ESTIMATING SALINITY INTRUSION EFFECTS DUE TO CLIMATE CHANGE ALONG THE GRAND STRAND OF THE SOUTH CAROLINA COAST

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Abstract: The ability of water-resource managers to adapt to future climatic change is especially challenging in coastal regions of the world. The East Coast of the United States falls into this category given the high number of people living along the Atlantic seaboard and the added strain on resources as populations continue to increase, particularly in the Southeast. Increased temperatures, changes in regional precipitation regimes, and potential increased sea level would have a great impact on existing hydrological systems in the region.

Six reservoirs in North Carolina discharge into the Pee Dee River, which flows 160 miles through South Carolina to the coastal communities near Myrtle Beach, SC. During the Southeast's record-breaking drought from 1998 to 2002, salinity intrusions inundated a coastal municipal freshwater intake, limiting water supplies. Salinity intrusion results from the interaction of three principal forces - streamflow, mean tidal water levels, and tidal range. To analyze, model, and simulate hydrodynamic behaviors at critical coastal streamgages along the Atlantic Intracoastal Waterway (AIW) near Myrtle Beach, SC, data-mining techniques were applied to over 20 years of hourly streamflow, coastal water-quality, and water-level data. Artificial neural network (ANN) models were trained to learn the variable interactions that cause salinity intrusions. Streamflow from the 12,700 square-mile Pee Dee River Basin that flows into the AIW are input to the model as time-delayed variables and accumulated tributary inflows. Tidal inputs to the models were obtained by decomposing tidal water-level data into a "periodic" signal of tidal range and a "chaotic" signal of mean water levels. The ANN models were able to convincingly reproduce historical behaviors and generate alternative scenarios of interest.

To evaluate the impact of climate change on salinity intrusion, inputs of streamflows and mean tidal water levels were modified to incorporate estimated changes in precipitation patterns and sea-level rise appropriate for the Southeastern United States. Changes in mean tidal water levels were changed parametrically for various sea-level rise conditions. Preliminary model results at the U.S. Geological Survey Pawleys Island streamgage (station 02110125) near a municipal freshwater intake indicate that a sea-level rise of 1 foot (ft, 30.5 centimeters [cm]) would double the frequency of water with a specific conductance value of 2,000 microsiemens per centimeter close to 4 percent. A 2 ft (61 cm) sea-level rise would quadruple the frequency to 9 percent.

INTRODUCTION

The Pee Dee River Basin, with approximately 12,700 square miles of drainage area in eastern North and South Carolina, supplies freshwater along the South Carolina coast from Little River Inlet to the north and Winyah Bay to the south (U.S. Geological Survey, 1986) (fig. 1). Six reservoirs in North Carolina discharge into the Pee Dee River, which flows 160 miles through South Carolina to the coastal communities near Myrtle Beach. During the drought between 1998 and 2002, salinity intrusion forced a municipal intake near the U.S. Geological Survey (USGS) Pawleys Island streamgage (station 021108125, fig. 1) to close until increased streamflow moved the freshwater-saltwater interface downstream from the intake.

