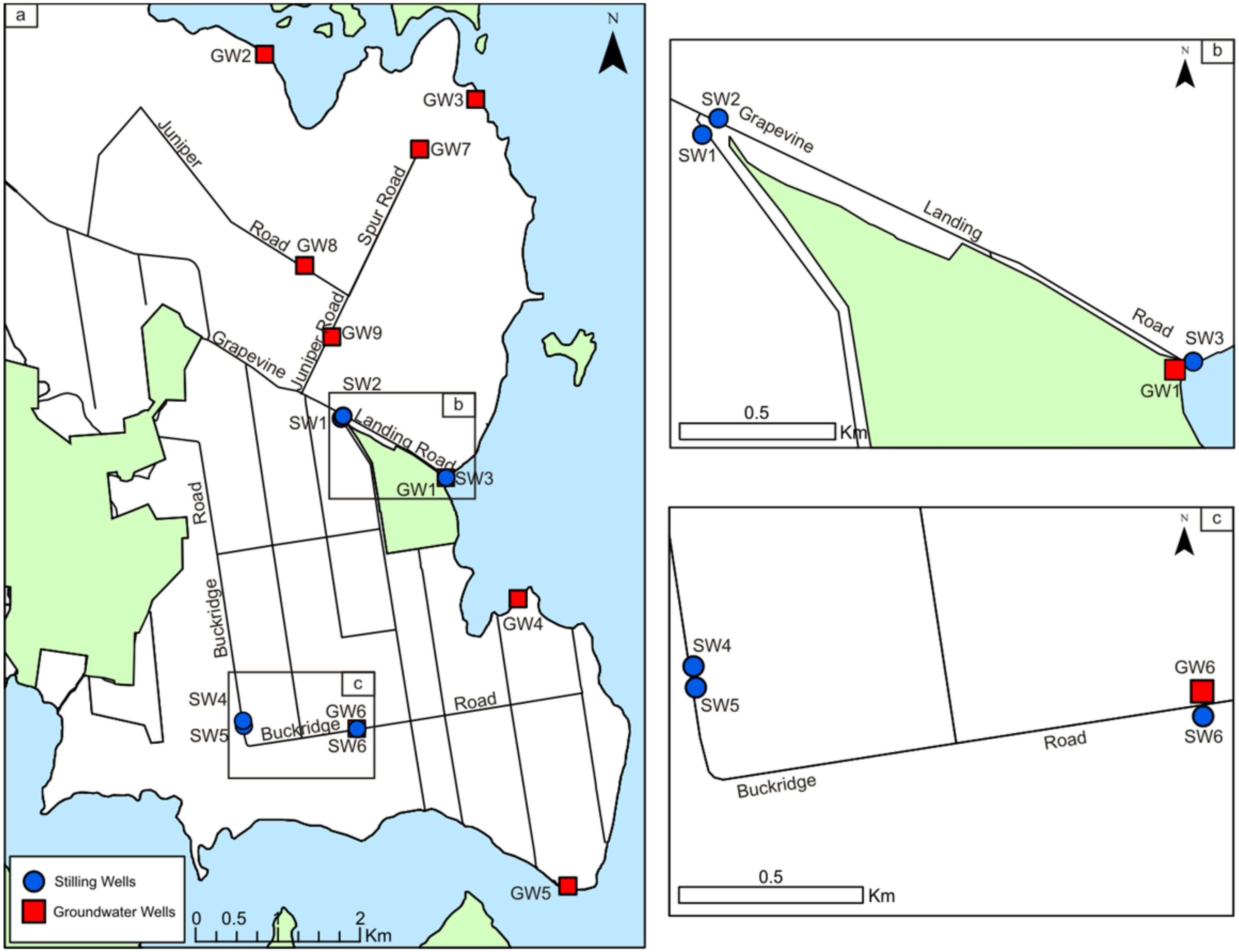

Figure 2-4: (a) Detailed study area with the approximate location of canals, roads, and types of observation wells: groundwater (GW) and stilling wells (SW). (b) Location of stilling well cluster A (SW-A) with SW1, SW2 and SW3. (c) Location of stilling well cluster B (SW-B) with SW4, SW5 and SW6.

vegetation-stabilized banks.

There are four major channels in the Reserve. These are the Basnight Canal and State Ditch channels that are located in the northwestern part of the Reserve, a canal along Grapevine Landing Road in the central part, and an unnamed canal in the southern part of the Reserve. Several small canals and ditches created from the excavation of material for road construction are present throughout the Reserve. These canals have diminished the quality of surface water and groundwater and altered the natural flow (Fuss, 2001). Canals in the region reduce recharge to groundwater by removing excess water to the estuaries and rivers. Channelized wetlands affect the quantity of water by reducing groundwater levels by forcing water to flow into artificial channels therefore reducing the hydraulic head in the surficial aquifer (Fuss, 2001). The flow of water in the channels is dependent on rainfall accumulation and is influenced by the water level in the Alligator River. During storms and wind tides, the channels may act as conduits that transport brackish and salt water into the interior of the Reserve (Fuss, 2001; Madden, 2005).

Several studies have documented the general hydrology and ecology of Buckridge Reserve (e.g., Fuss, 2001; Madden, 2005 and Ferrell et al, 2007). However, there has been little in-depth research to explain the temporal and spatial distribution of salinity in the Reserve. Fuss (2001), generalized hydrologic observations of the canals and categorized the vegetation and wetland types in the Reserve. Madden (2005) suggested a ‘salt wedge’ was present in the canals and peat soils that affected the AWC population. Sodium to chloride ratios of samples from piezometers in transects of healthy and unhealthy AWC indicated salt-water intrusion (Madden, 2005). It was determined that sampling stations further from the Alligator River had lower specific conductivity readings. Salinity levels in the peat soils increased after Hurricane Ophelia, (September 15, 2005) and remained elevated for 3-5 weeks. Salt-water intrusion from Hurricane Ophelia could imply consistent intrusion from raised sea levels, which may result in higher salinity of the canal water (Madden, 2005).

The US Geological Survey studied the effects of canals and roads on hydrologic conditions and ecology (Ferrell et al., 2007). Ferrell et al., (2007) found that the roads and canals can either have a detrimental or protective effect on water quality by restricting or facilitating movement of brackish water in the Reserve. This project set up transects of piezometers to measure conductivity and groundwater movement in healthy and unhealthy Atlantic white cedar sites (AWC). Ferrell et al., (2007) suggested that wind from a northerly and easterly direction showed an associated increase in water levels in the canals along Grapevine Landing Rd.

The objectives of this study are to assess the quantity and quality of the groundwater and surface water systems in Buckridge Reserve by analyzing water level, specific conductivity, and temperature data collected from groundwater wells and stilling wells. Specific conductivity is used as a proxy for salinity. Therefore, high specific conductivity values indicate high salinities whereas low specific conductivity values indicate low salinities. Using weather data, the driving mechanisms responsible for variations in salinity was investigated.

Methodology

A network of fifteen observation wells was installed in the Reserve to monitor water levels, temperature and specific conductivity in groundwater (GW) and surface water (SW) bodies (Fig. 2-4; Tables 2-1 and 2-2). Five of the groundwater wells (GW1-5) were installed 23 meters from the shoreline of the Alligator River (coastal wells), whereas four other wells (GW6-9) were installed in the interior of the Reserve (interior wells) (Fig. 2-4). Groundwater wells were installed by hand augering through the peat to the top of the mineral substrate, but in some cases, the wells were partially penetrating. Wells were constructed with 5.1-cm-diameter (2 inch) polyvinyl chloride (PVC) pipes fitted with machine-slotted PVC screens measuring between 2-4 m (Table 2-1). To prevent contamination from surface water infiltration, a 10.2-cm-diameter (4 in) section of PVC pipe fitted with a locking cover was installed over each well that extended about 0.3 m below the surface and about 0.5 m above the land surface.

Two stilling well clusters (SW-A and SW-B) were installed in the Reserve to monitor water levels and water quality conditions in the canals (Fig. 2-4). Cluster SW-A is located in the central part of the Reserve whereas cluster SW-B is located in the southern part of the Reserve on Buckridge Road about 1 km north of the Alligator River (Fig. 2-4). Two of the wells in cluster SW-A (SW1 and SW2) are located about 1.5 km west of the Alligator River on Grapevine Landing Road and the third well (SW3) is located in the Alligator River at Grapevine Landing Road (Fig. 2-4b). Two wells in cluster SW-B are located on the north-south trending canal, SW4 <0.1 km upstream from SW5, and SW6 is located about 1.5 km east of SW5. Stilling well clusters were installed close to sites where the NC Department of Environment and Natural Resources was going to install water control structures to regulate water levels and flow in the canals. The stilling wells were constructed of 6-meter-long (20 ft), 10 cm-diameter

(4 in) perforated PVC that was attached to a bracket alongside the canal bank (Fig. 2-5).

To characterize the water level and water quality in surface water and groundwater bodies, data recorders were installed in the observation wells from October 1, 2010 to October 31, 2011. Data were downloaded on a bi-monthly basis. However, due to logger malfunction, some data had incomplete records. Specific conductivity loggers manufactured by Dataflow systems were used to record specific conductivity (which as previously mentioned was used as a proxy for salinity), and temperature (accuracy of ±3% of full scale). Pressure transducers manufactured by Solinst Canada Ltd were utilized to measure water levels (Solinst water level loggers) and barometric pressure (Solinst barologger) (accuracy of ±0.05% of full scale). A barologger was deployed in SW3 to record barometric pressure at hourly intervals. An attempt was made to equip each well with two specific conductivity loggers (deployed at a shallow and deep depth), and a water lever logger to record data at 1-hour intervals (Fig. 2-6). The deep specific conductivity logger was installed close to the bottom of the well and the shallow SC logger was installed close to the water surface (Tables 1 and 2).

The elevations of the top of the stilling well casings were surveyed using a Topcon GTS-210 series electronic total station and referenced to a nearby North Carolina Geodetic Survey benchmark in meters above North American Vertical Datum of 1988 (NAVD 88). The land surface elevations at the locations of groundwater wells were determined using a 6-meter digital elevation model of Tyrrell County (http://www.nconemap.com). The coordinates of the wells in the Reserve were obtained by using a hand held Trimble GPS device that was referenced to the North American Datum of 1983 (NAD 83).

Precipitation and temperature data were obtained from a National Weather Service Cooperative Observer Program (NWS COOP) weather station near Gum Neck (accessed online at: http://www.ncwater.org/wrisars), about 2 km west of the Reserve (Fig. 2-1). The average annual precipitation in the region is 1,028 mm/year. The daily temperature, barometric pressure and rainfall measurements for the region is displayed in Fig. 2-7. The cumulative rainfall for the duration of the study (October 1, 2010 to October 31, 2011) was 1,377 mm which is higher than the average annual precipitation. Large precipitation events occurred during isolated storms and the passing of Hurricane Irene in August 2011. The average daily minimum and maximum air temperatures recorded at the weather station during the study period are 9.6°C and 21.6°C, respectively, with a mean of 15.6°C (Fig. 2-7).

Daily wind direction, wind speed and wind gusts were obtained for the research period from a Remote Automated Weather Station (RAWS)located in Fairfield, NC (accessed online at: http://www.wunderground.com), about 10 km southwest of the Reserve (Fig. 2-1). The wind direction and velocity were displayed as U and V vectors extending from equally spaced points along a horizontal line. The length of the direction vector and the magnitude of the velocity vector were converted to U and V, with U representing the length component in an east- west direction and V the length component in a north-south direction. Positive values of U_w (m/s) are southerly winds whereas negative values represent northerly winds.

Figure 2-5: Example of a stilling well (SW6) installed in the canal on Buckridge Road.

		Length of (m)			Elevation of logger (m above NAVD 88)				Depth to logger (m)		
Well ID	Peat thickness (m)	Well	Screen	TOC[1]	Land Surface	Shallow SC	Deep SC	Water level	Shallow SC	Deep SC	Water level
GW1	2.33	2.33	1.42	0.93	0.41	-0.21	-0.93	-1.00	0.62	1.34	1.76
GW2	>3.78	3.78	3.05	0.60	0.16	-0.55	-2.99	-3.13	0.71	3.15	3.29
GW3	3.67	3.67	2.61	1.05	0.29	-0.27	-1.57	-2.23	0.56	1.86	2.86
GW4	3.56	3.56	2.60	0.86	0.26	-0.25	-1.22	-2.65	0.51	1.48	2.91
GW5	>4.14	4.14	2.65	1.28	0.14	-0.70	-2.00	-2.81	0.84	2.14	2.95
GW6	2.12	2.12	1.07	0.98	0.23	-0.24	-	-1.09	0.47	-	1.33
GW7	3.07	3.07	1.84	1.23	0.27	-0.33	-1.38	-1.79	0.60	1.65	2.06
GW8	2.98	2.98	1.52	0.85	0.38	-0.68	-1.59	-	1.06	1.97	-
GW9	2.70	2.70	1.59	0.32	0.57	-	-1.18	-	-	1.75	-

[1] TOC= top of casing from ground surface

Table 2-1: Specifications of groundwater observation wells derived from the Emily and Richardson Preyer Buckridge Coastal Reserve, North Carolina.

	Length of (m)			Elevation of loggers (m above NAVD 88)				Depth to logger (m)		
Well ID	Well	TOC[1]	Plunge	Land surface	Shallow SC	Deep SC	Water level	Shallow SC	Deep SC	Water level
SW1	6.00	1.15	25	0.49	-0.33	-1.10	-1.23	1.55	2.32	2.45
SW2	6.00	0.95	25	0.48	-0.40	-1.17	-1.30	1.55	2.32	2.45
SW3	6.00	-	90	-	-0.14	-	-0.39	2.90	-	3.15
SW4	6.00	0.57	26	0.17	-0.59	-1.39	-1.53	1.60	2.41	2.54
SW5	6.00	0.68	30	0.26	-0.86	-1.77	-1.92	1.83	2.74	2.90
SW6	6.00	0.26	42	0.40	-1.13	-2.35	-2.56	2.45	3.67	3.87

[1] TOC= top of casing from ground surface

Table 2-2: Specifications of surface water observation points derived from the Emily and Richardson Preyer Buckridge Coastal Reserve, North Carolina.

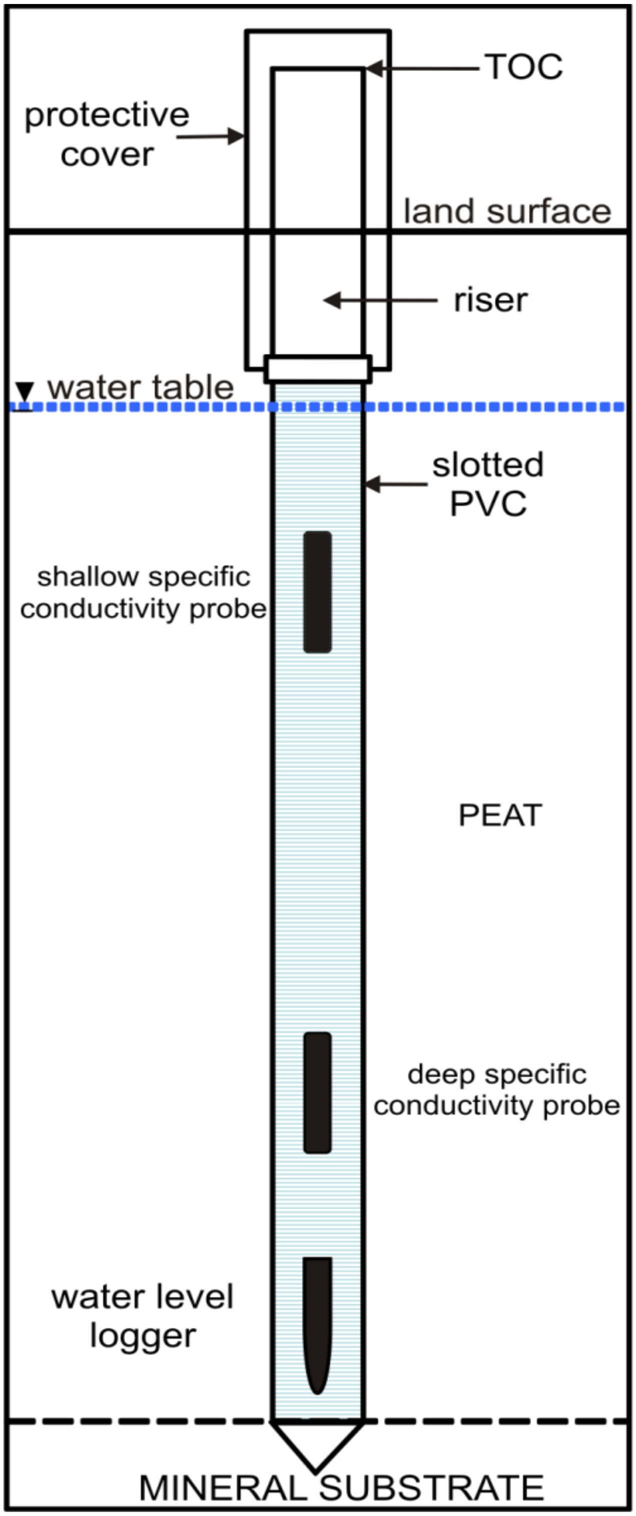

Figure 2-6: Example of a groundwater well and position of a water level logger, a shallow specific conductivity and temperature logger, and deep specific conductivity and temperature logger.

