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ESTIMATING SALINITY INTRUSION EFFECTS DUE TO CLIMATE CHANGE ON THE LOWER SAVANNAH RIVER ESTUARY

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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 may have a great impact on existing hydrological systems in the region.

The Savannah River originates at the confluence of the Seneca and Tugaloo Rivers, near Hartwell, Ga., and forms the state boundary between South Carolina and Georgia. The J. Strom Thurmond Dam and Lake, located 238 miles upstream from the Atlantic Ocean, is responsible for most of the flow regulation that affects the Savannah River from Augusta, Ga., to the coast. The Savannah Harbor experiences semi-diurnal tides of two low and two high tides in a 24.8-hour period with pronounced differences in tidal range between neap and spring tides occurring on a 14-day and 28-day lunar cycle. 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 in the Lower Savannah River Estuary, data-mining techniques were applied to over 15 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 data from the 9,850 square-mile Savannah River Basin were input into the model as time-delayed variables. 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.

Important freshwater resources are located proximal to the freshwater-saltwater interface of the estuary. The Savannah National Wildlife Refuge is located in the upper portion of the Savannah River Estuary. The tidal freshwater marsh is an essential part of the 28,000-acre refuge and is home to a diverse variety of wildlife and plant communities. Two municipal freshwater intakes are located upstream from the refuge. To evaluate the impact of climate change on salinity intrusion on these resources, 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 (USGS) Interstate-95 streamgage (station 02198840) for a 7½-year simulation show that historical daily salinity concentrations never exceeded 0.5 practical salinity units (psu). A 1-foot sea-level rise (ft, 30.5 centimeters [cm]) would increase the number of days of salinity concentrations greater than 0.5 psu to 47 days. A 2-ft (61 cm) sea-level rise would increase the number of days to 248.

KEYWORDS

Climate change, sea-level rise, salinity intrusion, drinking water intakes, data mining, artificial neural networks

INTRODUCTION

The Savannah River originates at the confluence of the Seneca and Tugaloo Rivers, near Hartwell, Ga., and forms the State boundary between South Carolina and Georgia (fig. 1). From Lake Hartwell, the Savannah River flows through two physiographic provinces, the Piedmont and the Coastal Plain. The city of Augusta, Ga., is on the Fall Line, which separates these two provinces. The slope of the river ranges from an average of about 3 feet per mile in the Piedmont to less that 1 foot per mile in the Coastal Plain (Sanders and others, 1990). Upstream from the Fall Line, three large Federal multi-purpose dams (Lake Hartwell, Richard B. Russell Lake, and J. Strom Thurmond Lake) provide hydropower, water supply, recreational facilities and a limited degree of flood control. Flow releases from Thurmond Lake are responsible for most of the flow regulation that affects the Savannah