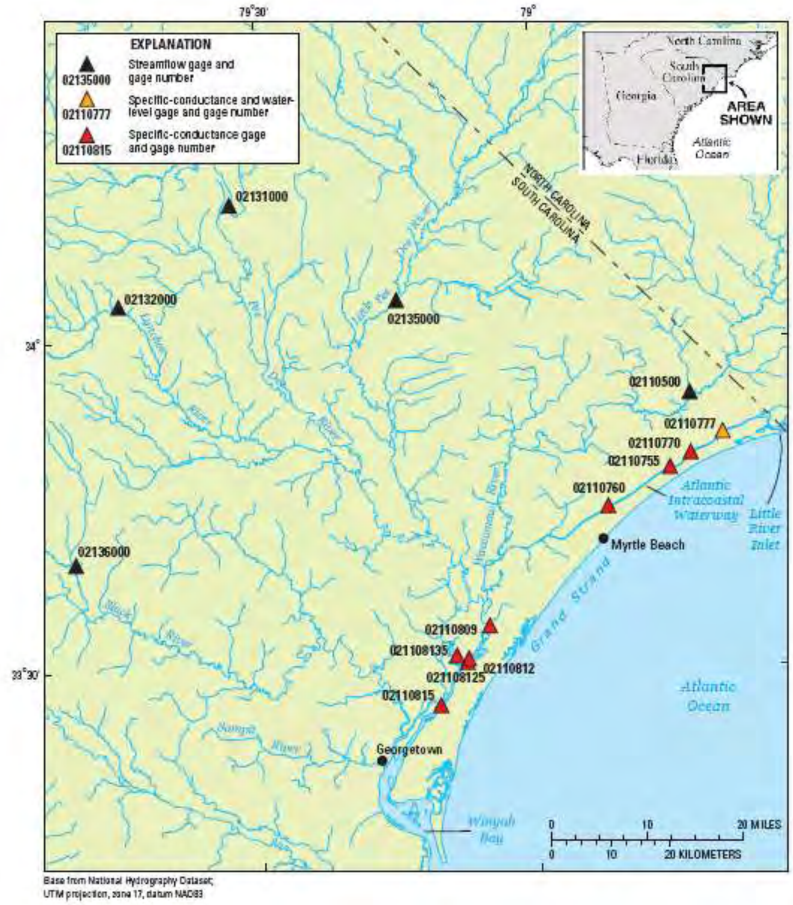

Figure 1. Study area including the Pee Dee and Waccamaw River Basins and Atlantic Intracoastal Waterway in South Carolina.

The balance between hydrological flow conditions within a coastal drainage basin and sea level governs the characteristics and frequency of salinity intrusion into coastal rivers. Saltwater intrusion into freshwater coastal rivers and aquifers has been, and continues to be, one of the most important global challenges for coastal water-resource managers, industries, and agriculture (Bear and others, 1999). Some of the major economic and environmental consequences of saltwater intrusion into freshwater aquifers and drainage basins include the degradation of natural ecosystems and the contamination of municipal, industrial, and agricultural water supplies (Bear and others, 1999). In the case of Myrtle Beach, increases in the frequency and magnitude of salinity intrusion into the Atlantic Intracoastal Waterway (AIW) and Waccamaw River could threaten the potability of two freshwater municipal intakes as well as the biodiversity of freshwater tidal marshes.

APPROACH

A previously developed model of the Pee Dee River Basin (Conrads and Roehl, 2007), was used to evaluate the potential effects of climate change on salinity intrusion. The simulation models of the Waccamaw River and the AIW (lower portion of the Pee Dee River watershed) is known as the "**P**ee Dee **R**iver and Atlantic **I**ntracoastal Waterway **S**alinity **M**odel" or PRISM. The model was developed using data-mining techniques, including artificial neural network (ANN) models to evaluate salinity impacts due to controlled reservoir releases from hydroelectric facilities as part of the Federal Energy Regulatory Commission (FERC) re-licensing of six reservoirs in North Carolina.

Results from previously developed ANN-based models of estuaries in Georgia and South Carolina (Roehl and others, 2000; Conrads and others, 2003; Conrads and others, 2006) have shown that ANN models, combined with data-mining techniques, are an effective approach for simulating complex estuarine systems. An ANN model is a flexible mathematical structure capable of describing complex nonlinear relations between input and output datasets. The architecture of ANN models is loosely based on the biological nervous system (Hinton, 1992). Although there are numerous types of ANNs, the most commonly used type of ANN is the multi-layer perceptron (MLP) (Rosenblatt, 1958). The type of ANN used was the multi-layered perceptron (MLP) described by Jensen (1994), which is a multivariate, non-linear regression method based on machine learning.

