Development of Decision Support Systems for Estimating Salinity Intrusion Effects due to Climate Change on the South Carolina and Georgia Coast

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Abstract. 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 gage locations along the Atlantic Intracoastal Waterway and Waccamaw River near Myrtle Beach, SC, and Savannah River near Savannah, GA, data-mining techniques were applied to over twenty years of hourly streamflow, coastal water-quality, and water-level data. Artificial neural network (ANN) models were trained to learn the specific variable interactions that cause salinity intrusions. Streamflows into the estuarine systems are input to the models 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 salinity dynamic behaviors in both systems.

For a 7 ½ year simulation period, preliminary model results near a municipal freshwater intake on the Savannah River indicate that a sea-level rise of 1 foot (ft, 30.5 centimeters [cm]) increases the number of days from zero to 47 that brackish water occurs, or 2 percent of the time. A 2-ft rise increases days of brackish water from zero to 278 days, or 12 percent of the time. The 1- and 2-ft sea-level rise would shift the portion of the estuary by I-95 during periods of low streamflow from a tidal freshwater system (less than 0.5 psu) to an oligohaline system (less than 5.0 psu).

INTRODUCTION

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).

There are many municipal intakes long the Southeastern coast of the United States with the potential of being affected by potential climate change (fig. 1, Furlow and others, 2002). Threatened intakes include those serving the Grand Strand in South Carolina and Beaufort and Jasper counties in South Carolina and the city of Savannah in Georgia. Increases in the frequency and magnitude of salinity intrusion could threaten the potability of four freshwater municipal intakes as well as the biodiversity of freshwater tidal marshes. Although both the Savannah and Waccamaw Rivers have been studied, this paper focuses on the Savannah River near Interstate 95 Bridge (just downstream from a municipal freshwater intake) was selected for analysis and discussion for this paper.

MODELING

Previously developed empirical salinity models of the Savannah River and the Waccamaw River and Atlantic Intracoastal Waterway (AIW) (Conrads and others, 2006; Conrads and Roehl, 2007), were used to evaluate the potential effects of climate change on salinity intrusion. Both models were developed using data-mining techniques, including artificial neural network (ANN) models. Results from the previously developed ANN-based models of estuaries in South Carolina (Roehl and others, 2000; Conrads and others, 2003; Conrads