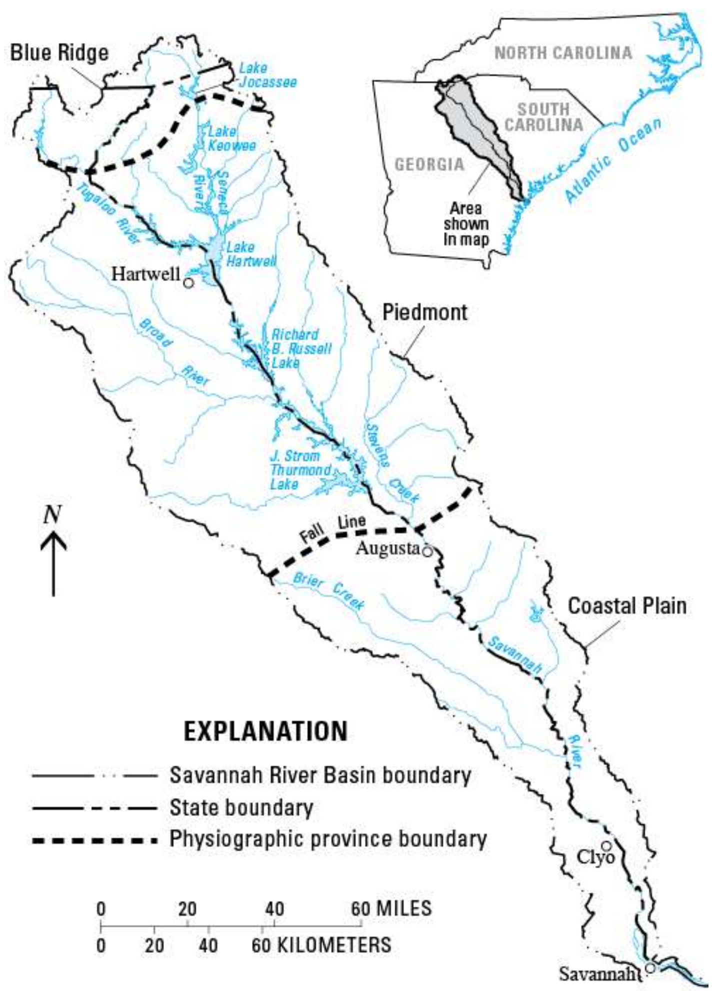

Figure 1. The Savannah River Basin in South Carolina, Georgia, and North Carolina

River from Augusta to the coast (Sanders and others, 1990).

From Augusta, Ga., the Savannah River flows 187 miles to the coast (fig. 1). The lower Savannah River is a deltaic system that branches into a series of interconnected distributary channels in the vicinity of the Savannah National Wildlife Refuge (fig. 2). The hydrology of the system is dependent upon precipitation, runoff, channel configuration, streamflow, and seasonal and daily tidal fluctuations (Latham 1990; Pearlstine and others, 1990). Savannah Harbor experiences semi-diurnal tides of two low and two high tides in a 24.8-hour period with pronounced differences in tidal range between neap and spring tides occurring on a 14-day and 28-day lunar cycle. Periods of lowest tidal amplitude are known as "neap" tides and periods of greatest tidal ranges are known as "spring" tides. The tidal amplitude in the lower parts of the estuary is approximately 5 to 6 feet (ft) during neap tides and greater than 8 ft during spring tides (Conrads and others, 2006). The resultant interaction of streamflow and tidal range allows the salinity intrusion to be detected more than 25 miles upstream near the Interstate 95 (I-95) bridge and the tidal water-level signal to reach approximately 40 miles upstream, near Hardeeville (fig. 2; Bossart and others, 2001).