Data Sets and Data Preparation: The USGS maintains a real-time streamgaging network of water-level and specific conductance (field reading to compute salinity) recorders in the Pee Dee and Waccamaw River Basins (fig. 1). For the streamflow stations, there is greater than 50 years of record at the majority of the stations. For the coastal water-quality stations, there are greater than 15 years of water-level and specific conductance data. Data from the Grand Strand network are a valuable resource for addressing the critical conditions for salinity encroachment on the Pee Dee and Waccamaw Rivers. During the past 15 years of data collection, the estuarine system has experienced various extreme conditions including large 24-hour rainfalls, the passing of major offshore hurricanes and other tropical systems, and drought conditions.

The development of the ANN models used a subset of the USGS data including nine coastal gaging stations that provided water-level and specific conductance data and five upland gaging stations that provided streamflow data. The data spanned 17½ years, but not all of the gaging stations were operating concurrently. The database for the study was augmented with rainfall data from six regional meteorological stations, and coastal wind speed and direction data from one additional meteorological station. The resulting database comprises 17½ years of hourly data (150,000+ time stamps) for 27 measured environmental variables.

Tidal systems are dynamic and exhibit complex behaviors that evolve over multiple time scales. The hydrodynamic and water-quality behaviors observed in estuaries are superpositions of behaviors forced by periodic planetary motions and chaotic meteorological disturbances. The primary chaotic inputs to this system are the flows and the chaotic oceanic disturbances represented in the chaotic component of water level in Little River Inlet and Winyah Bay. The primary periodic input to the system is the tide.

Signals were decomposed into periodic and chaotic components using filtering techniques. To filter the semi-diurnal tidal signal, nested 13- and 25-hour moving window averages were applied to the water-level and specific conductance time series. The resulting time series represents the daily change in the tidal signal for water level and specific conductance on a 60-minute time increment. Tidal dynamics are a dominant force for estuarine systems, and tidal range is an important variable for determining the lunar phase of the tide. Tidal range is calculated from water level and is defined as the water level at high tide minus the water level at low tide for each semi-diurnal tidal cycle. As shown in figure 2, the measured water level at Little River Inlet (station 02110777, fig. 2A) was decomposed into its periodic signal of tidal range time series (fig. 2B) and its chaotic signal of mean water level time series (fig. 2C).

Historically, streamflow in the Pee Dee River varies between 700 and 215,000 cubic feet per second (ft^3/s) (Cooney and others, 2003). Salinity in the lower Pee Dee River is constantly responding to changing streamflow and tidal conditions. Figure 3A shows the daily mean specific conductance values for the USGS Hagley Landing gaging station (station 02110815, fig. 1) and daily mean streamflow for Pee Dee River at Pee Dee (station 02131000, fig. 1) for the 1983 to 2003 water years[1]. The period includes a full range of flows for the system from high flows of the El Niño in 1998 and 2003 (approximately, 43,000 and 98,000 ft^3/s, respectively) to