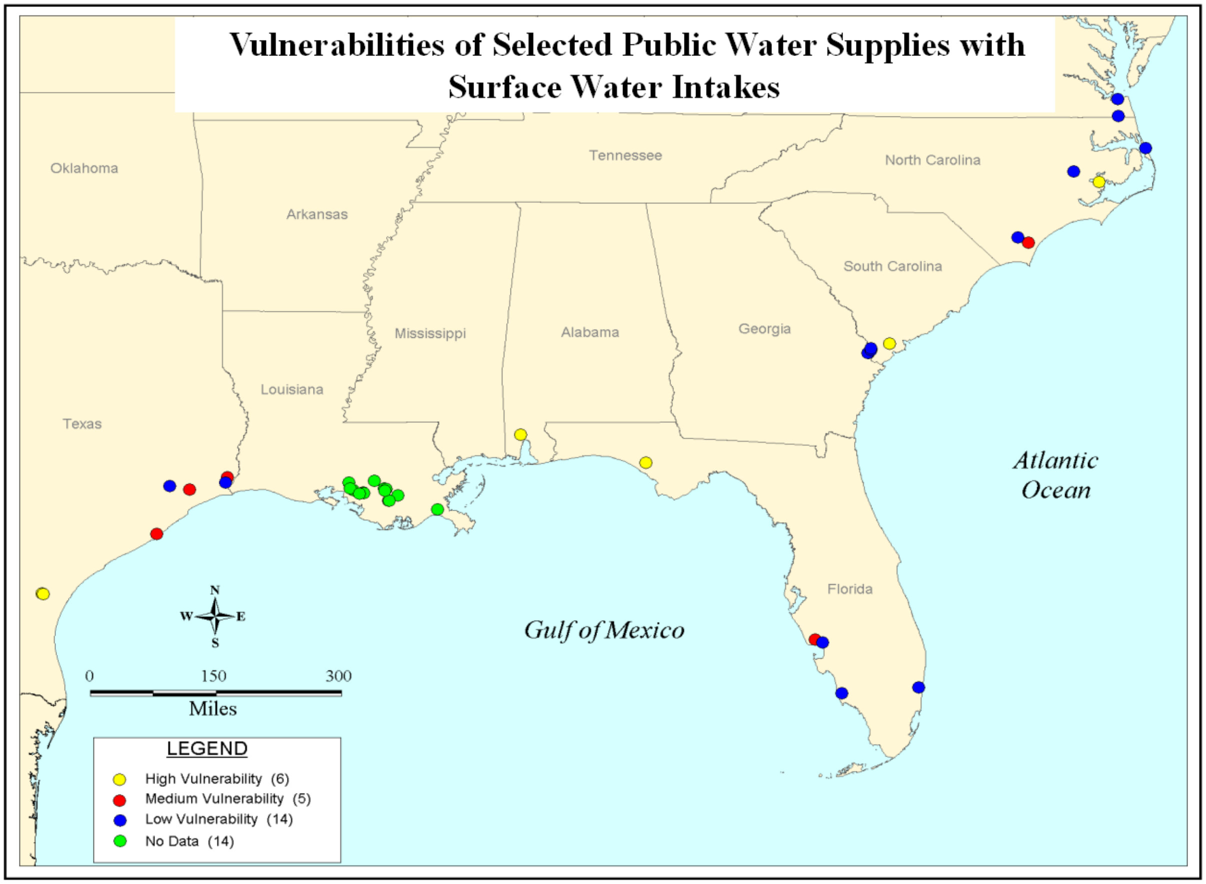

Figure 1. Vulnerabilities of selected public water supplies with surface water intakes to sea-level rise (from Furlow and others, 2002). Note intakes near Myrtle Beach are not shown.

and Roehl, 2007) 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 Lower Savannah River Estuary, Waccamaw River, and AIW. For the coastal water-quality stations, there are greater than 15 years of water-level and specific conductance data. These gaging networks are a valuable resource for addressing the critical conditions for salinity intrusion in these two systems. 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.

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 these systems are the flows and the chaotic oceanic disturbances represented in the chaotic component of water level in Savannah Harbor, Little River Inlet, or Winyah Bay. The primary period-

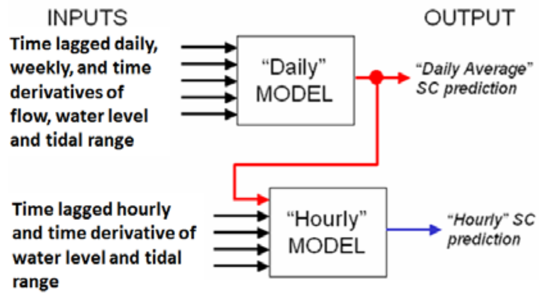

Figure 2. Artificial neural network architecture used to model specific conductance at each gage.

ic input to the system is the tide.

Signals, or time series, were decomposed into periodic and chaotic components using low-pass filtering techniques. 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.

Simulation of Salinity Intrusion. Subdividing a complex modeling problem into sub-problems and then addressing each one is a means to achieving the best possible result. Individual ANN models for simulating specific conductance were developed for the continuous coastal streamgages in the two systems. The models were developed in two stages (fig. 2). The first stage modeled the chaotic, lower-frequency portion of the signal, as represented by the filtered signals. The second stage modeled the periodic, higher-frequency, hourly specific conductance, using the predicted daily specific conductance as a carrier signal. Each model uses three general types of signals: 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. 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 streamgages. Generally, the daily models had coefficients of determination (R^2) values ranging from 0.85 to 0.87. The hourly models had R^2 values ranging from 0.57 to 0.87 (Conrads and others, 2006; Conrads and Roehl, 2007). Only the daily models are used for the climate change analysis. The I-95 stream gage (station 02198840) on the Savannah River (fig. 3), downstream from two municipal freshwater intakes, was selected for analysis and discussion for this paper. The meas-