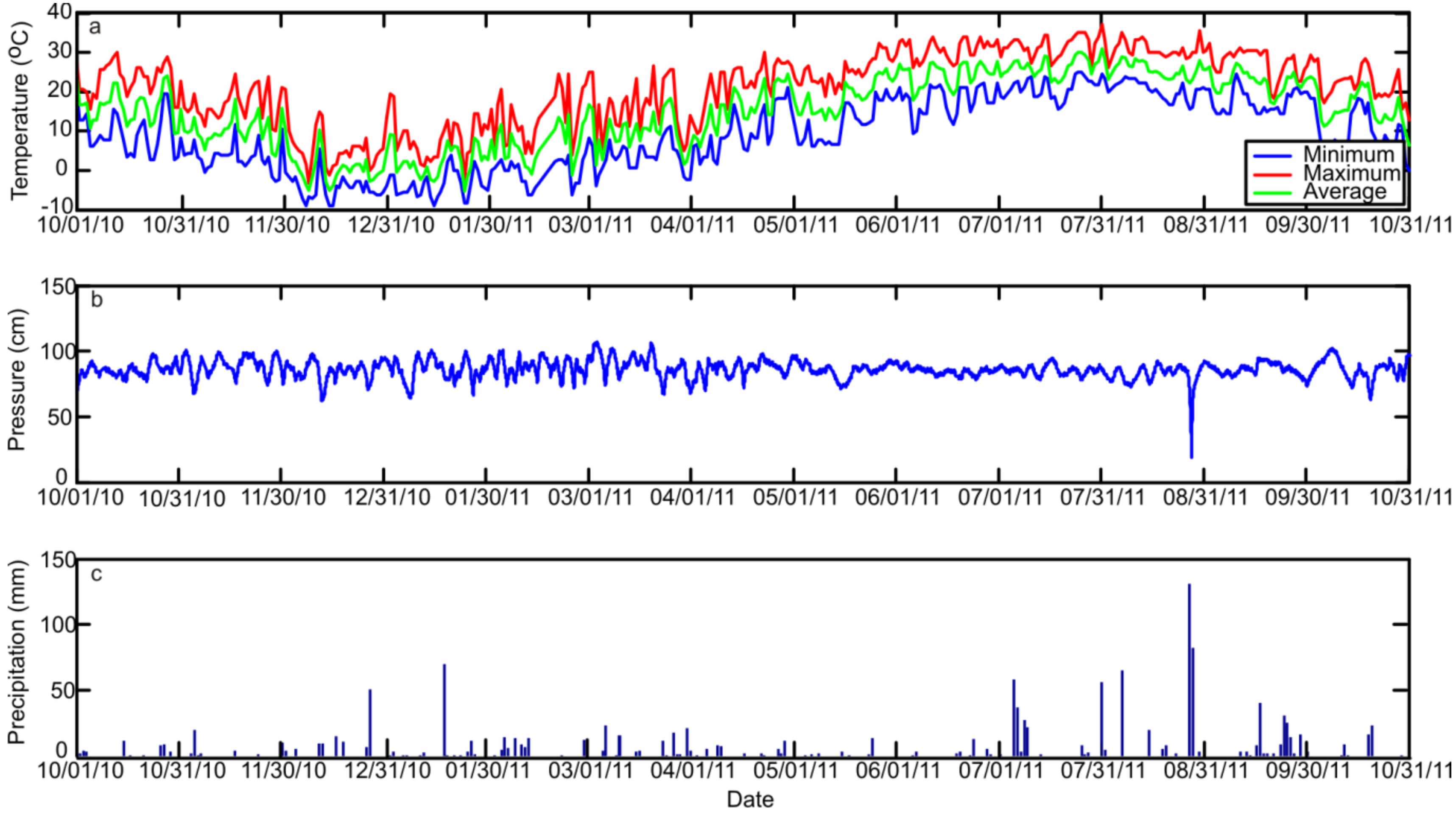

Figure 2-7: Weather data collected for the study area (Oct 1, 2010 to Oct 31, 2011) (a) Daily minimum, maximum and average air temperatures from Gum Neck rainfall station, (b) atmospheric pressure recorded at Buckridge Coastal Reserve (c) daily precipitation from the Gum Neck rainfall collection station.

Results and Discussion

Water quality

Specific conductivities, temperatures, and water levels of ground and surface water were monitored at fifteen sites throughout the Reserve. Daily precipitation was compared to specific conductivity, temperature, and water level data for groundwater wells and stilling wells (Fig. 2-8 and Fig. 2-9). Summary statistics for specific conductivity in observation wells at shallow and deep depths are provided in Table 2-3 and 2-4. Table 2-5 and 2-6 show summary statistics for temperature in the observation wells at shallow and deep depths. Refer to Appendices C-F for time series plots of temperature, water level, and specific conductivity for groundwater and surface water.

Overall, specific conductivity levels in the Reserve are more elevated in the surface water than the groundwater system. The seasonal variability and frequency in responses to specific conductivity is higher in the surface water system. There is less variability in specific conductivity in the groundwater system than the surface water.

The specific conductivity levels in surface water bodies measured by Madden (2005) were significantly lower than conductivity levels observed during this study. The average specific conductivity for the Alligator River was 1.9 mS/cm (Madden, 2005), whereas in this study the average was 3 mS/cm with a maximum of 13.4 mS/cm. The sampling rate during Madden (2007) was twice monthly from September to November, 2005, therefore possibly missing the opportunity to observe high salinity levels observed in this study. The maximum salinity observed in 2005 for the Alligator River at the Buckridge was 4.4 mS/cm. This observed increase in specific conductivity in the

Alligator River has been transported into the groundwater and surface water system in Buckridge Reserve.

Groundwater

The average shallow groundwater temperature for the study period was 16.7°C, which is 1.1°C higher than the average annual air temperature of the region (Fig. 2-8 and Table 2-5 and 2-6). The deep groundwater temperature averaged 15.8°C, which is 0.2°C warmer than the average annual air temperature. Groundwater temperatures do not indicate mixing but thermal stratification. Seasonal patterns of thermal stratification occur when water density changes with temperature variations. Shallow groundwater temperature is warmer than the deep groundwater temperature during the summer to late-autumn months, whereas the deep groundwater temperature is warmer in the winter and spring months.

Specific conductivity levels in the coastal groundwater wells showed little variability throughout the year until the beginning of May 2011 (Fig.2-8). There is more variation in specific conductivity during the warmer summer months marking the peak vegetation-growing season. With the passage of Hurricane Irene on August 27, 2011, there was overall minimal influence on specific conductivity levels on the surface water and groundwater system in Buckridge Reserve.

Specific conductivity was generally higher in the southern region of the Reserve along the Alligator River and lower in the northern region of the Reserve adjacent to the Frying Pan (Fig. 2-8). The most southerly groundwater wells located along the Alligator River, (i.e., GW4 and GW5), had the highest specific conductivities (Table 2-3). In the southern portion of the study area, specific conductivity was elevated in the shallow water and depressed in the deep groundwater. Generally, deeper groundwater had a higher specific conductivity than the shallow-water, however, GW4 and GW5 had higher shallow-water specific conductivity (Fig. 2-8). This is in contrast to what one may typically expect. The specific conductivity level at shallow and deep depth differed by 1.5 mS/cm and the. Higher specific conductivity at a shallow depth could also represent the effects of overwash events and partial mixing or evapoconcentration. Partial mixing occurs where salinity increases with depth. In the north, specific conductivity in the deep groundwater was more elevated than in the shallow water. Interior groundwater wells (GW7-GW9) had the lowest specific conductivity with values less than 2 mS/cm, which are similar to GW2 located in the Frying Pan. The difference in mixing between observation wells in the south and north can be attributed to the source of the saltwater being from the south of the Reserve, possibly emanating from the Alligator-Pungo canal. Observation well GW5 was more heavily influenced by wind tides than GW2. GW5 is in a location where it is exposed to southerly winds whereas, GW2 is located along the banks of the Frying Pan which is not affected by winds as much as the Alligator River. Overall, GW5 had higher specific conductivity levels than GW2 in both the shallow water and deep water (Table 2-2 and Table 2-3). Since the groundwater system is not heavily affected by wind tides, specific conductivity levels in the groundwater system were relatively low compared to the surface water system. There was less variability (i.e., lower frequency and lower magnitude variations) of specific conductivity in the groundwater than in the surface water.

Surface water

The average shallow surface water temperature for the study period was 16.4°C, which is 0.8°C higher than the average annual air temperature of the region (Fig. 2-7 and Table 2-5 and 2-6). The deep surface water temperature averaged 17.5°C, which is 1.9°C warmer than the average annual air temperature. Surface water temperatures changed daily and seasonally, and were responsive to precipitation and air temperatures (Fig. 2-9). Daily water temperature was observed to respond to the change in ambient air temperature. Water temperatures may vary spatially due to location in the Reserve and canopy cover. Shallow water was generally warmer than the deep water during the warmer months, whereas the reverse was true in cooler winter months. Seasonal thermal stratification and mixing of the water column was observed in SW1 and SW2 (Fig. 2-8). The Alligator River had more variation in temperature than the canal system (Fig. 2-9). The shallow water temperature in SW1 was slightly higher than SW2 and peaked before SW2. The same trend occurred in the wells in cluster SW-B, where the shallow water temperature in SW6 peaked before SW5 and SW4. Periods of higher temperatures and increased water levels coincided with salinity peaks (Fig 2-9 and Appendix C).

Overall, the specific conductivity of the surface water suggests a higher variability of salinity both spatially and temporally (Fig.2-9) than the groundwater system. Unlike the groundwater system, surface water bodies had a higher variation and frequency of specific conductivity peaks in the fall to spring months (mid-September through May) whereas the specific conductivity remained generally elevated in the summer months (May through mid-September). On average, the increase in specific conductivity during the winter and spring occurred at least twice a month. Specific conductivity in the canals was higher in the deep water and peaked earlier than that in the shallow water. Two types of processes can explain this occurrence in the surface waters: a salt wedge and partial mixing (Mann, 2000). A salt wedge is caused by a distinct boundary between the shallow freshwater and higher specific conductivity layer in the deep water. The increase in salinity ranges from 2-5 mS/cm. The Alligator River and canals had high frequency and high amplitude variations in specific conductivity throughout the year.

Canals not directly connected to the Alligator River have less variability of specific conductivity than canals that are connected to the river (Madden, 2005) which are influenced by wind tides. Overall, specific conductivity levels were higher in cluster SW-B in the south than SW-A in the north. These observations suggest that the source of the saline water may be from the south of the Reserve. Saltwater may therefore emanate from the Alligator-Pungo canal, part of the Intracoastal Waterway, which is connected to the more brackish Pamlico Sound by the Pungo River. Future work should focus on testing the hypothesis that the Alligator-Pungo canal is a conduit for saltwater from the Pamlico Sound to the Alligator River. Saltwater plumes exiting the Alligator-Pungo canal under the influence of wind tides could potentially be the source of the elevated specific conductivity levels observed in Buckridge Reserve.

Wind tides and water quality

Peaks in specific conductivity correspond with changes in wind direction and wind intensity. Using the time period from February 20 to March 5, 2011, as an example, the influence of meteorological factors, wind direction and wind speed, on specific conductivity and water levels were closely examined (Fig. 2-11). Southerly winds with wind velocities exceeding 16 km/h increased water levels, resulting in wind tides. In association with the wind tides, an increase in specific conductivity was observed in the Alligator River (SW3) and in the central canals (SW2 and SW1).

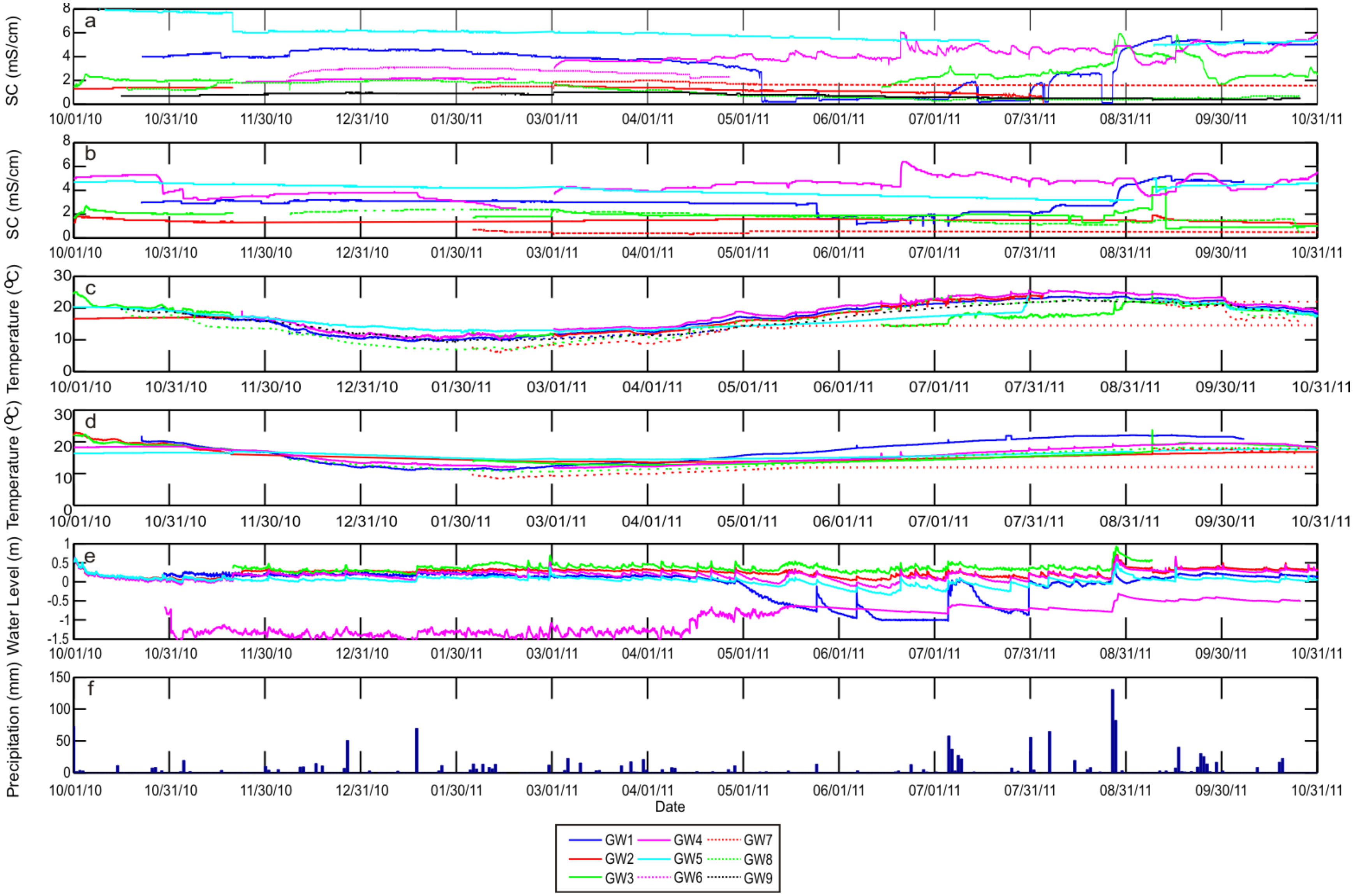

Figure 2-8: Groundwater data from observation wells GW1- GW9: (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) groundwater temperature from shallow depth, (d) groundwater temperature from deep depth, (e) elevation of water table and, (f) precipitation from Gum Neck rainfall collection station.