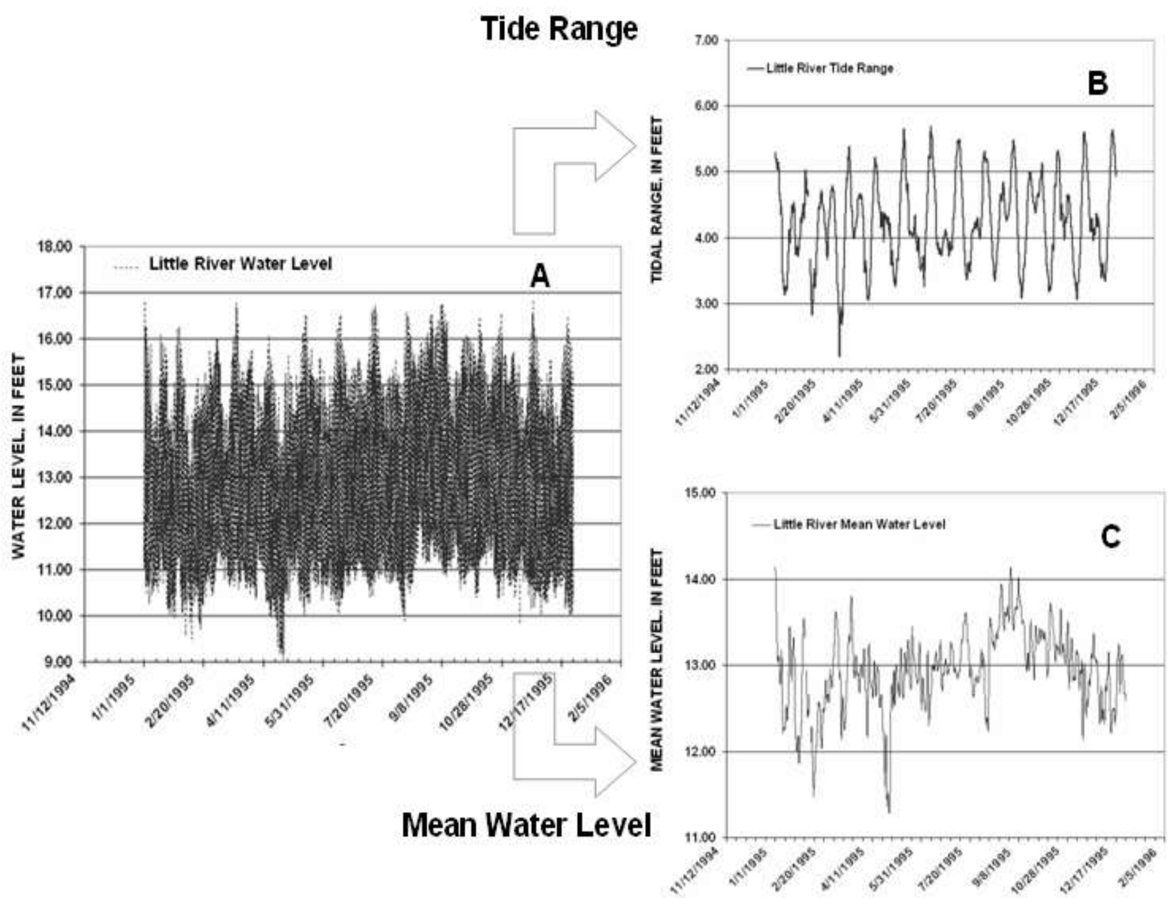

Figure 2. Little River Inlet tidal water-level signal (A), decomposition into a periodic signal of tide range (B), and a chaotic signal of mean water level (C).

[1] Water year is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends.

the low flows of the extended drought in the Southeast from 1998 to 2002 (fig. 3B).

During periods of medium and high flows (streamflow greater than 7,000 ft^3/s), the specific conductance values are low at Hagley Landing. During periods of low flow (streamflow less than 3,000 ft^3/s), values of specific conductance increase. During the low-flow period prior to the high-flow El Niño of 1998, salinity intrusion with specific conductance values ranging from 10,000 to 15,000 microsiemens per centimeter (µS/cm) were not uncommon. After the high flow of 1998 and during the extended drought, flows were even lower and remained lower for extended periods, which resulted in greater salinity at Hagley Landing with daily mean specific conductance values greater than 15,000 µS/cm.