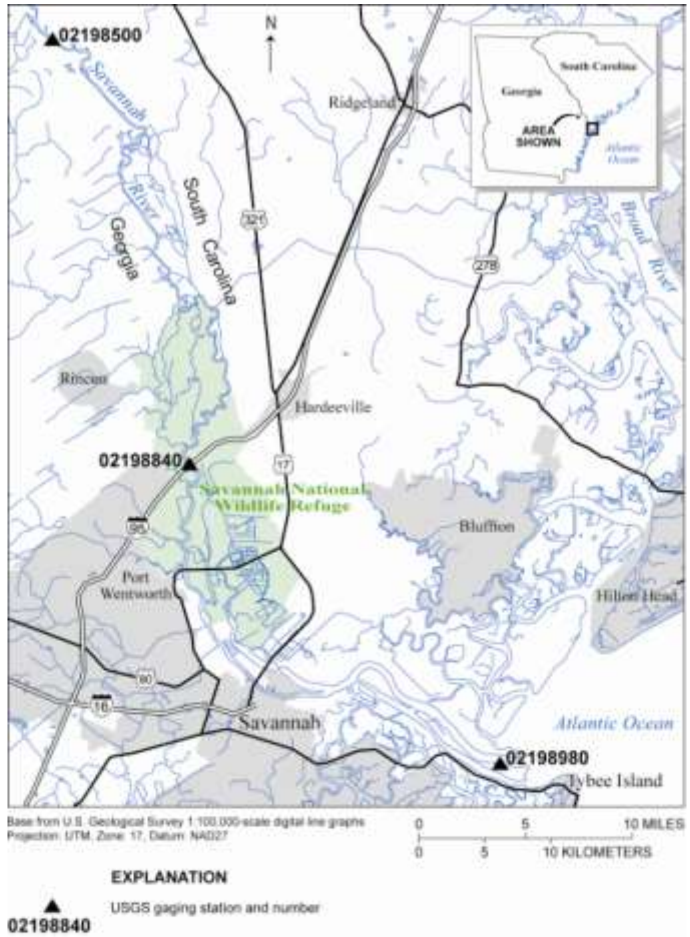

Figure 2. Map showing the location of the Savannah River at Clyo, Ga. (station 02198500), the I-95 (station 02198840), and the Ft. Pulaski, Ga. (station 02198980) streamgages.

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). Increases in the frequency and magnitude of salinity intrusion into the Lower Savannah River Estuary could threaten the potability of two freshwater municipal intakes as well as the biodiversity of freshwater tidal marshes.

APPROACH

A previously developed salinity model of the Savannah River (Conrads and others, 2006), was used to evaluate the potential effects of climate change on salinity intrusion. The model was developed using data-mining techniques, including artificial neural network (ANN) models, to evaluate salinity impacts due to potential deepening of Savannah Harbor on the freshwater tidal marshes proximal to the Savannah National Wildlife Refuge.

Results from the previously developed ANN-based models of estuaries in South Carolina (Roehl and others, 2000; Conrads and others, 2003; Conrads 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. For the coastal water-quality stations, there are greater than 15 years of water-level and specific conductance data. Data from the Lower Savannah River Estuary network are a valuable resource for addressing the critical conditions for salinity intrusion on the Savannah River. 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 this system are the flows and the chaotic oceanic disturbances represented in the chaotic component of water level in Savannah Harbor. The primary periodic 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. As shown in figure 3, the measured water level at Ft. Pulaski (station 02198980, fig. 2) was decomposed into its periodic signal of tidal range time series and its chaotic signal of mean water-level time series.

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. For the Lower Savannah River Estuary study, individual ANN models for simulating specific conductance were developed for the 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 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). Only the daily models are used for the climate change analysis. The I-95 gage (station 02198840, fig. 2), downstream from two municipal freshwater intakes, was selected for analysis and discussion for this paper. The measured and simulated daily specific conductances are shown in figure 4.