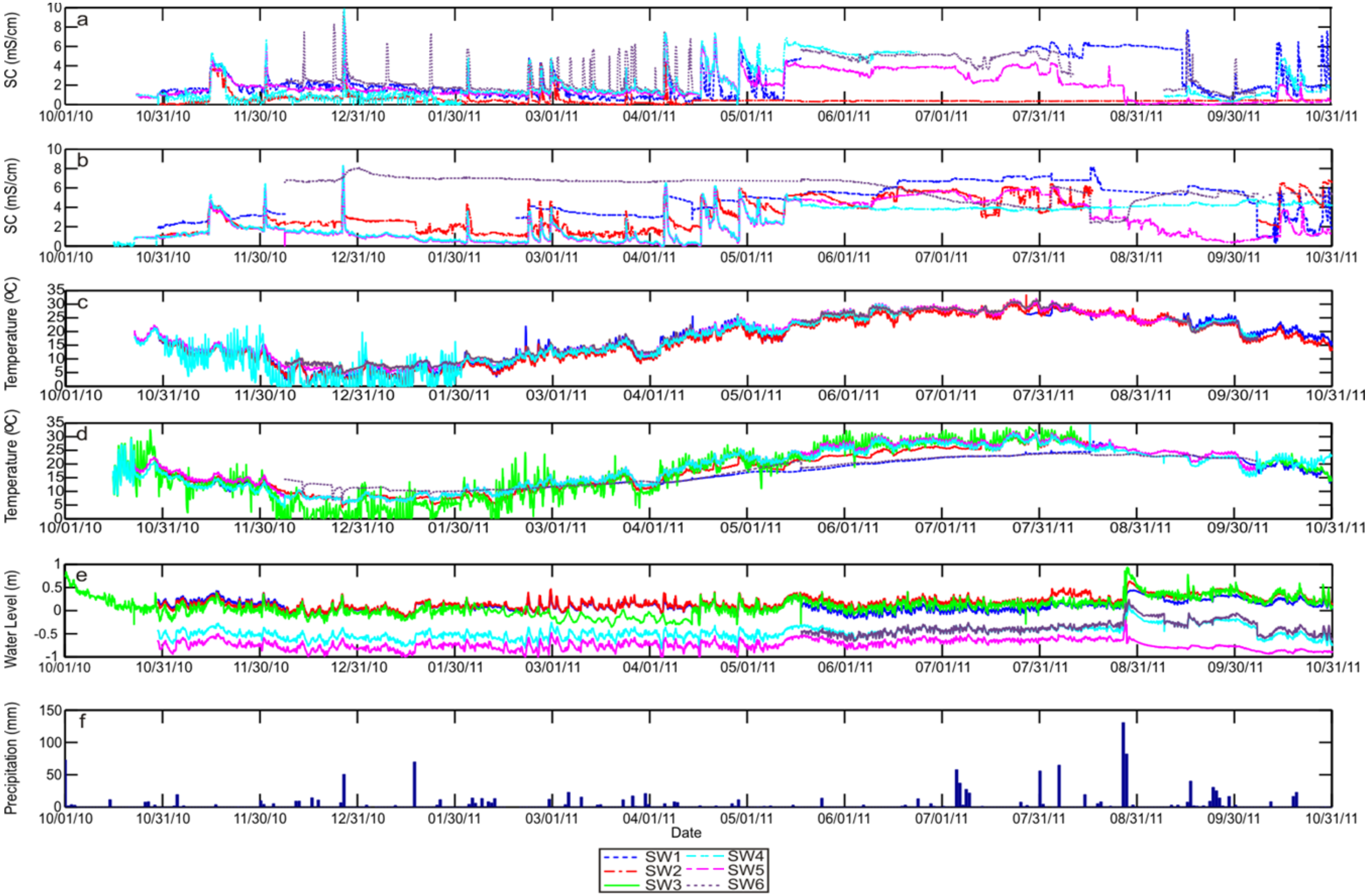

Figure 2-9: Surface water data from observation wells SW1- SW6: (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) groundwater temperature from shallow depth, (d) groundwater temperature from deep depth, (e) elevation of water table and, (f) precipitation from Gum Neck rainfall collection station.

Shallow Specific Conductivity (mS/cm)

Well ID	Mean	Min	Max	Std. Dev.
GW1	3.4	0.1	5.7	1.5
GW2	1.2	0.1	1.6	0.2
GW3	2.5	1.4	5.9	0.8
GW4	4.2	1.7	6.9	1.4
GW5	4.3	3.1	5.6	0.7
GW6	2.8	2.1	3.1	0.2
GW7	1.6	1.2	2.0	0.2
GW8	1.8	0.4	2.4	0.4
GW9	0.7	0.3	1.0	0.2
SW1	2.5	0.1	7.7	1.9
SW2	0.5	0.1	5.5	0.7
SW3	3.0	0	13.4	3.6
SW4	2.0	0	9.9	2.0
SW5	2.0	0	8.5	1.3
SW6	3.2	0.2	9.6	1.7

Table 2-3: Summary statistics for specific conductivity from shallow surface and groundwater observation wells (October 1, 2010 to October 31, 2011).

Deep Specific Conductivity (mS/cm)

Well ID	Mean	Min	Max	Std. Dev.
GW1	3.0	1.0	5.2	0.7
GW2	1.5	1.2	1.9	0.1
GW3	2.0	1.6	2.7	0.1
GW4	4.5	0.8	6.4	0.8
GW5	6.2	2.6	8.4	1.1
GW6	-	-	-	-
GW7	0.6	0.3	0.8	0.1
GW8	1.1	0.3	2.0	0.6
GW9	-	-	-	-
SW1	4.1	3.8	4.3	0.1
SW2	3.2	0.8	6.4	1.6
SW3	-	-	-	-
SW4	2.3	0.0	8.3	1.5
SW5	2.3	1.6	8.2	1.8
SW6	6.0	2.3	8.1	1.3

Table 2-4: Summary statistics for specific conductivity from deep surface and groundwater observation wells (October 1, 2010 to October 31, 2011).

	Shallow Temperature (°C)			
Well ID	Mean	Min	Max	Std. Dev.
GW1	17.0	9.6	23.6	4.1
GW2	17.2	11.2	24.1	3.2
GW3	18.2	11.0	25.3	3.2
GW4	18.6	10.0	25.6	4.4
GW5	16.3	14.4	22.4	1.7
GW6	11.0	9.9	13.4	0.9
GW7	14.9	5.8	22.6	5.4
GW8	15.5	7.0	23.7	5.1
GW9	16.3	9.3	22.4	4.1
SW1	15.3	1.1	29.2	7.1
SW2	16.8	0.6	33.3	8.0
SW3	15.8	-0.7	33.7	8.5
SW4	17.8	4.3	32.0	7.6
SW5	14.3	0.0	30.0	8.9
SW6	18.2	4.8	32.3	8.4

Table 2-5: Summary statistics for shallow water temperature from shallow surface and ground water observation wells (October 1, 2010 to October 31, 2011).

	Deep Temperature (°C)			
Well ID	Mean	Min	Max	Std. Dev.
GW1	17.1	11.1	22.2	3.3
GW2	16.4	13.5	22.9	2.4
GW3	16.4	12.8	23.7	2.7
GW4	17.0	11.7	19.5	2.2
GW5	16.9	12.2	23.8	2.7
GW6	-	-	-	-
GW7	13.0	8.3	18.0	3.2
GW8	14.1	10.6	18.8	2.6
GW9	-	-	-	-
SW1	17.6	8.1	28.3	4.7
SW2	16.5	4.1	31.2	7.3
SW3	-	-	-	-
SW4	18.5	5.4	32.0	7.2
SW5	17.8	4.0	34.2	6.9
SW6	17.3	6.8	23.9	5.4

Table 2-6: Summary statistics for water temperature from deep surface and ground water observation wells (October 1, 2010 to October 31, 2011).

Specific conductivity in the southern canals appeared to be influenced by a sudden change in wind direction from northeasterly to southerly. Generally, the peaks in specific conductivity occurred in the following sequence. For cluster SW-A the specific conductivity peaked first in SW3, followed by SW2, and finally SW1, suggesting an inland migration of saline water. For cluster SW-B, the specific conductivity first peaked in SW6, followed by SW5, and finally SW4. Observation well SW6 usually peaks higher than the Alligator River at SW3. These results suggest that under southerly winds, saltwater emanates from the Alligator River and is transported into the interior via the canal system.

A specific conductivity peak occurred in the Alligator River (maximum = 5 mS/cm) during a period of gusty winds (over 16 Km/h) from the north on February 25, 2011 (Fig. 2-11). When the wind direction changed from the northeast to the southwest, the specific conductivity in SW6 increased first, then SW5 and finally SW4 (about 6 hours later). The deep-specific conductivity logger responded almost immediately to an increase in specific conductivity in the canals. This pulse of saline water (~5 mS/cm) persisted for about a day. The specific conductivity at cluster SW-A (Fig.2-4b) responds to the change in wind direction before SW-B (Fig.2-4c), however, the magnitude of specific conductivity at SW-A is generally less than that SW-B. Therefore the distance to the Alligator River plays a role in magnitude and frequency of elevated specific conductivity levels.

Time series plots of specific conductivity and water levels that are compared to weather data from December 25-29, 2010 show similar trends in specific conductivity peaks (Fig. 2-12). Wind gusts of over 10 Km/hr produced a specific conductivity spike

(~10 mS/cm) in SW6 first, then SW1, SW2, SW5 and finally SW4. The specific conductivity in SW5 and SW4 was influenced about 1-2 hours after SW1 and SW2. The specific conductivity in SW-B peaked at about 10 mS/cm whereas the specific conductivity levels in SW-A peaked at 6 mS/cm which was less than the Alligator River.

Water quantity

Evapotranspiration and uptake by vegetation affect the water levels in the Reserve by lowering the groundwater table and decreasing surface water storage. Using the Thornthwaite method, potential evapotranspiration in the Reserve was estimated to range from 15 mm to 155 mm during the growing season (Fig. 2-10). High frequency variations in water levels during periods of no precipitation could be the effects of evapotranspiration.

Canal flow patterns are diverse in the Reserve. The canals along Juniper Road flow east to Grapevine Landing Road canal and drain into the Alligator River. The canal along Buckridge Road flows south toward the Alligator River (Fig. 2-1 and Fig. 2-4). During periods of strong southerly winds (>16 Km/hr), the water level in the Alligator River responded first by increasing in height, followed by the water levels in the canals. A change in flow direction of the surface water observed on October 7, 2011 was attributed to a change in wind direction from northerly to southerly. As a result of this change in wind direction, the water appeared to be flowing south from SW4 to SW5 toward the south. The data suggest that wind tides are caused by southerly winds. It is clear that the southerly winds push the near surface water upstream, but it may be

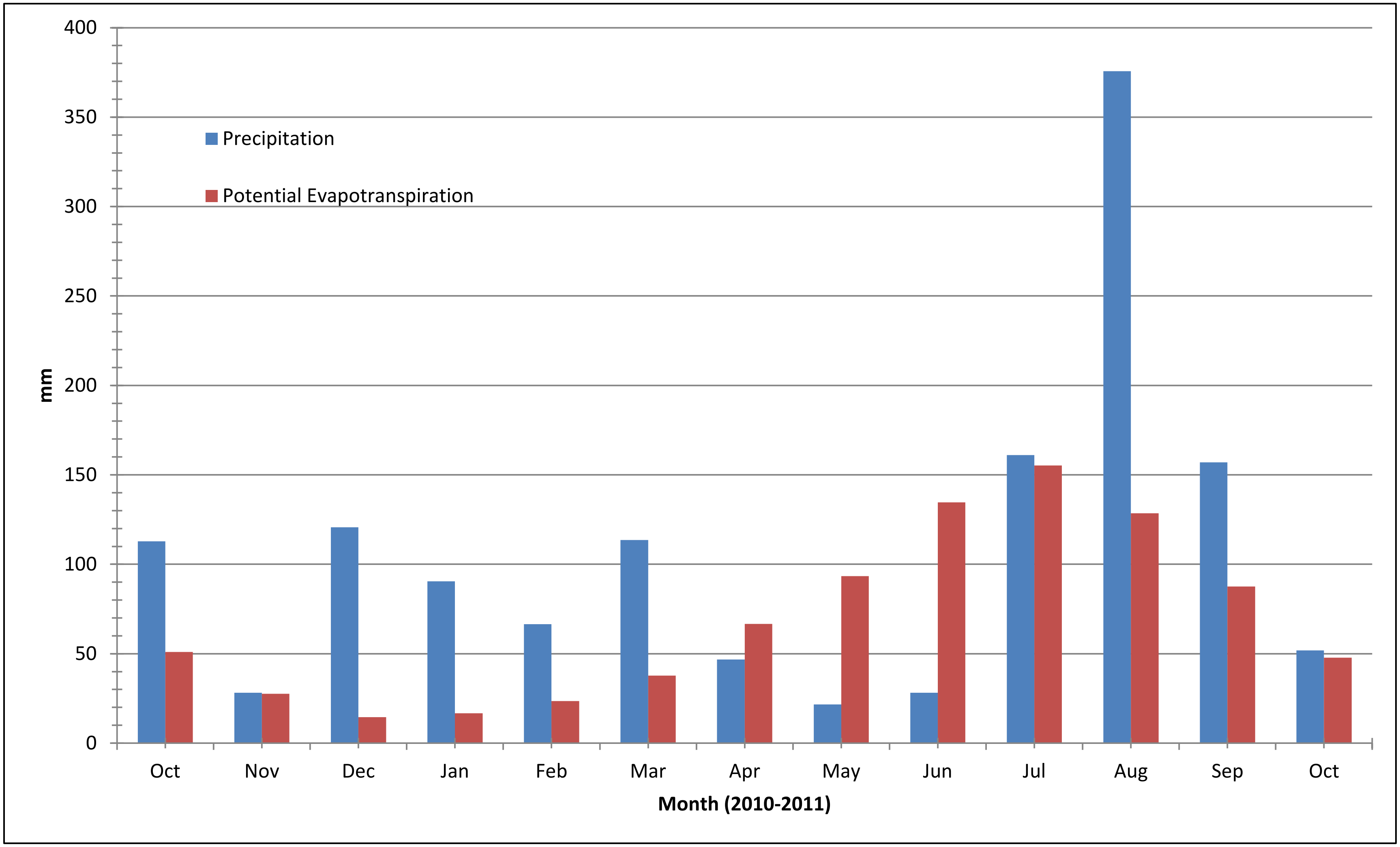

Fig 2-10: Monthly precipitation and potential evapotranspiration from October 2010 to October 2011 in Buckridge Coastal Reserve.