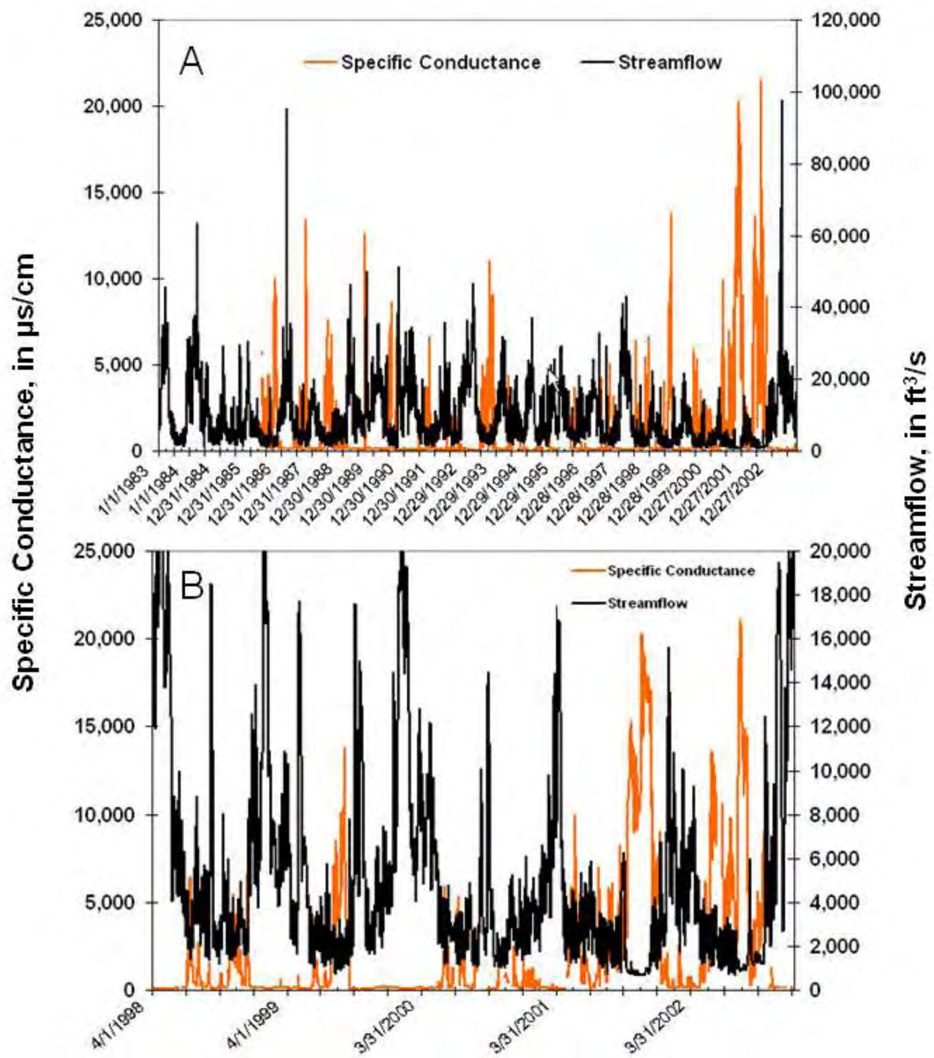

Figure 3. Graphs showing Pee Dee River flow (station 02131000) and specific conductance response at Hagley Landing (station 02110815) for the period 1983 to 2003 (A) and April 1998 to December 2002 (B).

Simulation of Salinity Intrusion: Similar to the approach taken in the Beaufort River (Conrads and others, 2003) and the Lower Savannah River (Conrads and others, 2006) estuary studies, subdividing a complex modeling problem into sub-problems and then addressing each one is a means to achieving the best possible result. For the Pee Dee study, individual ANN models for predicting specific conductance were developed for nine continuous coastal streamgages. The models were developed in two stages. The first stage modeled the chaotic, lower-frequency portion of the signal, as represented by the filtered specific conductance signals. The second stage modeled the periodic, higher-frequency, hourly specific conductance, using the predicted specific conductance as a carrier signal. Each model uses three general types of signals, or time series: streamflow signal(s), water-level signal(s), and tide-range signal(s). The signals may be of the measured series values, filtered values, and/or a time derivative of the signals. Most of the datasets that were used to develop the models were randomly bifurcated into training and testing datasets. Some datasets were too small to provide data for testing, but were fitted conservatively. All ANN models were carefully evaluated to ensure the models did not "overfit" the data.

A daily and an hourly model were developed for each of the nine streams. Generally, the daily models had coefficients of determination (R^2) values ranging from 0.62 to 0.96. The hourly models had R^2 values ranging from 0.69 to 0.92. An example of the measured and predicted daily and hourly specific conductance response models are shown in figure 4. The daily model is able to simulate the sharp specific conductance spikes (fig. 4A) and the hourly model is able to simulate the high-frequency specific conductance response (fig. 4B).