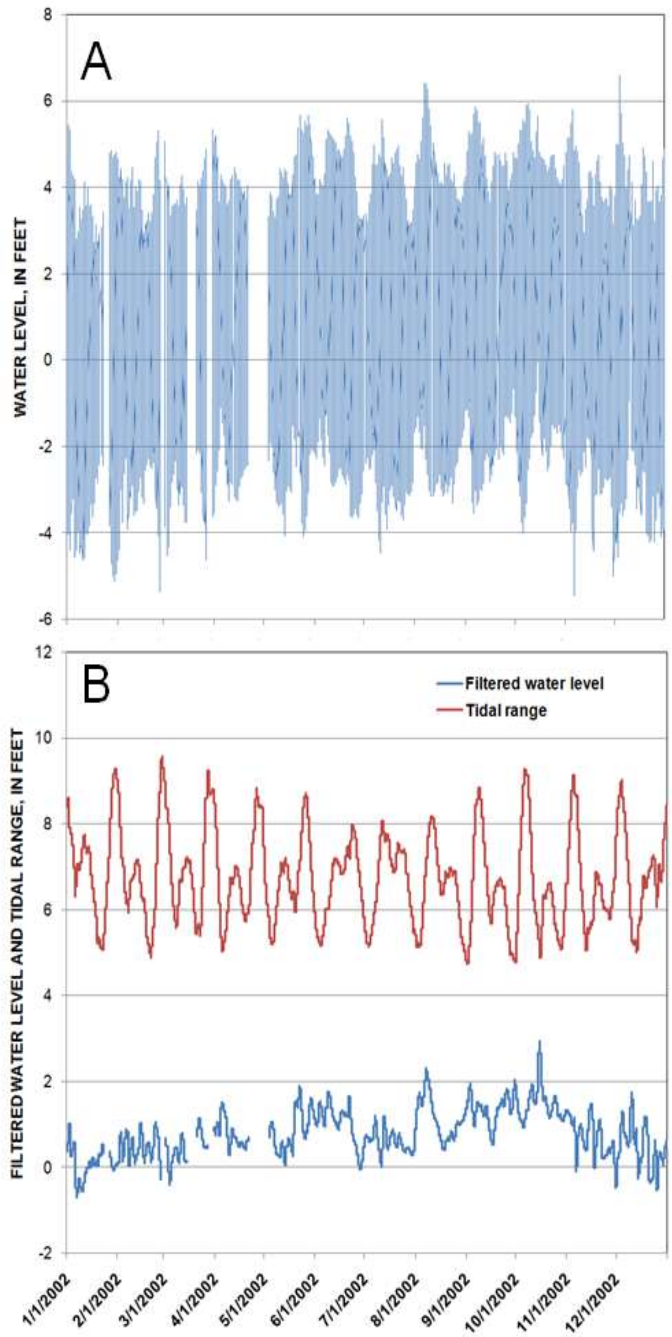

Figure 3. Decomposition of the Fort Pulaski (station 02198980)15-minute water-level signal (A) into the periodic component of tidal range and the chaotic component of daily water level (B).

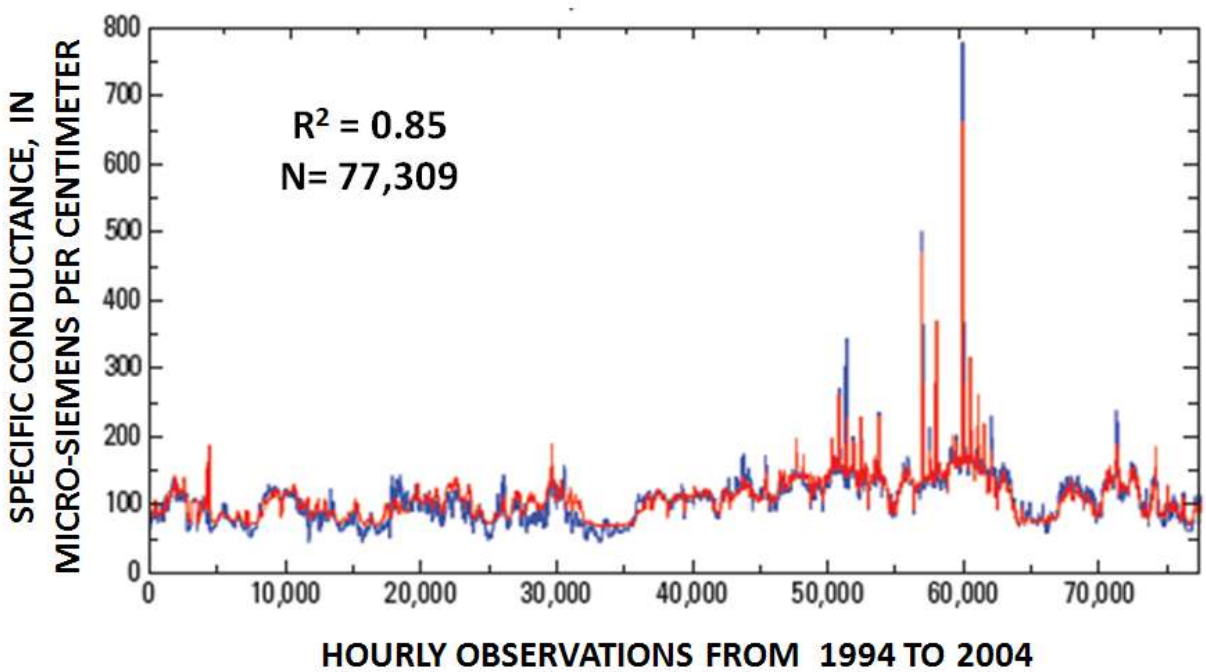

Figure 4. Measured (blue trace) and predicted (red trace) daily specific conductance for the Savannah River at I-95 (station 02198840).