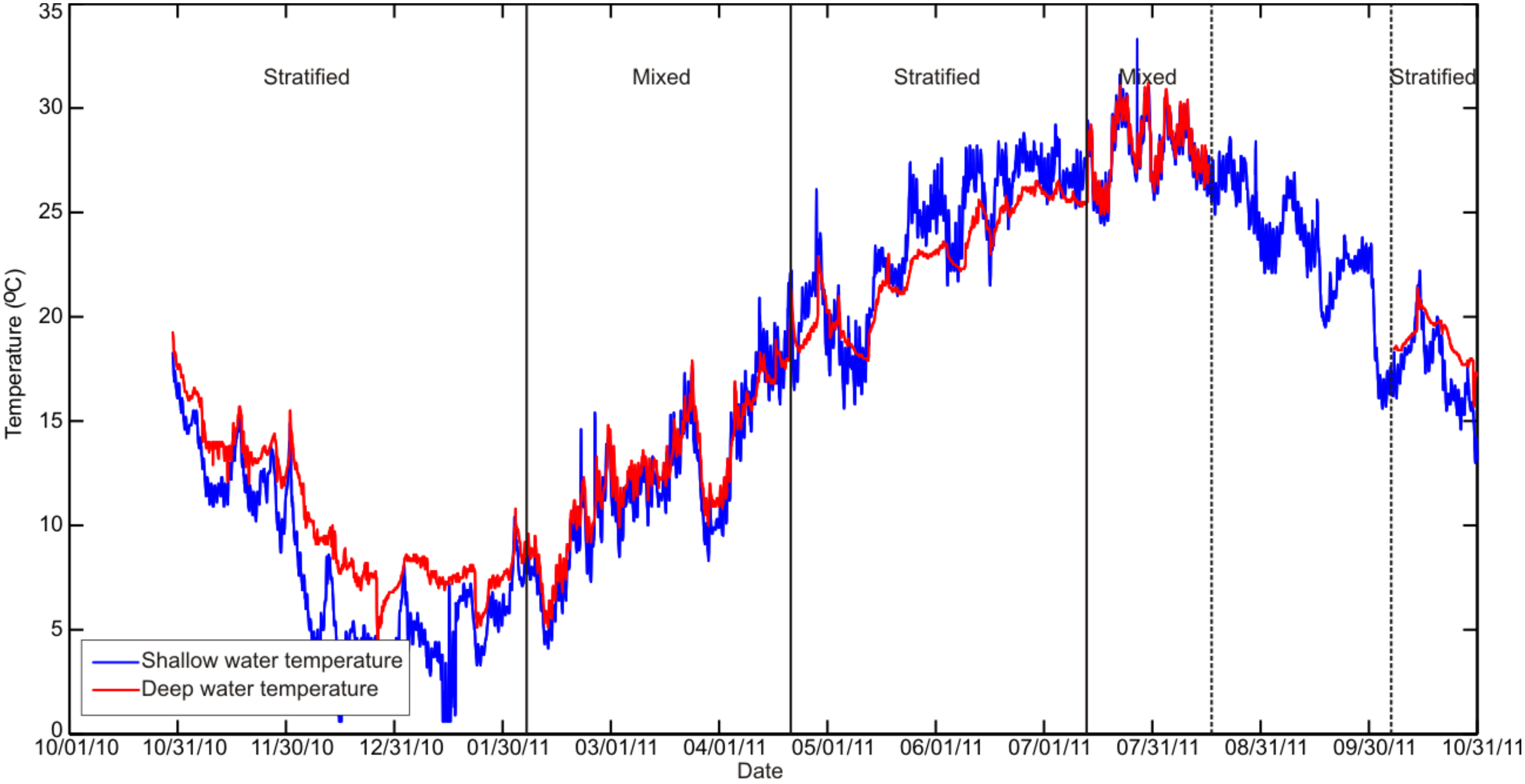

Figure 2-11: Daily shallow and deep-water temperature for surface water monitoring station SW2, showing seasonal thermal stratification and mixing, October 1, 2010- October 31, 2011. Missing data from August 16, 2011 to October 7, 2011are represented by gaps.

possible that the near-bottom water may still be flowing downstream. This is confirmed by consistent water level trends which show that surface water from the Alligator River is flowing into the Reserve (Fig. 2-9 and Appendix D and Appendix F). It is possible that the surface water is responding to wind forcing as the near-bottom waters are gravitationally influenced. Weisberg (1976), Elliot (1978) and Wang (1979) observed two-layer motions in response to wind forcing, the downwind flow in near-surface waters, and upwind flow near the bottom. This gradient influences specific conductivity and water levels in the Alligator River and is observed in the surface water system. Specific conductivity and water level data suggest that a southerly wind may promote estuarine circulation, thereby increasing the flushing rate causing a specific conductivity gradient in the Alligator River that decrease towards the north.

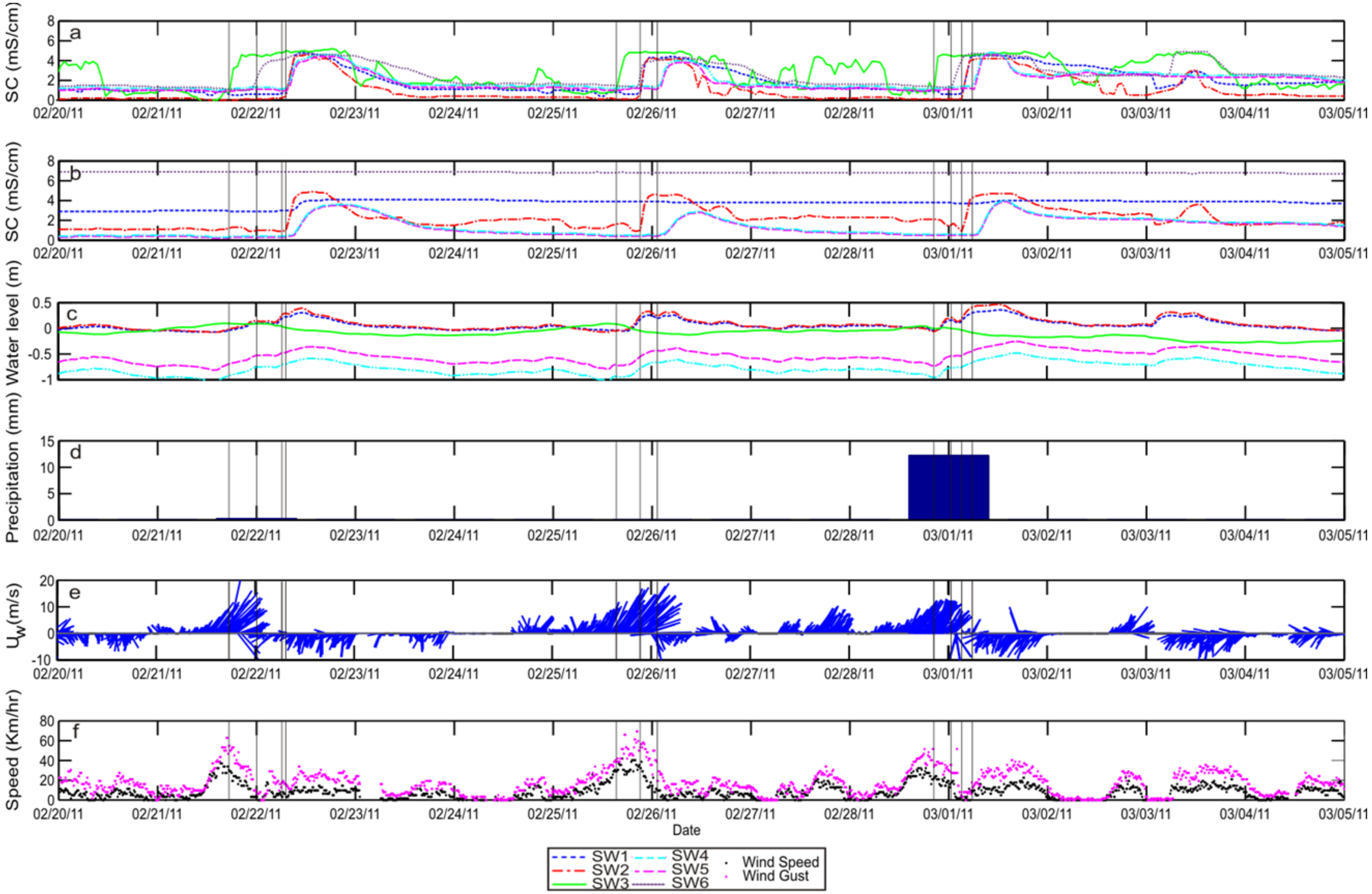

Figure 2-12: Time series of salinity recorded in stilling wells showing association between specific conductivity and wind direction (February 20- March 5, 2011) (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) elevation of water level, (d) precipitation from Gum Neck rainfall collection station, (e) wind direction from Fairfield weather station, (f) wind speed and wind gusts.

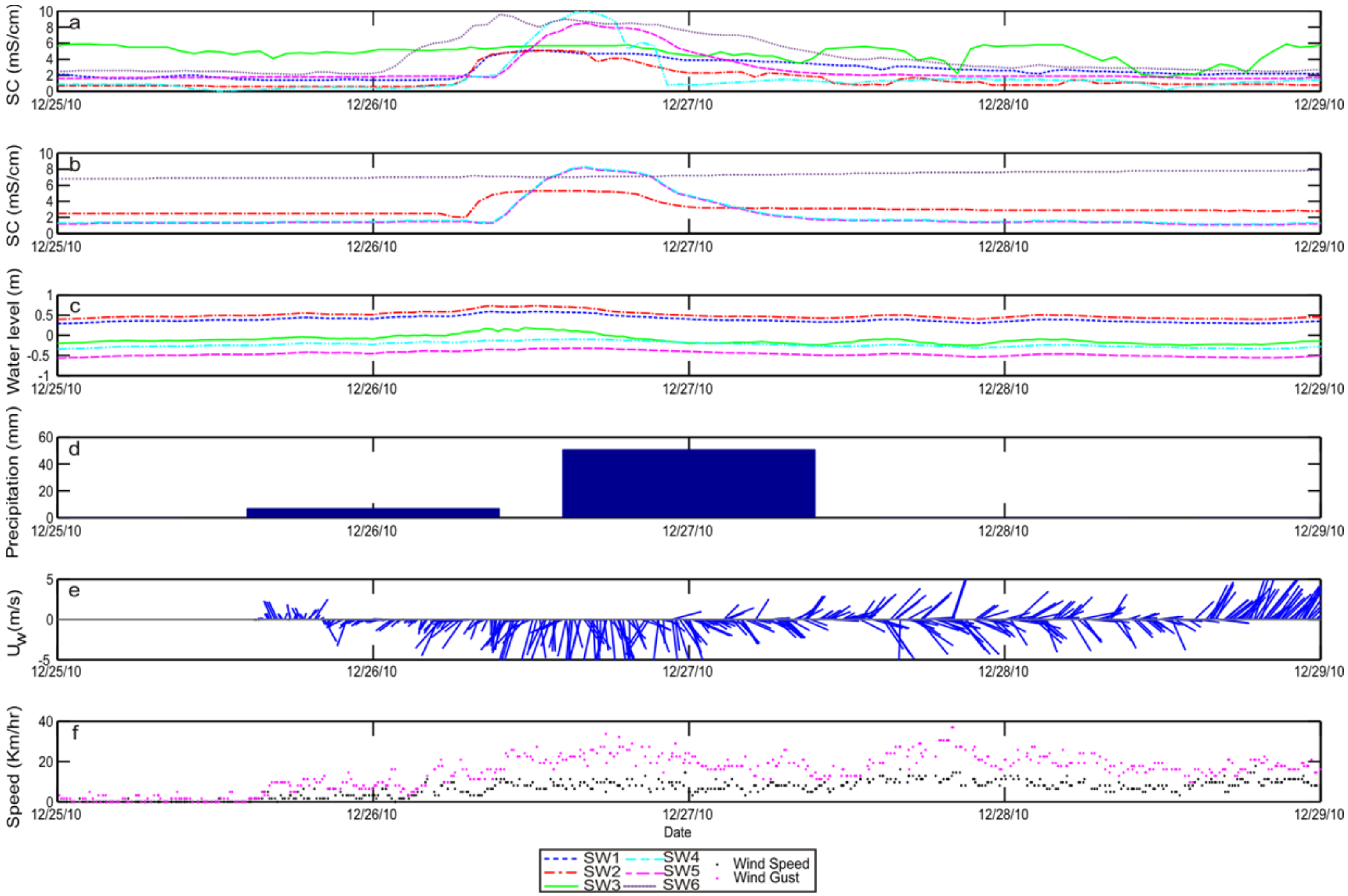

Figure 2-13: Time series of salinity recorded in stilling wells showing association between specific conductivity and wind direction during a low-pressure system (December 25- 29, 2010) (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) water level elevation, (d) precipitation from Gum Neck rainfall collection station, (e) wind direction from Fairfield weather station and, (f) wind speed and wind gusts.

Tropical Storms

On average, North Carolina is affected by two hurricanes each year (http://www.NHC-NOAA). In 2011, only one hurricane made landfall in North Carolina. Hurricane Irene made landfall over North Carolina’s Outer Banks on August 27, 2011 at 7:30 am EDT as a Category 1 storm with ~97 km/h sustained winds and produced over 130 mm of precipitation in the Reserve (Fig. 2-12). Catastrophic winds and waves produced by Hurricane Irene had a direct and devastating effect on property and various infrastructures along the coast.

The storm had major effects on coastal natural resources and shorelines along the Outer Banks and Eastern North Carolina. The hurricane forced waters up into the Currituck and Albemarle sounds and when winds shifted from the southwest to the northeast, the storm surge waters came rushing back toward the south (http://www.NHC.NOAA.gov). Post storm surveys indicate a surge of 2.5 m to 3.5 m occurred in portions of Pamlico Sound (http://www.NHC.NOAA.gov). The passing of the hurricane provided an opportunity to analyze the influence of a storm event on saltwater intrusion into the Reserve.

The track of Hurricane Irene as seen in Figs 2-14 and 2-15 affected groundwater and surface water levels. The Hurricane produced localized flooding in the Reserve and an increase of water levels in canals due to wind forcing and precipitation (Figs. 2-14 and 2-15). Water levels in the Alligator River were affected by the change in wind direction that was also seen in the Pamlico and Albemarle Sounds (http://www.NHC.NOAA.gov). Water levels in the groundwater wells and canals increased by approximately 0.5 m (Fig. 2-14 and Fig. 2-15) and remained elevated for about 2 weeks after the Hurricane.

The angle of approach and the shape and characteristics of the shoreline affects the level of inundation from storm surges. The location of the coastal groundwater wells (GW1-GW5) highlighted the magnitude of storm surge and saltwater intrusion in the groundwater system during Hurricane Irene. The coastal wells located on the eastern facing shore along the Alligator River, (i.e., GW1, GW3 and GW4) (Fig. 2-4) experienced a change in specific conductivity in shallow water. The specific conductivity at shallow depth in GW1 and GW4 increased before the Hurricane made landfall, when the winds were blowing from the south at 20 Km/hr. The specific conductivity in GW3 later peaked when the eye of the Hurricane was passing over the Reserve (Fig. 2-14). Specific conductivity levels in GW1 remained elevated through the end of October 2011.

Overall, specific conductivity levels in the canals were affected minimally by the Hurricane (Fig. 2-13). Specific conductivity levels in SW4 slightly decreased in the canal, and stayed relatively low thereafter whereas the rest of the canals showed no change in specific conductivity in shallow water. The deep-water specific conductivity in SW2 (Fig. 2-15) decreased after the Hurricane passed the Reserve (August 27, 2011), whereas all other deep-water salinities remained stable after the hurricane. Specific conductivity levels in SW4 showed a low frequency response and decreased water levels to the passing of the Hurricane.