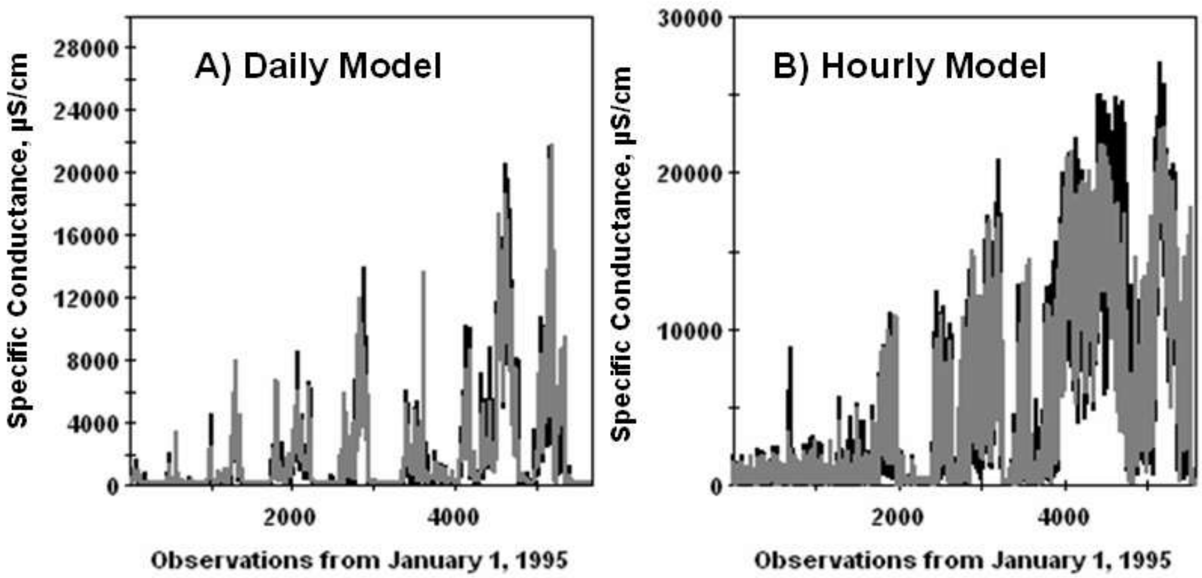

Figure 4. Graphs showing measured (black trace) and predicted (gray trace) specific conductance for Hagley Landing (station 02110815). Results for the daily model are shown on the left (A) and the hourly model on the right (B).

Simulation of Sea Level Rise: To simulate the effects of sea-level rise, the chaotic input of mean coastal water levels was parametrically incremented by 0.2, 0.5, 1.0, and 2.0 ft. It was assumed that sea-level rise would not affect tidal ranges of the ocean and those values were not changed. Daily specific conductance values were simulated for the nine coastal streamgages (fig.1) for each incremental rise in sea level from the period July 1995 through December 2002.

MODEL RESULTS AND DISCUSSION

The Pawleys Island streamgage (station 021108125), just downstream from a municipal freshwater intake, was selected for analysis and discussion for this paper. The daily model performance is shown in figure 5A. The coefficient of determination for the daily model is 0.90 and the root mean square error is 499 µS/cm. The model satisfactorily simulates the specific conductance in the 2,000 µS/cm range and accurately simulates the high intrusion event in August 2002 that exceeded 12,000 µS/cm. The cumulative frequency distribution of the measured and simulated specific conductance values at the Pawleys Island streamgage is shown in figure 5B. The frequency of the cumulative occurrence of measured and simulated specific conductance values is similar below 250 µS/cm and above 1,500 µS/cm.