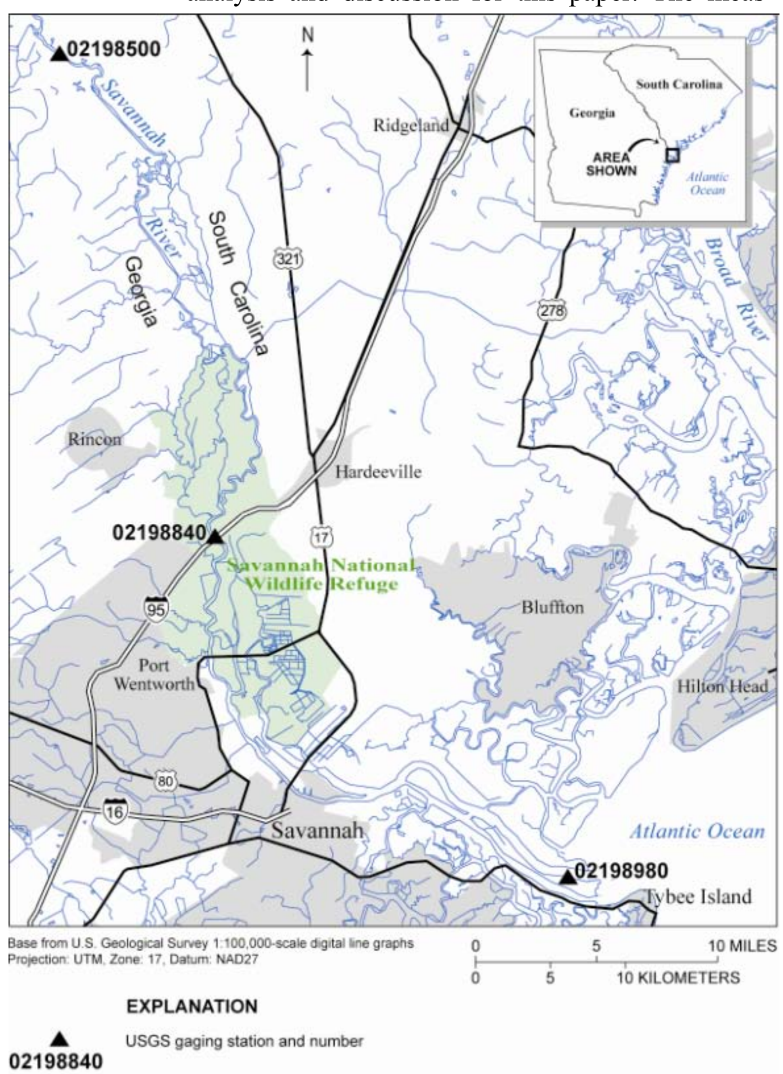

Figure 3. Map showing the location of the Savannah River at I-95 (station 02198840).

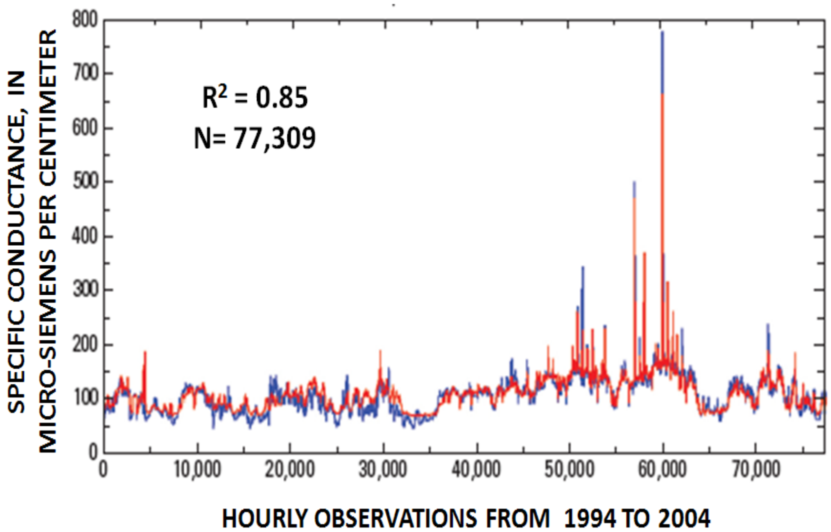

Figure 4. Measured (blue trace) and predicted (red trace) daily specific conductance for the Savannah River at I-95 (station 02198840). High specific conductance values around observation 60,000 occurred during the drought of 2002.

ured and simulated daily specific conductance are shown in figure 4.

Simulation of Sea-Level Rise. The Intergovernmental Panel on Climate Change (IPCC) projected sea-level rises of 8 inches to 2 ft by the end of this century (Karl and others, 2009). To simulate the effects of sea-level rise, the chaotic input of mean coastal water level was parametrically incremented by 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 salinity concentrations values (computed from specific conductance) were simulated for each incremental rise in sea level during the period July 1995 through December 2002.

MODEL RESULTS AND DISCUSSION

Municipal water treatment plants have operational limitation when the salinity concentration of the source water exceeds 0.5 psu. Of greater concern than the magnitude of salinity intrusion events is the frequency and duration of higher salinity water. For the 7½-year simulation period, daily salinity values never exceed 0.5 psu at the I-95 streamgage. A 1-ft sea-level rise increases the number of days to from zero to 47, or 2 percent of the time, and a 2-ft rise increases it from zero to 278 days, or 12 percent of the time. The 1- and 2-ft sea-level rise would shift the portion of the estuary by I-95 during periods of low streamflow from a tidal freshwater system (less than 0.5 psu) to an oligohaline system (less than 5.0 psu).

The duration of salinity intrusion can increase substantially with an incremental rise in sea-level. There was an historic drought in 2002 that resulted in an increase in salinity intrusion events that year. In 2002, there were no maximum daily salinity concentration values above 0.5 psu. A 1-ft sea-level rise increases the simulated duration of salinity concentration values above 0.5 psu to 20 days and a 2-ft sea-level rise increases the simulated duration to 95 days.

CONCLUSIONS

Although sea-level rise simulations of 1- and 2-ft show substantial effects with operational consequence for municipal water-treatment plants, the climate change scenarios shown in this paper allow water-resource managers to plan for adaptation efforts to minimize the effects of increased source water salinity. Adaptation efforts may include timing of withdrawals during outgoing tides, increased storage of raw water, timing larger releases of regulated flows appropriately to move the saltwater-freshwater interface downstream, and the blending of higher salinity surface water with freshwater from an alternative source such as groundwater.

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