The effects of storm surges on saltwater intrusion from two hurricanes were compared. In 2005, Hurricane Ophelia increased the specific conductivity levels in the canals over 3 mS/cm and remained elevated at the bottom of the canal for 5 weeks

(Madden, 2005). Specific conductivity levels in the peat soils increased after Hurricane Ophelia and remained elevated 3-5 weeks until the saltwater flushed from the canals. Madden (2005) suggested that the saltwater intrusion from Hurricane Ophelia could imply consistent intrusion from raised sea levels, which may result in higher specific conductivity in the canal system. The difference in wind intensities and wind directions that caused significant flooding as a result of high storm surges could have influenced the salinity levels in the Albemarle and Pamlico Sounds thus altering the specific conductivity in the Reserve.

The extent of saltwater intrusion from wind and storm events depend on storm path, intensity and storm surge which is directly related to wind direction and speed (Walker et al., 1987). The eye of Hurricane Irene's track was ~2 Km west of the Reserve whereas Hurricane Ophelia did not make landfall and traveled approximately parallel to the coastline for two days (Fig. 2-14). Hurricane Ophelia produced sustained wind speeds exceeding 120 Km/hr and gusts of over 148 Km/hr, whereas Hurricane Irene produced wind speeds of between to 107- 125 Km/hr. The difference in the hurricane track and duration of sustained high winds during Hurricane Ophelia and Irene could explain the level of saltwater intrusion observed in the Reserve.

The difference in magnitude of saltwater intrusion during the two hurricanes suggests that the wind forcing from an east-northeastern moving storm such as Hurricane Ophelia has a higher potential for storm surge (Fig. 2-14) than a northeastern moving storm. The key difference between Hurricane Irene and Ophelia was the location of the track with respect to the ocean (onshore and offshore) and field site. The storm surge produced from Hurricane Ophelia (1 to 1.83 m above normal tide levels) inundated many portions of the coast, especially the western side of the Pamlico Sound including the lower reaches of the Neuse, Pamlico, and Newport Rivers (http://www.NHC.NOAA.gov) (Fig. 2-14). The increase in specific conductivity in the groundwater and surface water in the Reserve can be attributed to the storm surge produced in the Pamlico Sound by Ophelia.

The source of saltwater in the Pamlico and Albemarle Sounds are the inlets located on the Outer Banks. Oregon, Ocracoke, and Hatteras inlets connect the Pamlico Sound to the Atlantic Ocean, which allow interaction between water masses from the continental shelf and the estuaries. The Albemarle Sound is generally fresher than the Pamlico because it has no direct connection to the ocean. The storm surge produced from Hurricane Irene affected the sound side of the barrier islands and produced storm surges that ranged from 1.5 - 3.5 m above normal tide levels. Hurricane Ophelia was a slow moving hurricane that produced heavy localized precipitation, however only 30 mm of rainfall was recorded near the study area. The heavy precipitation (130 mm) produced from Hurricane Irene increased surface water runoff that potentially diluted saltwater emanating from the Alligator River. This may explain

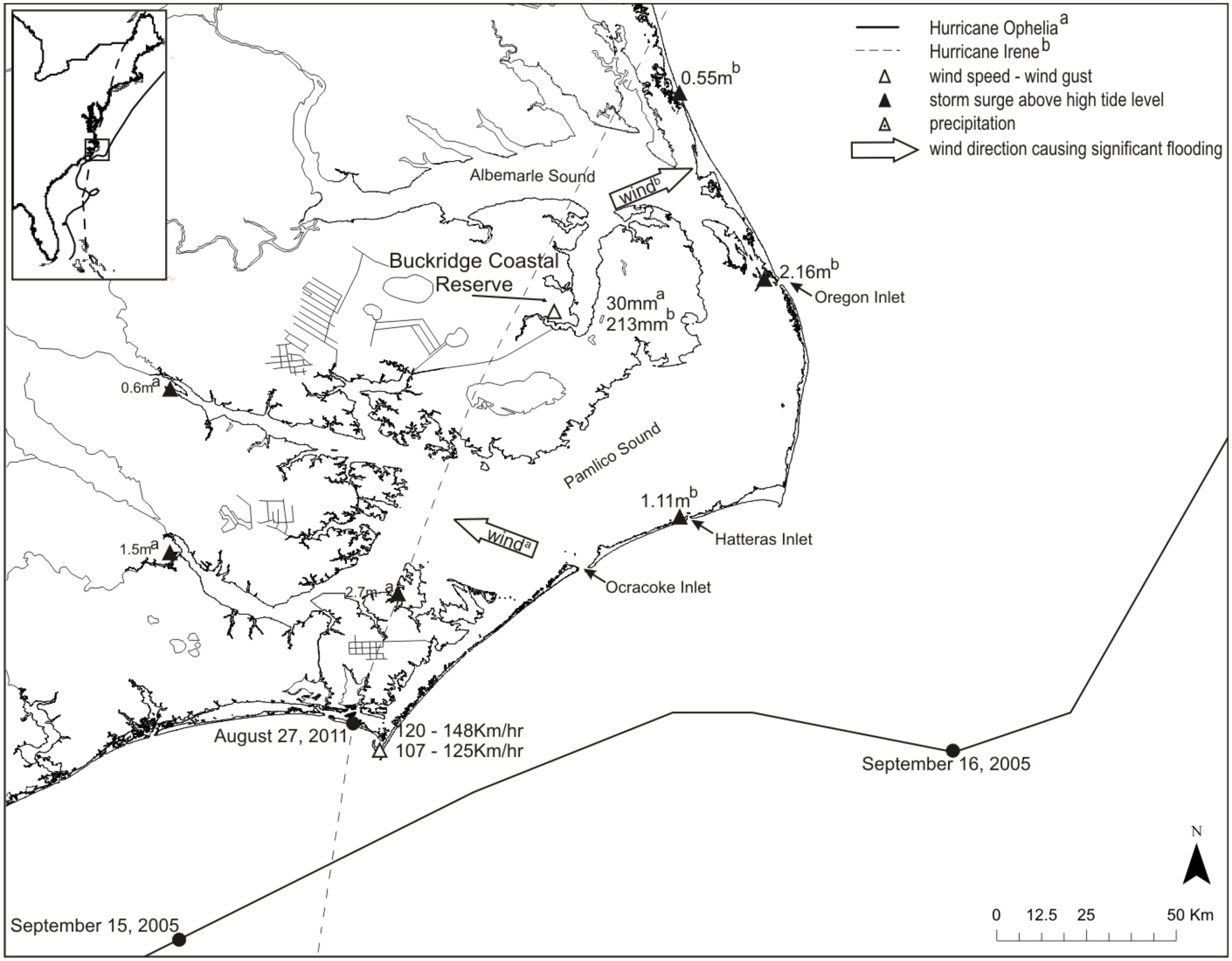

Figure 2-14: Tracks of Hurricanes Ophelia (2005) and Irene (2011), highest recorded observations for sustained wind speed, wind gusts, and storm surge above high tide level. Potential hurricane storm surge for category 1-5 hurricanes (Data collected from NHC.NOAA.gov).

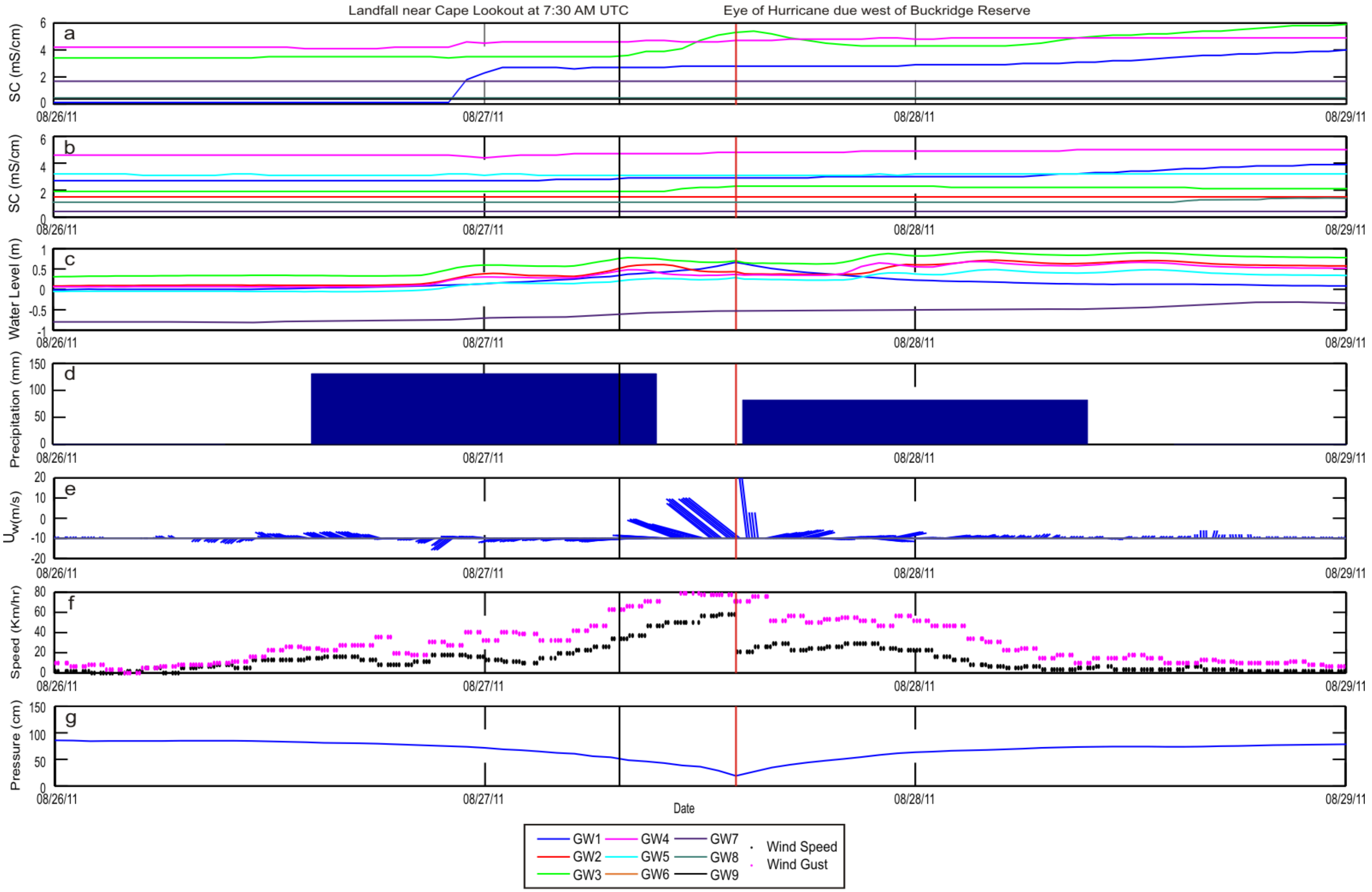

Figure 2-15: Groundwater conditions in GW1- GW9 during Hurricane Irene (August 26- 29, 2011) (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) elevation of water table, (d) precipitation from Gum Neck rainfall collection station, (e) wind direction from Fairfield weather station and, (f) wind speed and wind gusts, and (g) barometric pressure.

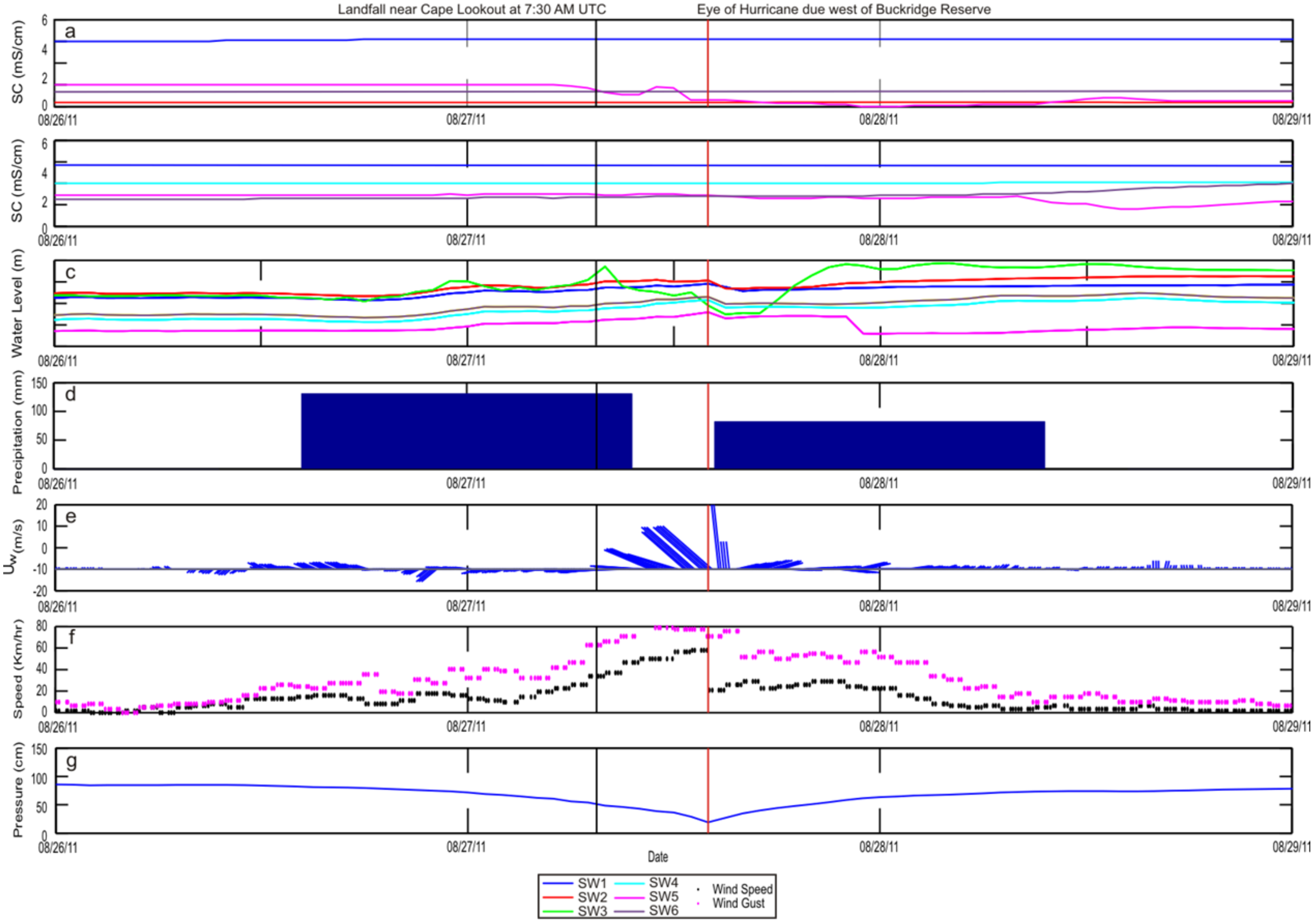

Figure 2-16: Surface water conditions in SW1- SW6 during Hurricane Irene (August 26- 29, 2011) (a) specific conductivity from shallow logger, (b) specific conductivity from deep logger, (c) elevation of water table, (d) precipitation from GumNeck rainfall collection station and, (e) wind direction from Fairfield weather station.

why the magnitude of saltwater intrusion differed from Hurricane Ophelia and Hurricane Irene.

Significance for water management strategies

This study has shown that saltwater intrusion is occurring in the surface water and shallow groundwater systems of the Reserve via wind tide events. The primary management strategy in the Reserve is to restore the natural water quality which will encourage mature and regenerating vegetation to persist (Fuss, 2001). Appropriate restoration and management strategies therefore need to address wind-driven saltwater intrusion. The installation of water control structures, such as tide gates can prevent the intrusion of saltwater from the Alligator River into the canal network.