The coefficient of determination for the I-95 daily model is 0.85, the root mean square error (RMSE) is 13 micro-Siemens per centimeter (µS/cm), and the percent model error (RMSE/range of measured data) is 1.7 percent (Conrads and others, 2006). The model satisfactorily simulates the daily specific conductance in the 200 µS/cm range and accurately simulates the high intrusion event in August 2002 that exceeded 750 µS/cm.

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 other, 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. The cumulative frequency distribution of the salinity 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 5. 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

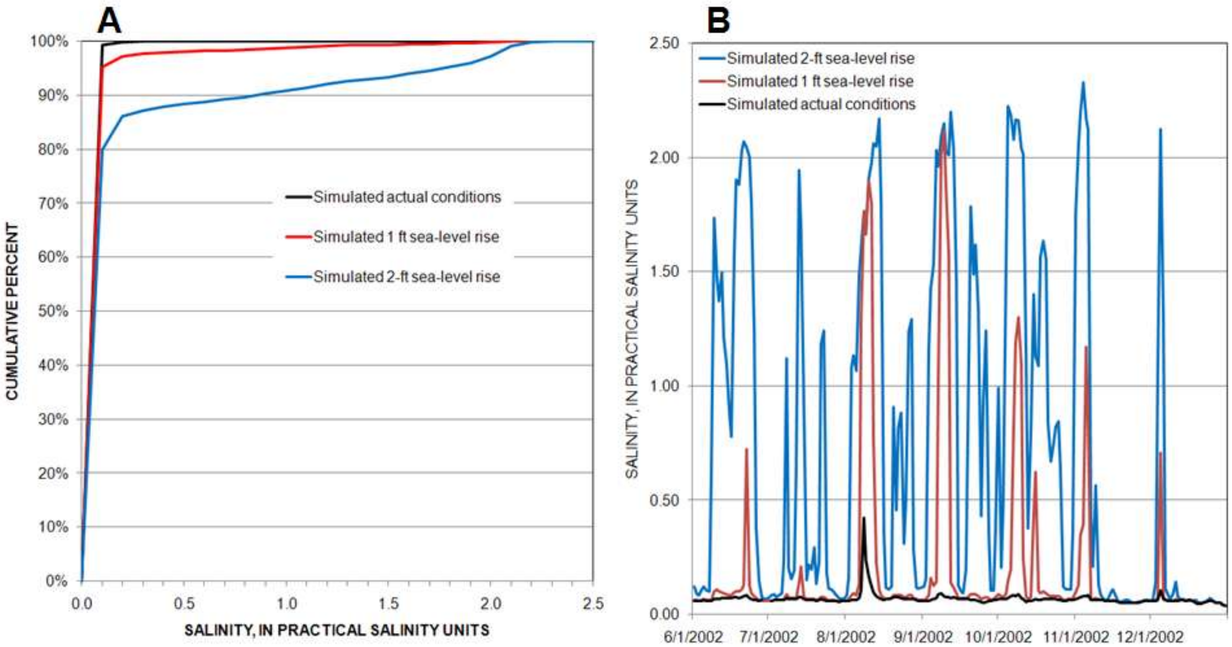

Figure 5. Salinity response to a 1-ft and 2-ft sea-level rise. Plot on the left (A) shows the cumulative frequency distribution for a 7½ year simulation. Plot on the right (B) shows the time series for the daily response during 2002.

the number of days to 47, or 2 percent of the time, and a 2-ft rise increases it to 278 days, or 12 percent of the time. The 1- and 2-ft sea-level rises 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. Figure 5B shows salinity concentration values for 2002 if the conditions occurred with a 1-ft and 2-ft rise in sea level. 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.

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 described in this paper allow water-resource managers to plan for mitigation efforts to minimize the effects of increased source water salinity. Mitigation 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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