It is problematic for the operations of municipal water treatment plants when the specific conductance values for source water are greater than 1,000 to 2,000 µS/cm. Of greater concern than the magnitude of salinity intrusion events is the frequency and duration of higher

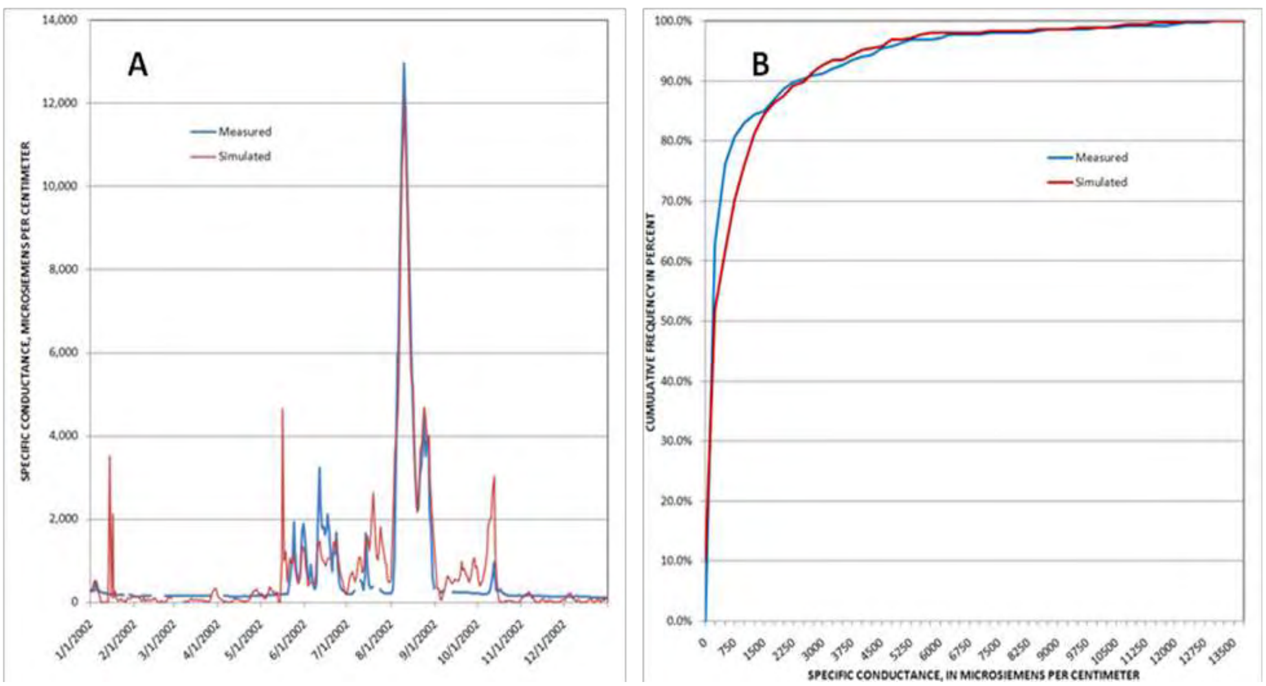

Figure 5. Graphs showing the performance of the daily specific conductance model for the Pawleys Island gage (station 021108125, fig. 1). Time series of measured and simulated values for 2002 are shown in the graph on the left and the cumulative frequency distribution of measured and simulated values are shown on the graph on the right.

conductance water. The cumulative frequency distribution of the specific conductance response to a 1.0 ft (30.5 cm) and a 2.0 ft (61 cm) sea-level rise for the period July 1995 to December 2002 is shown in figure 6. A 1-ft sea-level rise doubled the frequency of occurrence of specific conductance above 1,500 µS/cm to 3 percent. A 2-ft sea-level rise nearly quadrupled the frequency to 8 percent of the time. For the 7½-year simulation period, the number of days of specific conductance level at or above 2,000 µS/cm was 99 days for the measured sea-level conditions. A 1-ft sea-level rise increases the number of days to 198 and a 2-ft rise increases it to 345 days.