Tide gates are culverts with moveable doors that control the flow of water by responding to a change in water levels (Giannico and Souder, 2004) by tides or flood events. The door of the tide gate opens when the upstream water levels are higher and the tide is going out and closes when the tide is rising, preventing inflow of saltwater. The direct source of saltwater in the Reserve is the Alligator River therefore, in concurrence with Madden (2005), a tide gate should be placed in the canal on Grapevine Landing Rd. However, the location of the tide gate in the canal should not interfere with local fishing boats and the drainage of adjacent agricultural land. Based on the results derived from this study, tide gates and saltwater intrusion management strategies should be focused on locations in the south of the Reserve. Tide gates should be constructed at the mouths of canals that are directly connected to the Alligator River, where the highest salinities were observed. Tide gates would reduce the potential of surface runoff, sediment, and nutrient transport and outflow rates of the canals. The installation of tide gates could create an environment favorable for nutrient loss that could potentially affect biota. The NC Department of Environment and Natural Resources have constructed tide gates in various locations to manage saltwater intrusion in the Reserve. The relative effects of the tide gates on the upstream and downstream water quality have not been assessed. The assessment of the tide gates and their effects on water quality provide opportunities for additional research. The installation of tide gates in the Reserve could potentially slow the inevitable inundation of the land from sea level rise.

Conclusions

Canals in Buckridge facilitate the movement of saline water into the interior of the Reserve. Specific conductivity levels observed in the canals during this study are significantly higher than specific conductivities observed by Madden (2005). Overall, the surface water system had higher specific conductivity levels than observed in the groundwater system. Wind tides, caused by southerly winds, affect the specific conductivity levels in the canals in the Reserve. The saline water persisted in the canals as long as the wind tide events occurred in short time scales. Overwash during wind tide events has been observed to affect the specific conductivity in the shallow groundwater along the Alligator River. The southern region of the Reserve had higher specific conductivities in the groundwater and surface water bodies than those in the north, suggesting the presence of a salinity gradient. Based on these results, it appears as though the source of the saltwater is to the south of the Reserve, perhaps the Alligator-Pungo canal which may be the conduit for saltwater transport from the Pamlico

Sound to the Alligator River under wind tide events. Future research should focus on monitoring specific conductivity levels in the Alligator-Pungo canal.

The effects of Hurricane Irene on salinity levels were unexpectedly minimal, compared to Hurricane Ophelia, which increased specific conductivities in the groundwater and surface water system. The difference in specific conductivity levels was attributed to variations in hurricane tracks, wind intensity, and precipitation totals. The installation of a tide gate and beaver dam at SW-B between SW4 and SW5 may have diminished the possibility of saltwater intrusion occurring inland during Hurricane Irene. Restoration and management plans should continue to focus on installing tide gates in the Reserve along canals that are open to the Alligator River in the south. To avoid disrupting fish and other biota additional studies are needed to determine the exact location of tide gates along the Alligator River.

CHAPTER 3: STORM SURGE PREDICTION MODEL WITH APPLICATION TO HURRICANE IRENE

Introduction

Historically, hurricane induced flooding risk is a common occurrence in coastal locations. The low relief, use of canals and drainage ditches combined with urban growth increases the risk for flooding in Eastern North Carolina. A storm surge is the rise in water level caused by the combination of wind and pressure from approaching hurricanes or other severe storms. The storm surge height is dependent on multiple factors including pressure, wind velocity, speed of storm, bathymetry, and tidal level along the coastline. The level of inundation is not uniform along the coastline due to the physical structure of the storm and the topographic irregularities. Storm surges are often predicted using hurricane parameters in spatially distributed Geographic Information System (GIS) models. A constant surge height model provides implications of sea level rise and storm induced flooding that can present insight on restoration and management strategies.

Methodology

To assess the level of storm inundation in the Reserve, a hydrologically connected bathtub model (Fig. 3-1) was produced using light detection and ranging (LIDAR) data in ESRI's *ArcGIS* 10. This storm surge model is based on a constant surge height that does not account for the characteristics of the storm or coastline topography. The surge model was run with inundation levels of 0.15 m (0.5 ft), 0.30 m (1 ft), 0.91 m (3 ft). The inundation levels were chosen to simulate wind driven tides, weak and strong storms. A digital elevation model (DEM) (Fig.3-2) of Tyrrell County (http://www.NCONEMAP.com) (with a cell resolution of 15.2 meter (50 foot) and a vertical accuracy of 25 cm (10 inches) and a raster file representing the water source was used to run the model.

The water source was created by masking the DEM by assigning the land a zero value and the water a value of one. The DEM and water source was then reclassified. The cost distance function was used to calculate the effective distance, a measure for the least distance modified with the cost to move between ground surface elevations. The DEM was reclassified on a scale of zero to one to show areas of inundation. Pixels were assigned a zero if they represented elevations below the level of inundation and a one was assigned to pixels that were higher than the designated surge height. The raster output of the cost distance function was reclassified to show the areas of inundation. The National Hurricane Center predicted a maximum storm surge for the Southern Albemarle Estuarine System to be less than 0.5 meters during Hurricane Irene The 0.3-meter inundation map was compared to water level data collected during Hurricane Irene.

Storm surge was calculated using the maximum water level before the storm passed west of the Reserve. For the groundwater wells, the surge was referenced to the ground surface elevation and the surface water was referenced to canal baseflow. The storm surge is referred to the maximum height of the water level and the difference in height (Δh) is the storm surge produced from the Hurricane. Refer to Tables 2-2 and 2-3 for well specifications and Tables 3-1 and 3-2 for surge heights.

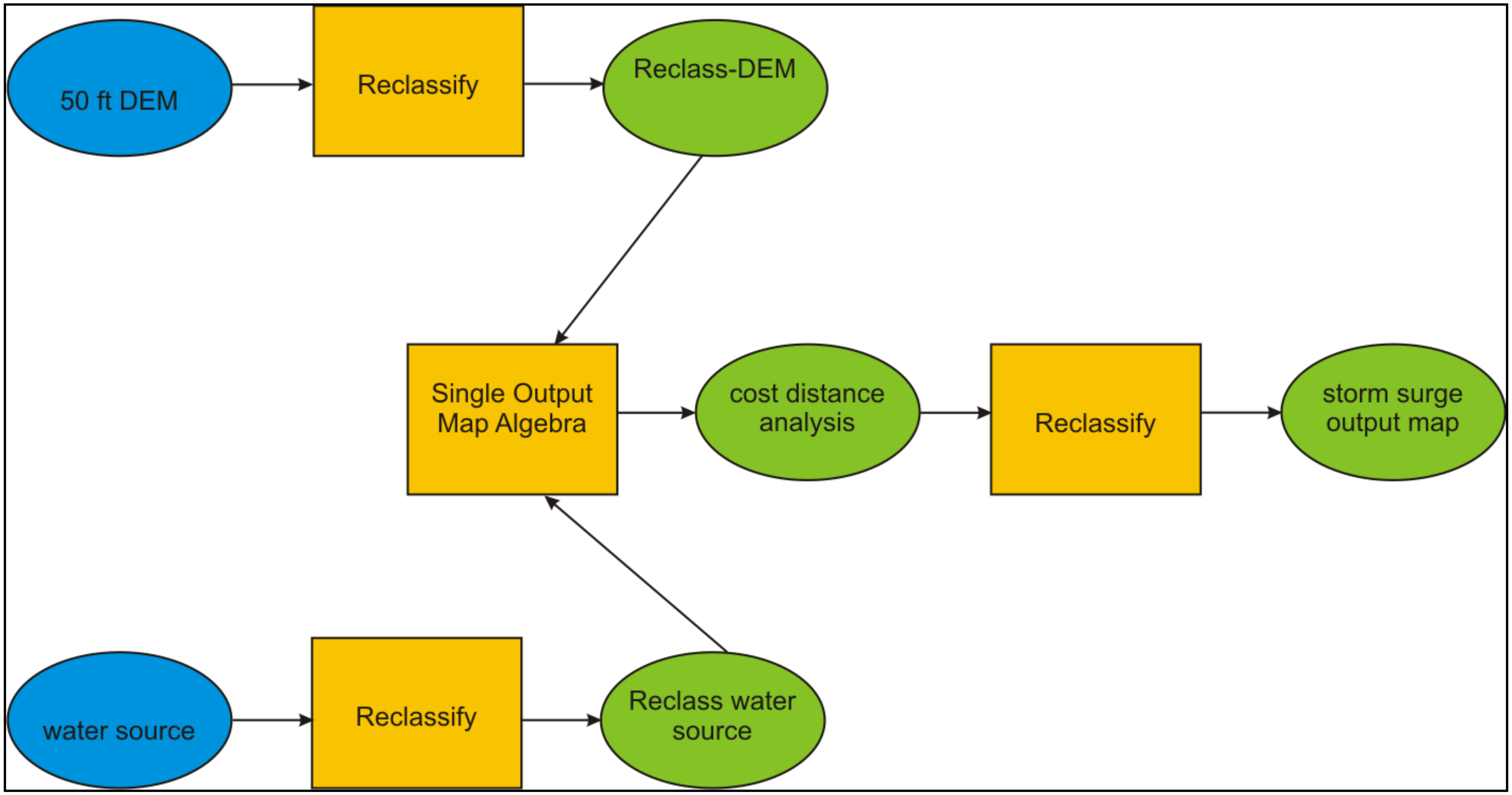

Figure 3-1: Storm surge inundation model created in ArcMap.

Results

The model was run to calculate the level of inundation along the Alligator River, in Buckridge Reserve, for different storm surge heights. The Reserve would experience inundation for a 0.15 m (0.5 ft), 0.30 m (1 ft), and 0.91 m (3 ft) surge (Fig. 3-3). The predicted inundation for the Reserve during a 0.15 m (0.5 ft) storm surge is located along the coastline and west of Buckridge Road (Fig. 3-4). The model predicted a rise in water levels in observation wells GW3 and GW5. This level of inundation can occur with prevailing southerly wind or in occurrence with heavy precipitation. Most of the Reserve is at sea level or about 0.3 meters above mean sea level (MSL); therefore a weak hurricane or storm system can completely inundate the entire area. Figure 3-5 illustrates the level of inundation for a 0.3-meter (1 ft) storm surge. The 0.3-meter (1 ft) storm surge output predicted inundation at every observation well.

Surge model with application to Hurricane Irene

Storm surges produced from Hurricane Irene (Figs. 3-6, 3-7 and Table 3-1) exceeded the 0.3 meter model (Fig. 3-5) in the coastal groundwater wells and SW-A. The observed storm surge in the Reserve ranged from 0.15 m to 0.73 m. The northern part of the Reserve had the highest observed storm surge produced from Hurricane Irene. The inundation level in the coastal groundwater wells did not exceed 0.5 m above the ground surface. Observation well GW3 had the highest observed storm surge at 0.49 m (Fig. 3-5). The groundwater wells in the south, GW4 and GW5, had the lowest observed inundation (Table 3-1, Fig. 3-1 and Fig. 3-7).

Observation wells SW-B (Fig. 2-4b) had a higher observed storm surge than SW-A (Fig. 2-4c). An observed storm surge of 0.71 m at SW3 (Fig. 3-5), peaked when the

Hurricane made landfall (Table 3-2). The decrease in barometric pressure by the approaching storm corresponded to a decrease in water levels in the Alligator River. Once the Hurricane passed west of the Reserve the water levels quickly increased and crested at 0.73 meters at SW3 (Fig.3-8). The canals had a delayed response in water levels in comparison to the Alligator River and later peaked when the Hurricane was passing west of the Reserve. Surge heights in SW1 (0.33 m) and SW2 (0.34 m) did not exceed the Alligator River (Fig.3-8). The storm surge observed in observation wells SW-B were about 0.1 m higher than SW-A.

Well ID	Ground surface (m)	Storm surge (m)	Δh (m)
GW1	0.41	0.66	0.25
GW2	0.16	0.61	0.45
GW3	0.29	0.78	0.49
GW4	0.26	0.48	0.22
GW5	0.14	0.29	0.15
GW7	0.27	-	-

Table 3-1: Summary of Hurricane Irene storm surge and storm surge above ground level (Δh) in groundwater observation wells.

Well ID	Base level (m)	Storm surge (m)	Δh (m)
SW1	0.13	0.45	0.33
SW2	0.20	0.54	0.34
SW3	0.13	0.85	0.73
SW4	-0.64	-0.21	0.43
SW5	-0.39	0.07	0.46
SW6	-0.30	0.15	0.45

Table 3-2: Summary of Hurricane Irene storm surge and change in water level height (Δh) in surface water observation wells.

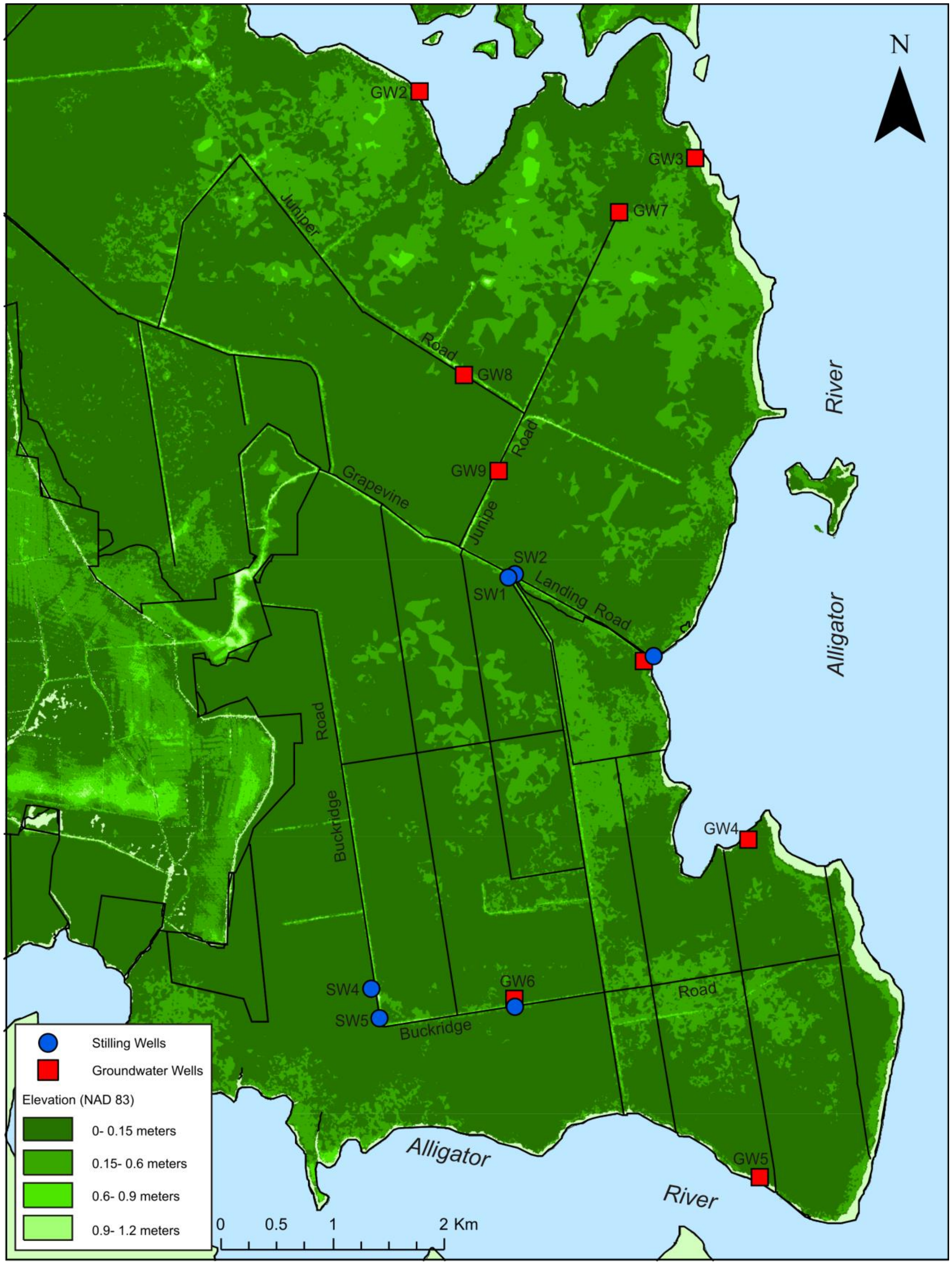

Figure 3-2: Digital elevation model (DEM) of Emily and Richardson Preyer Buckridge Coastal Reserve (obtained and from http://www.NCONEMAP.com) and location of observation wells.

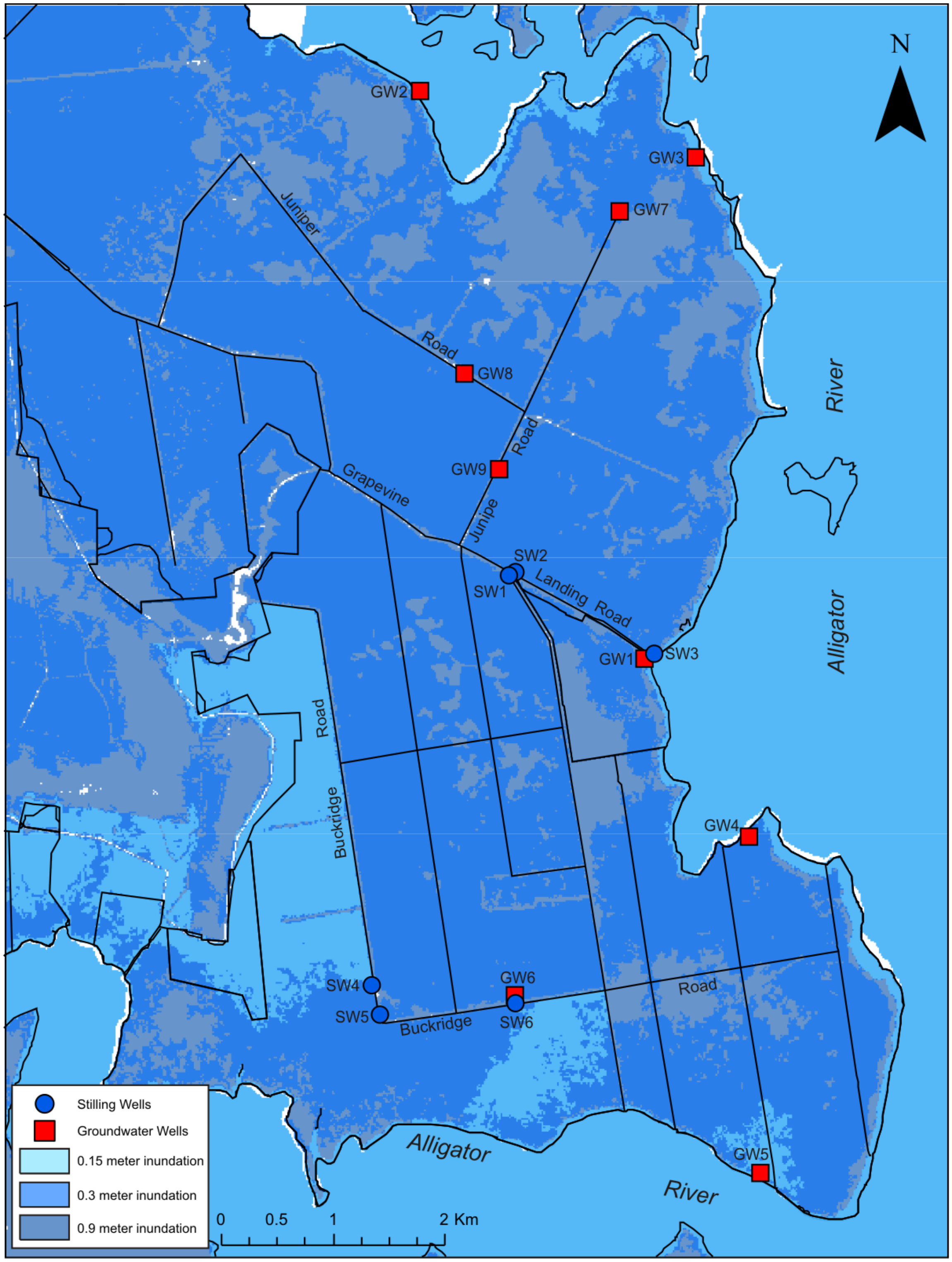

Figure 3-3: Output map for 0.15 m, 0.3 m, and 0.9 m storm surge inundation in the Emily and Richardson Preyer Buckridge Coastal Reserve.

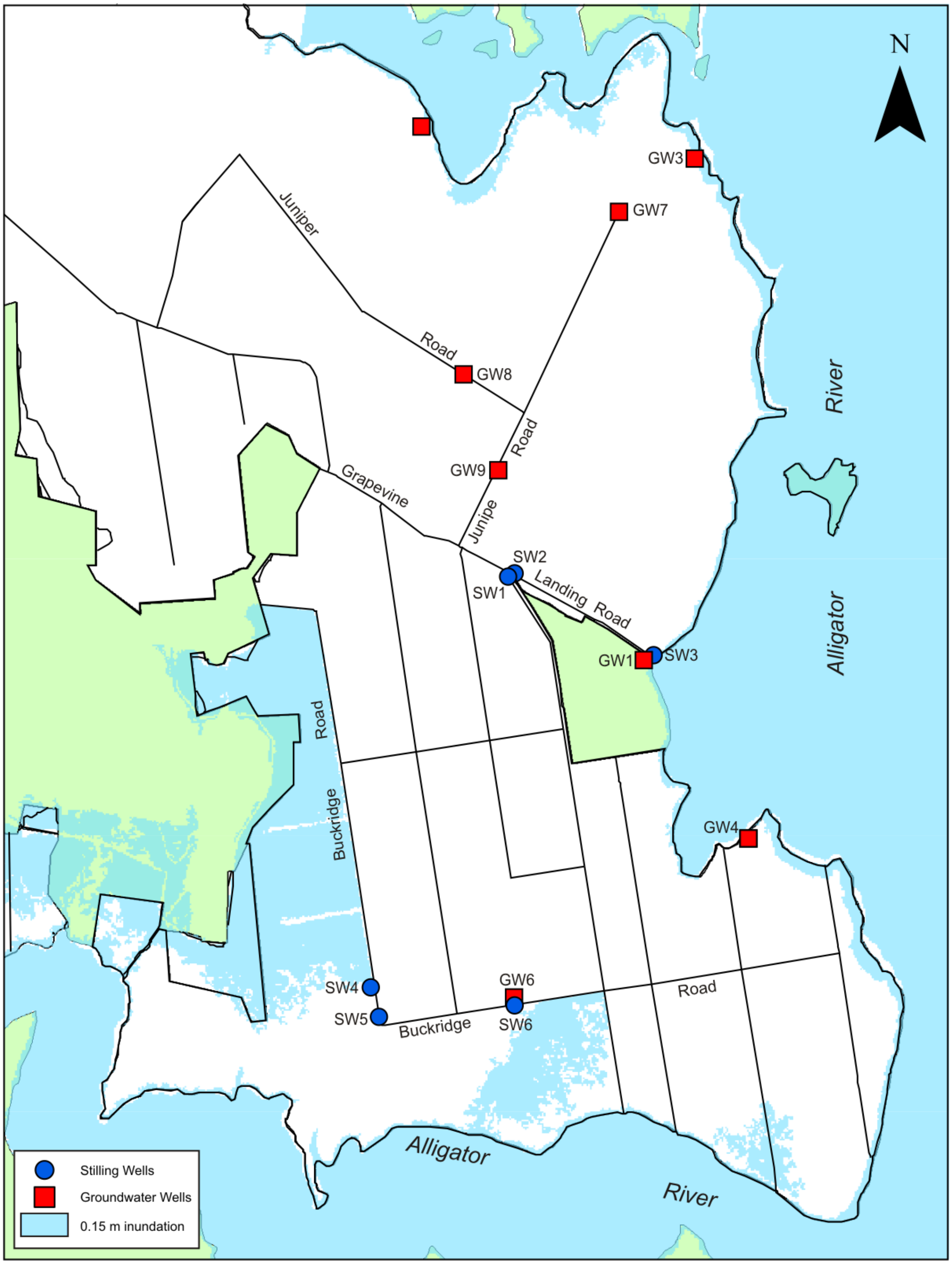

Figure 3-4: Output map for 0.15 m storm surge inundation in the Emily and Richardson Preyer Buckridge Coastal Reserve.

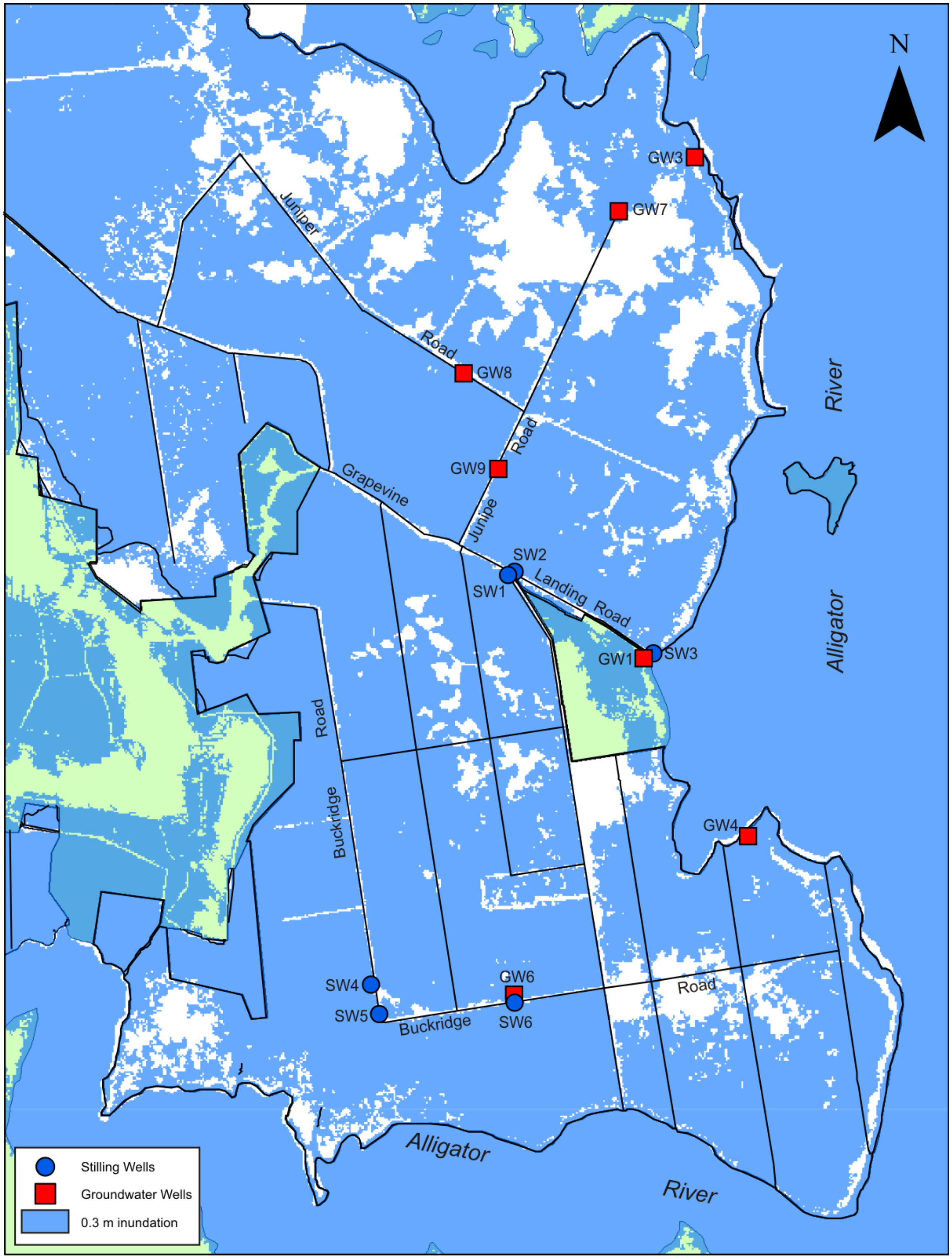

Figure 3-5: Output map for 0.3 m storm surge inundation in the Emily and Richardson Preyer Buckridge Coastal Reserve.

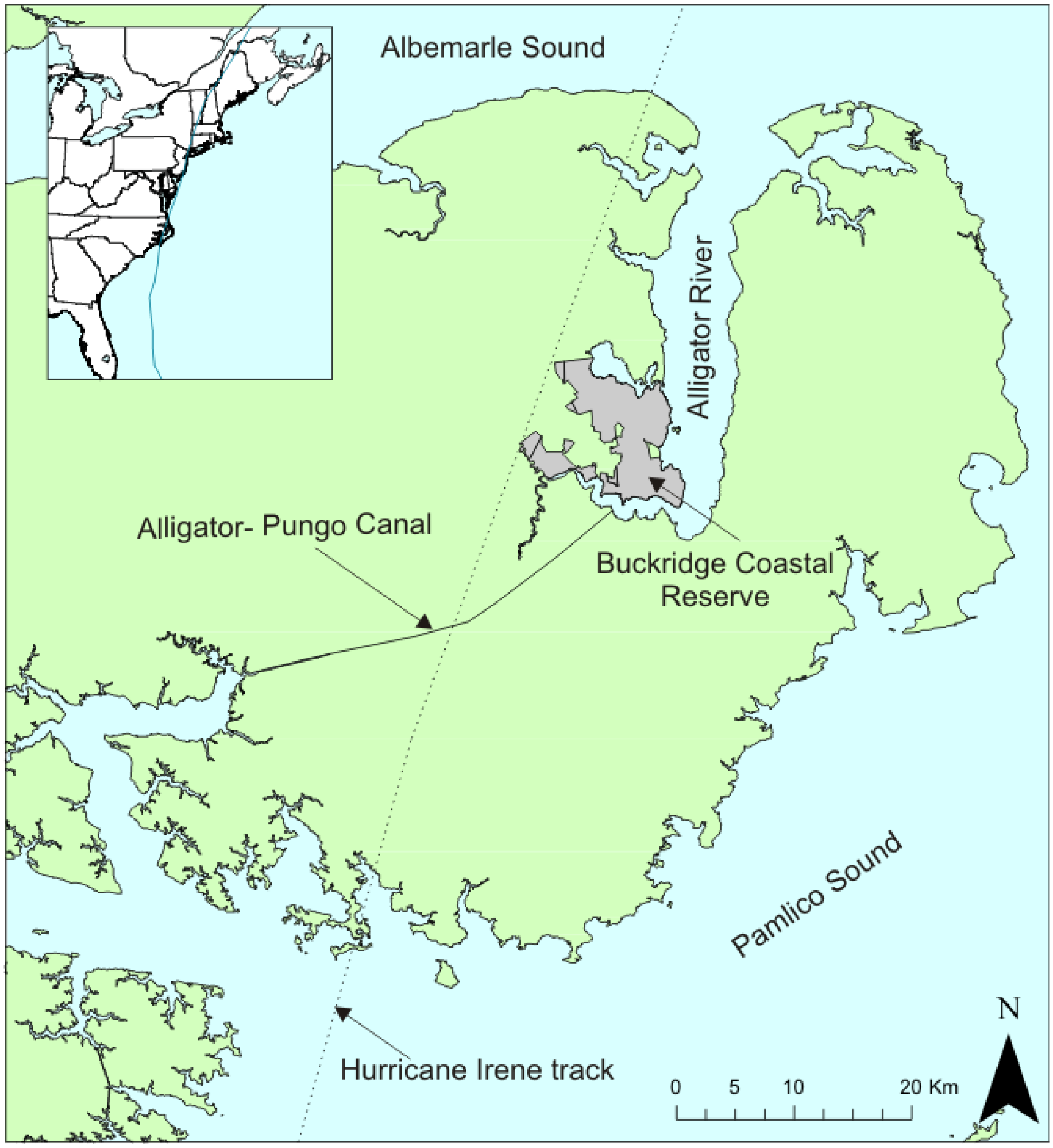

Figure 3-6: Hurricane Irene track.