The duration of salinity intrusion can increase substantially with an incremental rise in sea level. There was an historic drought in 2002 and the salinity intrusion caused the intake above the Pawleys Island streamgage to be taken offline. Figure 6B shows specific conductance values for 2002 had the conditions occurred with a 1-ft and 2-ft rise in sea level. In 2002 the specific conductance values were above 2,000 µS/cm for 27 days. A 1-ft sea-level rise increases the duration of specific conductance values above 2,000 µS/cm to 54 days and a 2-ft sea-level rise increases the duration to 104 days.

Although increases of sea-level rises of 1- and 2-ft show substantial effects that would have operational consequence for municipal water-treatment plants, the climate change scenarios shown in this paper would allow water-resource managers to plan for mitigation efforts to minimize the effect of increase salinity of source water. Mitigation efforts may include timing of withdrawals during outgoing tides, increased storage of raw water, timing larger releases of

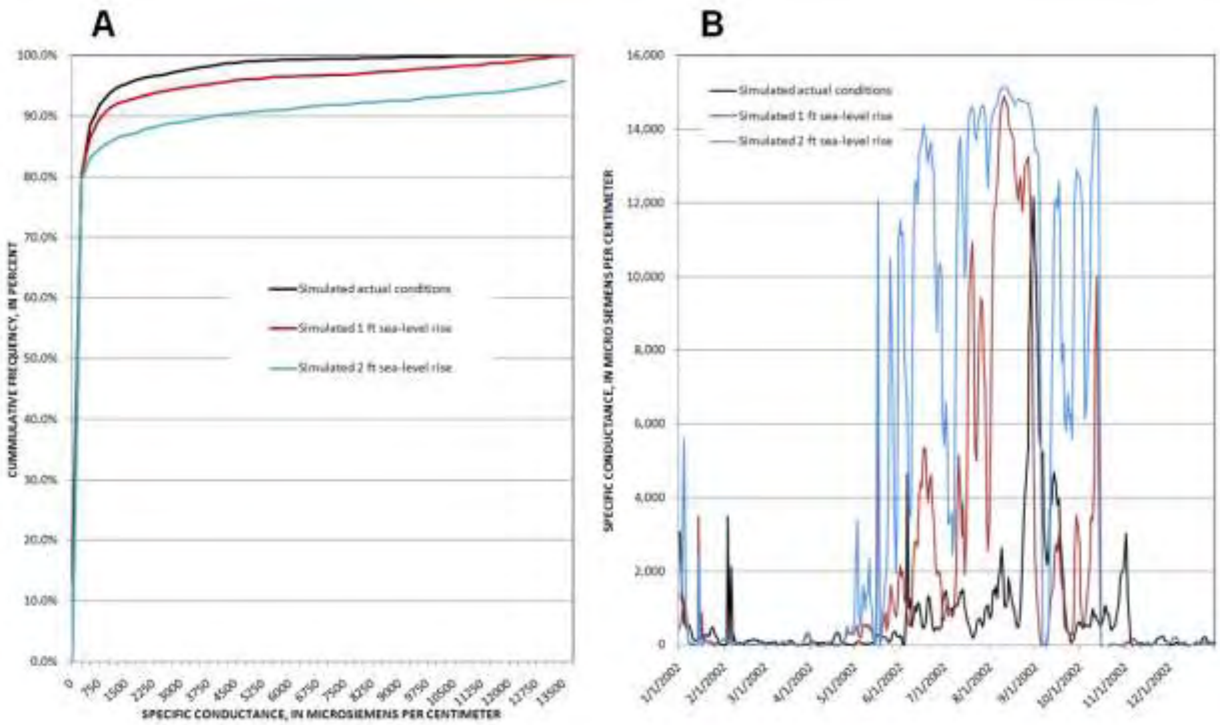

Figure 6. Graphs showing the specific conductance response to a 1-ft and 2-ft sea-level rise. Plot on the left shows the cumulative frequency distribution for a 7½ year simulation. The graph on the right shows the time series for the daily response during

regulated flows appropriately to move the saltwater-freshwater interface downstream, and the blending of higher conductance surface water with lower conductance water from an alternative source such as groundwater.

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