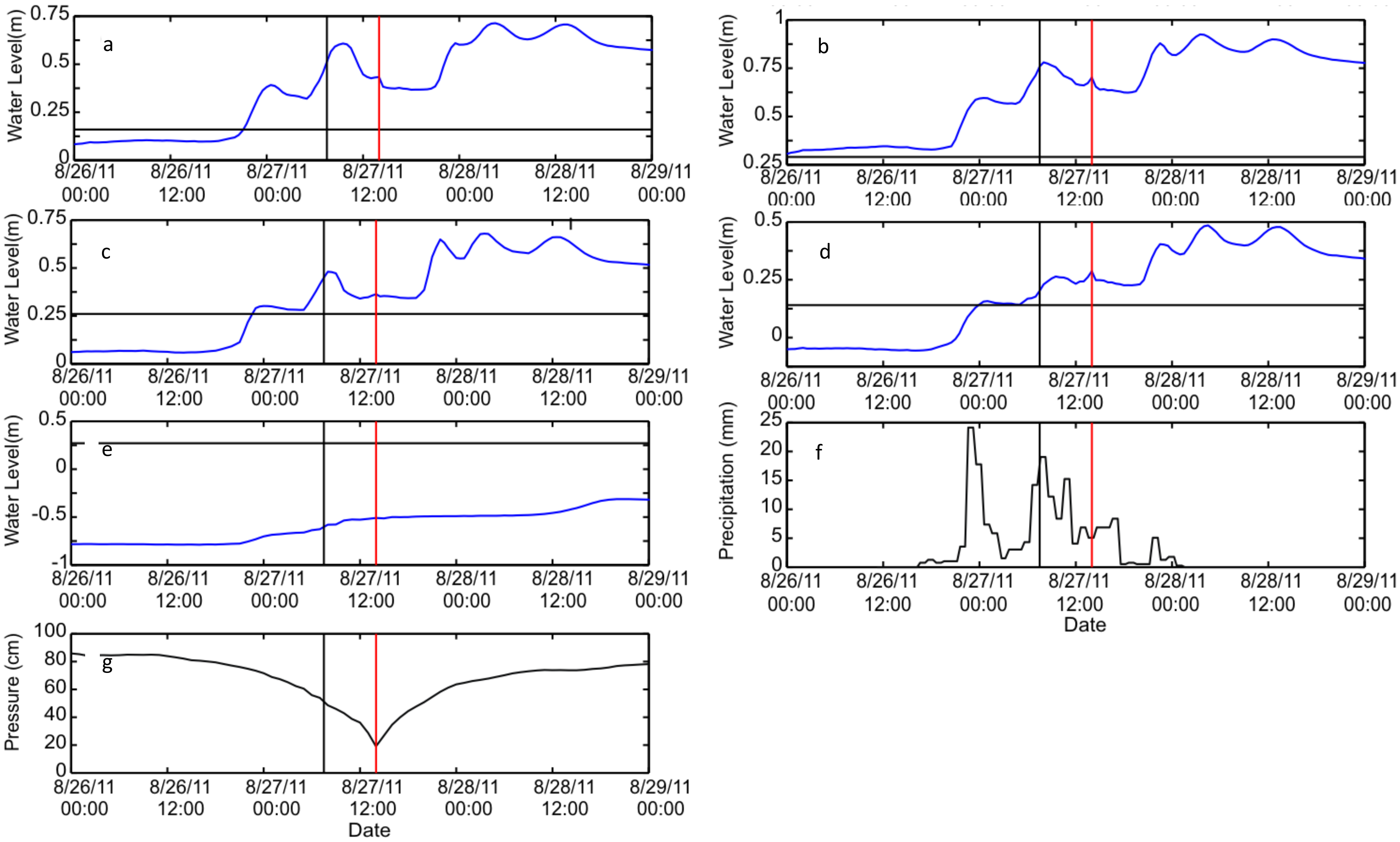

Figure 3-7: Time series of groundwater water levels in monitoring wells: (a) GW2, (b) GW3, (c) GW4, (d) GW5 and, (e) GW7. Water level elevation was compared to (f) hourly precipitation and (g) barometric pressure. The graphs show inundation of the land surface associated with precipitation and decrease in barometric pressure from the approaching Hurricane.

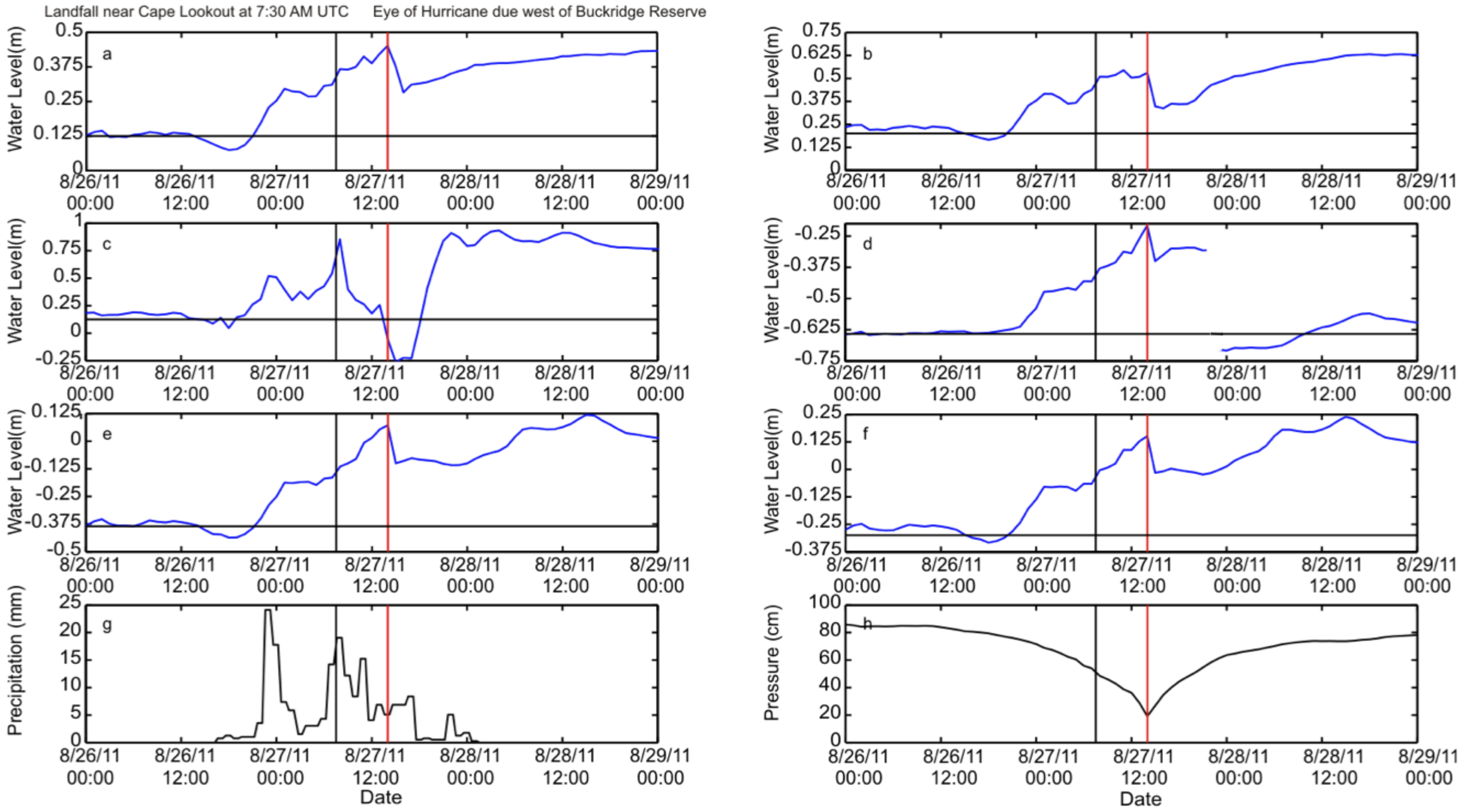

Figure 3-8: Time series surface water levels in monitoring wells: (a) SW1, (b) SW2, (c) SW3, (d) SW4, (e) SW5 and, (f) SW6. Surface water level elevation was compared to (g) hourly precipitation and (h) barometric pressure. The peak storm surge in the canals occurred when the eye of the Hurricane was passing the Reserve.

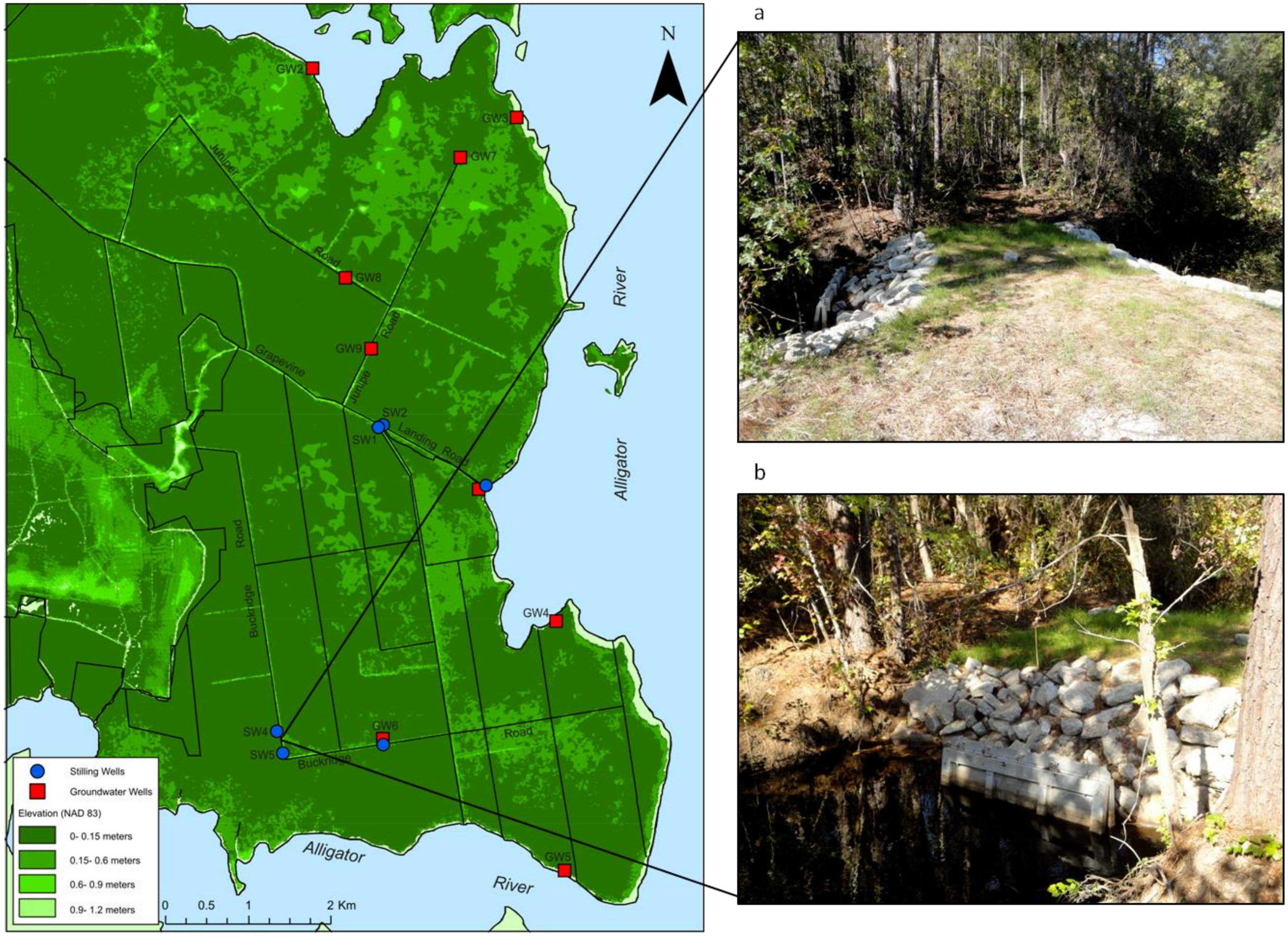

Figure 3-9: Location of tide gate on Buckridge Road (a) side view of tide gate, upstream to the left and downstream to the right; and (b) front view of tide gate on the upstream side.

CHAPTER 4: SUMMARY OF FINDINGS AND APPLICATION TO COASTAL ZONE MANAGEMENT

Implications of results on sea level rise

Global climate change is causing sea levels to rise and increasing storm intensity and frequency. The predicted relative sea level (RSL) rise in coastal North Carolina is 3.3 mm/yr whereas the global average ranges from 0.18 meters to 0.59 meters (IPCC, 2007). The RSL rise near the Reserve could reach over 75 cm by 2100 (Madden, 2005). If the rate of sea level rise increases, the vertical accretion of peat would not be able to prevent submergence of wetlands in the Reserve. The combination of sea level rise and increased storm frequency has caused North Carolina wetlands to currently erode at a rate of about 800 acres per year (Moorhead and Brinson, 1995). If sea level rises by 1.5 m, then much of coastal North Carolina will be inundated and salinized considering most of the land is less than 1.5 meters in elevation (Fig. 3-3).

The decomposition of peat soils and slow accretion rates in the region result in subsidence of the land surface which would encourage flooding and saltwater intrusion. Increased rates of flooding and saltwater intrusion result in plant mortality inland. The resulting conditions would be unsuitable for intolerable terrestrial plant species (Michener, 1997; Moorhead and Brinson, 1995) and may accelerate the conversion of freshwater marshes into brackish or saline marsh types (Baldwin and Mendelssohn, 1998). Restoration and management efforts must consider the projected sea level rise and potential loss of the coastal peatland.

Future Studies

This study provides baseline data on water quantity and water quality in the Reserve. The data provide the opportunity for additional monitoring and research. An additional year of water quality data is necessary to understand seasonal variations on a year-to-year basis. Using similar groundwater and surface water monitoring methods, the effects of roads and freestanding ditches on water quality should be explored in detail. There is an opportunity to understand the effects of wind tides and determine the flow patterns of the canals. The salinity of in the Alligator River and the Alligator-Pungo Canal should be investigated to determine the fate and transport of saltwater in the southern part of the Reserve. The close proximity of the adjacent agriculture lands could provide the opportunity to explore the nutrients in drainage waters and the effects they have on the fish and wildlife.

The installation of the tide gates will provide insight on water quality changes upstream and downstream of the water control structures over time. Restoration and management efforts should consider the effects of the tide gates in the Reserve before installing additional structures.

Conclusions

This study is an assessment of quality and quantity of the groundwater and surface water systems in the Reserve. From October 1, 2010 to October 31, 2011, water level, specific conductivity, and temperature data from a monitoring network of groundwater wells and stilling wells were collected and analyzed. The spatial and temporal variations and distribution of specific conductivity in the surface and groundwater systems were assessed. This variation and distribution of specific conductivity in the canals was compared to wind tides that occurred in the Alligator River. The specific conductivity was observed to be elevated in the southern part of the Reserve, whereas the northern portion remained relatively low. Elevated specific conductivity levels in the surface and groundwater system suggest saltwater is originating from the south of the Reserve. Saltwater intrusion in to the canal system was also linked to southerly wind tides generated in the Alligator River. Storm surge models of the Reserve predict a complete inundation of the Reserve; with a 1-foot rise in water levels; however, the observed inundation of Hurricane Irene was less. Hurricane Irene (2011) compared to Hurricane Ophelia (2005) provided insight on how the characteristics of storms affect saltwater intrusion. The Emily and Richardson Preyer Buckridge Coastal Reserve provides many opportunities to explore the coastal peatland system in Eastern North Carolina and the anthropogenic effects of saltwater intrusion.

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